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HANDBOOK OF SALMON FARMING

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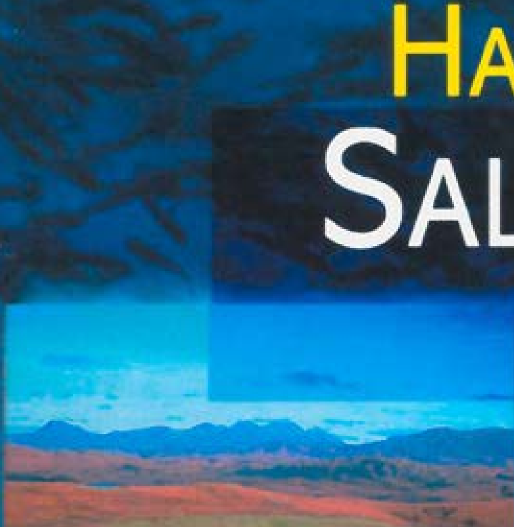

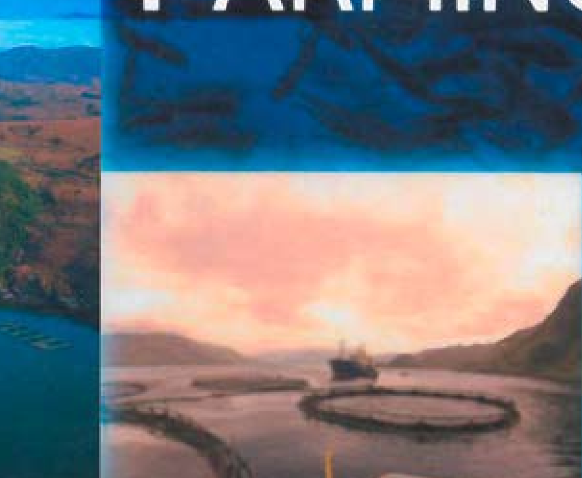

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Selina M. Stead
and Lindsay Laird

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Selina M. Stead and Lindsay Laird

Handbook of Salmon Farming

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The authors and publisher dedicate this book to the memory of Lindsay Laird, whose sparkling personality touched all who were privileged to work with her and to know her over the years. Lindsay's enthusiasm, dedication and professionalism never wavered, despite the illness which she fought so bravely for so long. Lindsay, and her contribution to aquaculture as a scientist, editor and author, will always be remembered.

Contents

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Foreword

This book goes to print as many of us who knew and worked with Lindsay Laird are in the early stages of coming to terms with her death. Lindsay maintained her engagement with this project right to the very end and it is entirely fitting that a book which so ably mixes science with issues of public policy and practical management should stand as her final contribution.

The salmon farming industry faces a number of major challenges. It is now an international industry with major multinational involvement. International competitive pressures are intense and likely to increase so the need for 'value added' and product differentiation is great. The industry is subject to increasing environmental scrutiny and, given both the physical environment in which it operates and the significance of the wild salmon lobby, this is inevitable. The Scottish industry has also recently confronted the threat of infectious salmon anemia.

Although the challenges are great the opportunity for the industry to continue to make a contribution to the economic and social development of our more isolated and vulnerable communities is equally great. Salmon farming should be the industry that most closely fits the test of sustainable development: economic growth, social development and environmental enhancement. To achieve that will require sustained engagement: this handbook represents Lindays's sustained engagement with the industries and the issues that confront it.

Professor John Sewell
September 2001

Preface

In 1988 the handbook *Salmon and Trout Farming* was published; in their preface the editors expressed the hope that the authors had produced a work that could be used on the farm; judging by the response to the book their wish has been fulfilled. Although now out of print and out of date there are still frequent requests for copies.

To reprint *Salmon and Trout Farming* or even update it would have been a mistake; so much has changed since 1988. It was therefore decided to prepare a completely new work, taking into account the huge changes that have occurred over that period. The first major decision was to restrict the book almost entirely to the commercial culture of Atlantic salmon for the food market; trout, ranching, production for restocking and some technologies such as recirculation deserve their own volumes. The growth of aquaculture has resulted in specialisation comparable with that of agriculture – only the most basic text would cover both pigs and cattle.

The salmon farming industry has expanded massively both in volume and in geographical range. Such changes are demonstrated by the fact that Chile, a southern-hemisphere, Pacific country has become the second biggest producer of (North) Atlantic salmon. Technological advances have affected all stages of the production cycle, from hatchery to processing. Such changes include control of environmental factors (light, temperature, water quality), holding facilities (bigger, stronger cages, recirculation systems) and the use of computers to plan production and control feeding and oxygenation. Better understanding of health management and the development and use of vaccines have improved stock survival. Improved knowledge of genetic tools for stock selection and improved feed formulation and manufacturing processes have contributed to better overall performance. This has led to more predictable growth and survival and facilitated the management of farms in business terms. One of the most noticeable changes in terms of ownership of salmon farms is that there has been a shift from smaller and sometimes individually run units to larger production systems that are owned by multinational companies.

Other changes over the past decade include increased interest on the part of the public in the way that food is produced and greater demands placed on food safety. The aquaculture industry is increasingly working towards improving the public image of its products such as salmon, particularly in light of negative media coverage. Changes include the development of new regulations and legislation, routine inspections concerning environmental impacts of aquaculture and the quality of the product when marketed. A major shift is that salmon are no longer marketed only as fresh, frozen or smoked fish but are also sold in a variety of prepared forms including ready made meals, competing with other convenience foods.

The growth and increase in complexity of the salmon farming industry is being accompanied and aided by specialists in fish health, feed technology, fish physiology, marketing and many other areas. It is clear that there is still a great deal of progress to be made. With this in mind we invited some of these experts to produce chapters detailing current and possible future developments in their diverse fields. Allowing specialists a relatively free rein has resulted in a fascinating range of up to date chapters. Because of the choice of topics it is inevitable that there is a small degree of overlap; however, this allows the presentation of more than one view and emphasises that a definite recipe for success in salmon farming does not yet exist. Perhaps this is something for the next edition in 2012 or beyond!

Selina Stead and Lindsay Laird
Aberdeen, 2001

Abbreviations

AA	amino acid
ACTH	adrenocorticotrophic hormone
AMR	active metabolic rate
ANF	antinutritional factor
APP	acute phase proteins
ASV	air saturation value
AT	alpha-tocopherol
ATP	adenosine triphosphate
AZE	allowable zone of effect
BHA	butylated hydroxanisole
BHT	butylated hydroxytoluene
BKD	bacterial kidney disease
BOD	biological oxygen demand
BSE	bovine spongiform encephalitis
BWC (%)	body weight consumed (percentage)
CAP	controlled atmosphere packaging
CO	capelin oil
COX	constitutively expressed enzyme
CPC	canola protein concentrate
CPE	cytopathic effect
CRP	C-reactive protein
CSW	chilled sea water
DE	digestible energy
DO	dissolved oxygen
DP	digestible protein
EAA	essential amino acids
EFA	essential fatty acids
EHN	epizootic haematopoietic necrosis
EIA	environmental impact assessment
ELISA	enzyme-linked immunosorbant assays

EQS	environmental quality standards
ERM	enteric red mouth disease
FAQ	fair average quality
FCR	food conversion rate; feed conversion ratio
FE	feed efficiency
FR	feed rate
GF	thermal growth coefficient
GH	growth hormone
GMO	genetically modified organisms
GRC	glass-reinforced concrete
GRP	glass-reinforced plastic
GTH	gonadotropin hormone
HDL	high density lipoprotein
HKS	haemorrhagic kidney syndrome
HUFA	highly unsaturated fatty acid
ICZM	integrated coastal zone management
IFAT	immuno-fluorescent antibody techniques
IEM	integrated environmental management
Ig	immunoglobulin
IHN	infectious haematopoietic necrosis
IMSFS	integrated management strategy for the farming of salmon
IPN(V)	infectious pancreatic necrosis (virus)
ISA	infectious salmon anaemia
K	condition factor or index
LP	linear programming
LPS	lipopolysaccharide
LT	low temperature; leukotrienes
LX	lipoxins
MAI	marker-assisted selection
MAP	modified atmosphere packaging
MAS	marker-assisted selection
MCAs	marine consultation areas
MHC	major histocompatibility gene complex
MIS	marketing information systems
MOPA	moisture, oil, protein and ash
MRL	maximum residue level
NCC	non-specific cytotoxic cells
NK	natural killer
NO	nitric oxide
PCR	polymerase chain reaction
PD	pancreas disease
PG	prostaglandins
PO	Peruvian anchovy oil
POV	peroxide value method
PRL	prolactin

PUFA	polyunsaturated fatty acid
RAG	recombination activating genes
RAPD	randon amplified polymorphic DNA
ROA	return on assets
ROE	return on equity
RSPB	Royal Society for the Protection of Birds
SACs	special areas of conservation
SAP	serum amyloid P component
SD	sustainable development
SDA	specific dynamic action
SEDD	Scottish Executive Development Department
SERAD	Scottish Executive Rural Affairs Department
SEPA	Scottish Environment Protection Agency
SGR	specific growth rate
SMR	standard metabolic rate
SO	soybean oil
SPA	Special Protection Area
SRS	salmon rickettsial syndrome
TBAR	thiobarbaturic acid reactive compound
Tc	cytotoxic T cells
TcR	T cell receptor
Th	helper T cells
TSA	tryptic soya agar
TSH	thryotropin
TX	thromboxanes
VHS	viral haemorrhagic septicaemia

1

Biology of salmon

1.1 INTRODUCTION

Animal husbandry depends on meeting the food and environmental requirements of the species concerned in a protected environment in order to realise enhanced survival and growth compared with that which would be obtained by harvesting from the wild. Most terrestrial farm animals such as poultry, sheep and cattle have been selectively bred and farmed since Neolithic times, whereas cultivation of the entire life cycle of the Atlantic salmon (*Salmo salar* L.) within captivity has only been widely practised within the last 30 years. Enclosing salmon that would otherwise migrate over possibly thousands of kilometres during the course of their life cycle places a greater responsibility on the aquaculturist for animal welfare than is normal in most terrestrial animal husbandry. The support of salmon in captivity requires monitoring and control of temperature, oxygen, light and water flow in a way that would be totally alien to upland sheep farmers in tending their stocks. Success in salmon farming can only be achieved through detailed knowledge of the fishes' biological requirements. In this chapter we consider the basic anatomy and physiology of the salmon in relation to aquaculture.

Zoologists divide the fishes into three Classes: the Agnatha (jawless fish, lampreys and hagfish), the Chondrichthyes (cartilaginous fish, sharks and rays) and the Osteichthyes (bony fishes, a group that includes most of the familiar fish species). The bony fishes, from which land vertebrate animals are descended, have a long evolutionary history going back to heavily-armoured forms that lived in the seas in the Devonian era 500 million years ago. The salmon belongs to a modern group of bony fish known as the Teleostei that first appeared 150 million years ago during the Jurassic when large reptiles dominated on land prior to the emergence of mammals. The evolution of about 20,000 species of teleost fishes that now occupy all aquatic environments on Earth from the deepest oceans to the highest mountain streams has been contemporary with the spread of birds and mammals. The diversity of teleosts is immense: it includes tiny guppies (*Poecilia*), the enormous blue fin tuna (*Thunnus thynnus*), flying fish (*Exocetus*), deep-sea angler fishes (*Ceratioidei*) and bottom-living forms such as sole (*Solea*). Amongst this tremendous variation the salmon has a very basic primitive body form little changed from that of the first fossil teleosts from the Jurassic.

1.2 ANATOMY

1.2.1 External features

The salmon has two kinds of fins: the median fins and the paired fins. The paired fins are the pectoral fins, which are attached to the pectoral girdle just behind the head, and the pelvic fins, which are attached to the pelvic girdle half way along the body. The pelvic fins have an axillary process, which fills the angle between the fin and the body, aiding streamlining. The main median fins are the dorsal fin, anal or ventral fin and the caudal fin (Figure 1.1). Bony rays support all these fins. The rays are remarkably complex structures, each with at least two pairs of muscles at the base: one pair tilts the ray to the left or right and a second pair erects the ray forwards to down and backwards. In this way the fin can be moved and waved in complex ways for purposes of swimming and display. The rays are made up of stacks of small bones threaded together by tendons which enable the rays to be bent or stiffened by the action of the basal muscles (Figure 1.2). Quite subtle movements are possible. In addition to the rayed fins, the salmon has an adipose fin which has no rays and is made up of fatty and connective tissue just like the pelvic axillary process.

The adipose fin is often clipped in order to batch mark groups of fish and, by international convention, is used to denote the presence of coded internal tags in wild Atlantic salmon. Clipping axillary processes is inconspicuous and provides a useful 'confidential' mark for special purposes. Even if clipped as parr or smolts, adults never regenerate the adipose fin. Other fins can be partially clipped for marking purposes; they are capable of regeneration but discontinuities in the rays remain evident. In farmed conditions persistent damage to fins with constant minor infections often leads to stunted or missing fins. The status of the fins is a good indicator

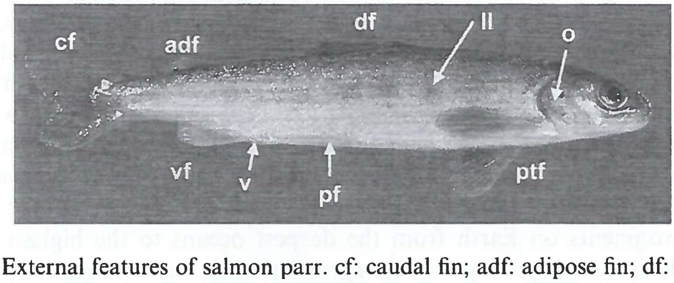

Figure 1.1. External features of salmon parr. cf: caudal fin; adf: adipose fin; df: dorsal fin; ll: lateral line; o: operculum (gill cover); ptf: pectoral fin (paired); pf: pelvic fin (paired): v: vent; vf: ventral or anal fin.

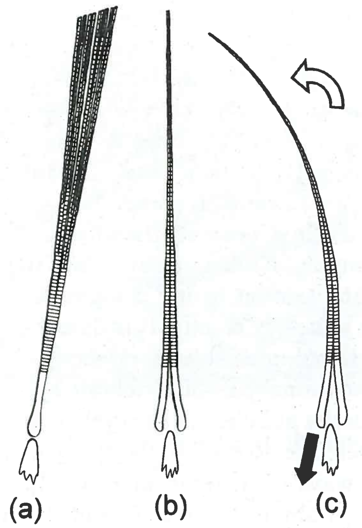

Figure 1.2. The branching or 'soft' ray as found in fins of the salmon. (a) Side (lateral) view of one fin ray showing the branching structure made up of numerous small bones. (b) Anterior view showing how the ray is made up of two identical halves. (c) The same view as (b) indicating how muscle tension on the base of one side results in bending. Other muscles can move the ray fore and aft to erect and retract the fin respectively. (After Videler, 1993.)

of the quality of the past husbandry history of the individual fish; the aquaculturist should strive to produce fish with well-developed fins with straight rays.

Three sets of sense organs are visible externally: the nostrils, eyes and the lateral lines (Figure 1.3). On the dorsal surface of the snout there are openings to the

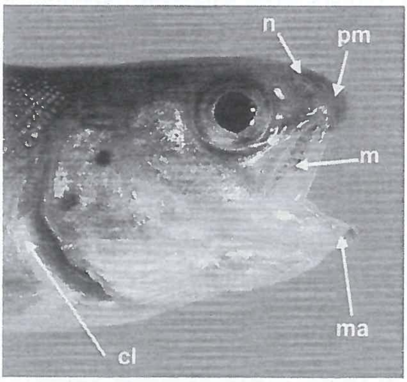

Figure 1.3. Detail of the head of a salmon parr with the mouth open. cl: cleithrum; ma: mandible; m: maxilla; pm: premaxilla; n: nostril.

olfactory organs. On each side is a forward-directed opening into which water normally flows, and a backward-directed opening out of which water flows. Beneath the pair of pores on each side there is a cavity with a floor covered with much folded sensory epithelium known as the olfactory rosette. This is connected to the forebrain by the first cranial olfactory nerve. The fish thus samples the water flowing over its snout by using the extremely sensitive olfactory organ which detects substances dissolved in the water and passes that information directly to the forebrain. There is no connection between the olfactory chambers and the buccal (mouth) cavity as in mammals. Recent research has suggested that the magnetic sensitivity which enables the salmon to use compass direction to navigate during migration is located in the olfactory rosette. It is thought that magnetite particles in the epithelium generate a signal in the olfactory nerve.

The salmon has a conventional pair of vertebrate eyes lying in orbital sockets on either side of the head. Muscles attached to the eyeball can move the eye to a certain extent within the orbit. There are no eyelids; the eyes remain permanently open. The field of view of each eye is wide, with a binocular overlap zone between the two eyes in the forward direction and ability to look up and down. The only entirely blind area is directly behind. The eye has a spherical lens beneath the cornea, surrounded by an iris with limited ability to change aperture. The retina is equipped with both colour-sensing cones and dark/light-sensing rods. The cones are of four types with colour sensitivity extending from the red (long wavelengths) to ultra-violet (short wavelengths). During development, changes take place in the colour sensitivity of the eye. Ultra-violet sensitivity is only present in juveniles, and when adapting to seawater conditions at smoltification the rods and cones change their light-sensing pigments to shorter wavelengths enhancing the blue sensitivity that is necessary for oceanic life. It is thought that this is reversed upon migration back into freshwater.

In contrast to the human eye where the cones with colour sensitivity are concentrated in a central fovea area of the retina, the salmon eye has more-or-less equal colour sensitivity over the whole retina so the fish would be able to identify correctly food items and potential danger from whatever direction of approach. Each eye is connected to the brain by a large optic nerve (II) running directly to the mid-brain tectum.

Along each side of the fish is a lateral line organ. This consists of a tube lying under the skin connected at frequent intervals to the surrounding water. Vibrations or movements in the surrounding water are transmitted directly to the lateral line canal in which lie clustered hair cell sensors that detect movement and transmit information via a lateral line nerve to the hind brain. The lateral line organ works like a low-frequency hearing organ; it can detect and locate movements of other fish, for example, and enable the fish to maintain its position in a shoal in the dark simply by following the vibrations of adjacent fish. The organ makes the salmon very sensitive to changes in water flow, which is so important in successfully negotiating obstacles to migration in rivers. When branding or marking fish it is obviously undesirable to damage the lateral line.

The skin of the salmon is a very important structure since this is the primary barrier between the animal and the surrounding environment. In contrast to

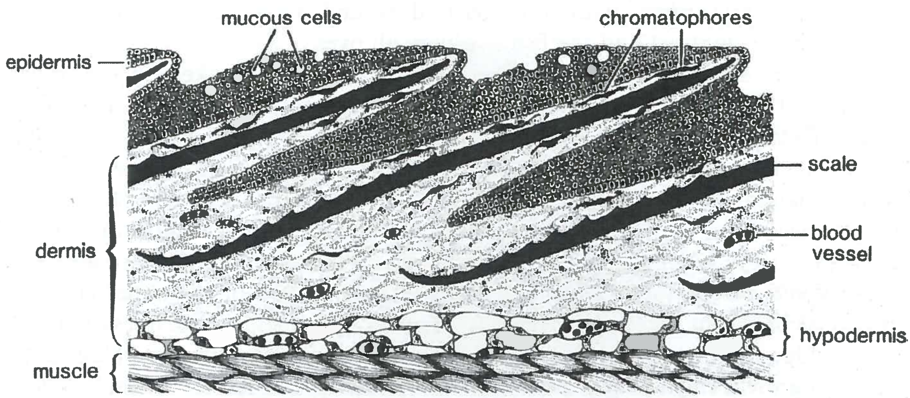

Figure 1.4. Diagram of a longitudinal section through the skin. The scales lie beneath the epidermis in pockets penetrating into the dermis.

mammals, in teleost fishes the outer layer of skin is not a dead cornified layer but a thin layer of transparent living cells known as the epidermis (Figure 1.4). The scales lie beneath the epidermis so it is the epidermis which is the first line of protection for the fish and keeps out bacteria, viruses and fungi. Loss of scales or damage to the epidermis leave the fish vulnerable to infection. Wounds, however, close up very quickly; for example a new layer of cells grows over a missing scale within 24 hours. This thin emergency epithelium immediately begins to regulate salt and water balance across the skin while longer-term repair, including growth of replacement scales, occurs beneath the protection of this barrier. Loss of an excessive area of skin is lethal owing to the amount of salts and water lost, depending on whether the fish is in fresh, brackish or salt water. The epidermis has mucous cells that open to the surface and exude the mucus which covers the surface of a healthy fish. The mucus has mild bactericidal and fungicidal properties, providing some protection against infection. In times of stress mucus production can be excessive.

The skin is also responsible for the external colour and appearance of the fish. The epidermis itself is transparent—a layer of needle-like guanine crystals in the dermis imparts the characteristic silvery appearance of the salmon. Overlying this are colour pigment cells known as chromatophores. The chromatophores can expand and contract in diameter. When contracted, they are almost invisible and reveal the underlying silver layer. When expanded, however, they darken the appearance of the fish. Particularly in freshwater it is normal for fish to adopt coloration that matches the background as closely as possible. Fish kept in light colour tanks adopt a much paler appearance than is normal. When stressed through disease or low rank in a dominance hierarchy they tend to become dark as a result of the effect of stress hormones expanding the chromatophores. Thus runts or diseased fish in tanks can often be recognised by their dark coloration. A similar darkening occurs during anaesthesia. Post-mortem, the skin goes through a series of colour changes before the chromatophores finally stop working; this often gives freshly-harvested fish a blotchy appearance, with some parts dark and others silvery, until all the chromatophores contract and the fish is silvery all over.

The scales are solid calcareous structures embedded in pockets in the tough lower dermal layer of the skin. Most of the body, excluding the head region, is covered in scales which overlap one another like slates on a roof so that only 20% of each scale is visible. In the region of the lateral line the scales have pores through which the lateral line canal passes—the Atlantic salmon has 114–130 such pored scales in a row from the head to tail. If the skin is scraped, scales can be torn out of their pockets and examined under a microscope. The visible part normally has epidermis and chromatophores attached but the 'root' part of the scale has concentric lines on it that reflect the growth history of the individual. The lines or circuli are hard ridges on the upper surface of the scale. They are not directly analogous to the annual growth rings on trees; each year is marked by a number of circuli. When growth is fast the circuli are far apart, but when growth is slow the circuli are close together. Annual rings allowing ageing of fish therefore appear as dense bands of circuli close together, reflecting slow growth during the winter. In salmon the number of winters in freshwater and then the acceleration in growth on transfer to seawater is very distinct. The annual rings in a farmed fish, which has a more continuous food supply and selection for a short life cycle, are never as distinct as in wild fish. Farmed fish also have a tendency to lose scales, and replacement scales can be recognised by the absence of circuli during the phase before the new scale reaches the correct size. Further growth then has circuli. The scale may regress in size and show erosion if a fish is starved, or during the spawning season. Subsequent growth is not concentric with the original circuli so a permanent record of the growth check is evident in the scale. Skilled reading of a selection of scales (never use just one scale) can reveal much about the history of the individual fish (Figure 1.5).

The mouth of the salmon opens directly into the buccal cavity on either side of which are four gill arches (Figure 1.6). During normal breathing the salmon takes in water through the mouth which is then passed out on either side of the buccal cavity through the gills and out under the opercular flaps on either side of the head. This flow of water is sustained by movements of the jaws and the sides of the head and the operculum (Figure 1.3). First the buccal cavity expands to suck water in through the mouth, next the mouth closes and the floor of the buccal cavity moves upwards to compress the volume of water taken in which is then forced out through the gills. The operculi also exert a suction effect, which depends on a flexible layer of skin along the margin of the operculum that acts as a non-return valve. If the margin of the operculum is damaged, as sometimes occurs during poor husbandry, the salmon's breathing movements will be laboured to compensate for the back leakage that occurs. When swimming at speed or resting in fast water flows there is no need for respiratory movements of the mouth and operculum; the fish can use ram ventilation, holding the mouth open so that water flows through the gills naturally.

Feeding uses an exaggerated breathing movement. To pick up a pellet of food the salmon swims towards it, at the same time sucking in water so that the food item moves towards its mouth instead of being swept away by the bow wave of the head.

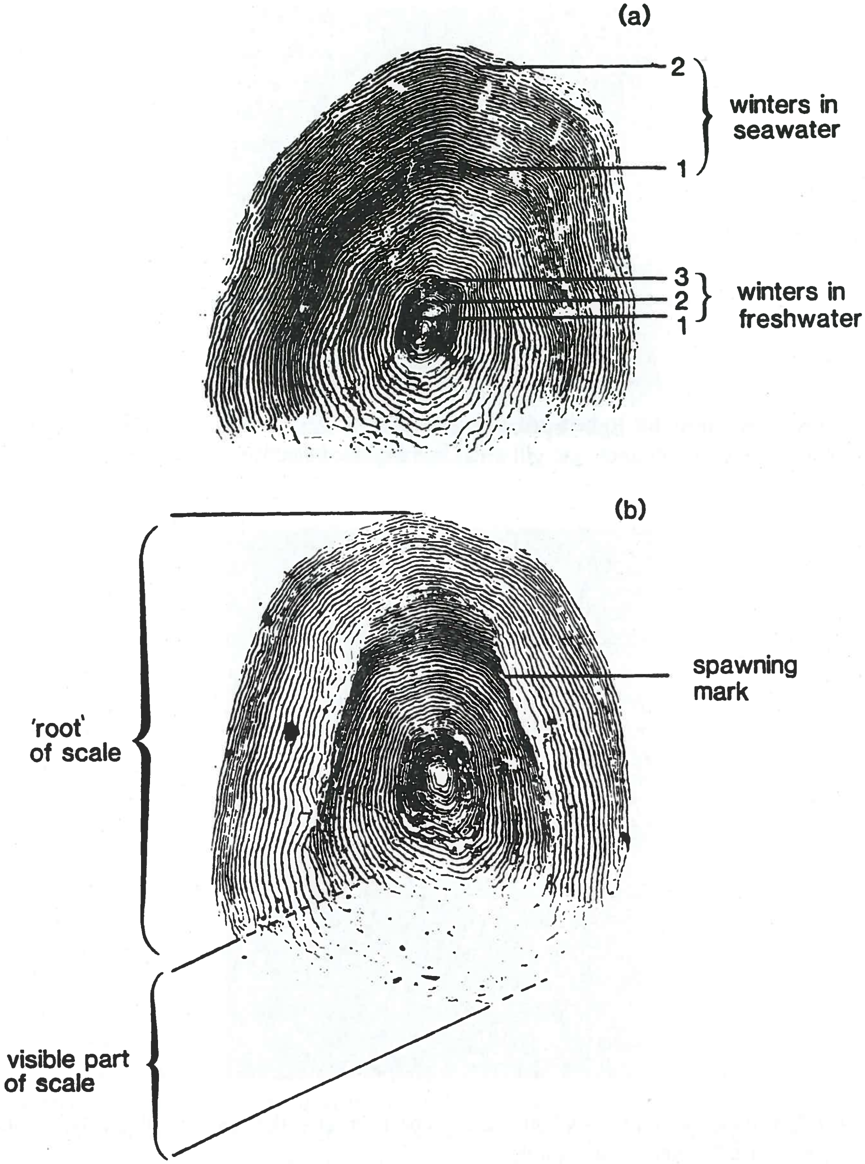

Figure 1.5. Scales of wild Atlantic salmon showing growth rings. The circuli, ridges on the scale, are visible on the 'root' portion of the scale which is normally embedded in the dermis. (a) This fish spent three winters in freshwater before going to sea. The bands corresponding to two winters at sea are visible. This fish is described as 3.2+. (b) Scale showing a spawning mark. This fish has spawned previously, and the erosion of the scale correlated with starvation and loss in weight during spawning is evident. The scale has then regrown as the fish recovered upon return to seawater, but the discontinuity is evident in the circuli.

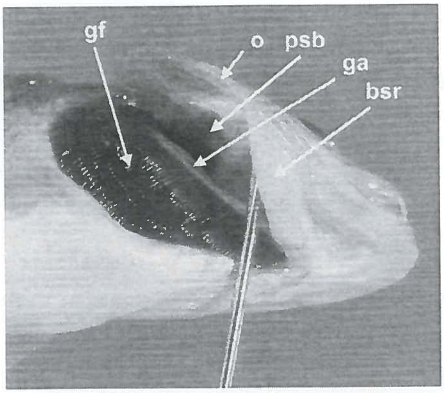

Figure 1.6. View into the right opercular cavity of a salmon parr. gf: gill filaments; o: operculum; psb: pseudobranch; ga: gill arch; bsr: brachiostegal rays.

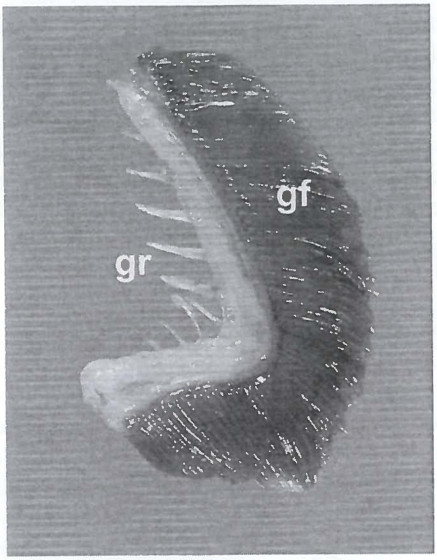

Figure 1.7. First gill arch of an Atlantic salmon parr. gr: gill rakers; gf: gill filaments. The full complement of gill rakers is not visible.

When the mouth opens, the upper jaw maxilla bones swing downwards to close the side of the mouth, aiding the suction effect from the forward direction (Figure 1.3). Suction feeding is important, particularly in young fish picking up food from the bottom. Using pure suction salmon can pick up items from some distance in front of the head without having to move the whole body. Damage to jaws and operculi not only makes breathing difficult, it also makes feeding inefficient (Figure 1.7).

The gill arches are equipped with rakers, 17–24 on each side of the first gill arch in Atlantic salmon. These act as filters, retaining food in the buccal cavity while water flows out across the gills. The distance between the gill rakers gives an indication of the minimum size of food particles upon which the salmon can efficiently feed. The fish can reverse the water flow over the gills by using a distinctive 'coughing' movement. This is used to clear detritus and mucus from the gills and excessive coughing is indicative of poor water quality. The breathing rate of salmon varies according to fish size (slower in bigger fish) and temperature (faster with increase in temperature). Individuals with abnormally high breathing rates are showing evidence of stress, perhaps from recent handling, or it may be evidence of disease. High breathing rates may be compensating for gill damage, anaemia or other disorders.

The urinary ducts, genital openings and the anus all open together at the vent just in front of the ventral or anal fin. This marks the end of the body and behind the vent is the tail region of the fish (Figure 1.1).

1.2.2 Internal structures

1.2.2.1 The skeleton

The salmon backbone is made up of 59–60 vertebrae, which are approximately equal in size from head to tail. The last few vertebrae in the tail curve upwards to support epiural plates above and hypural plates below to which tail fin rays and muscles are attached. The upward curvature of the spine, hidden by overlying muscles and tendons, is a link with the primitive heterocercal tail arrangement of the teleost ancestors. The brain is enclosed in a protective cranium mounted on the front end of the spine and the spinal cord runs back along the body through neural arches on the upper (dorsal) surface of the vertebrae. The centrum, or body, of each vertebra is made up of two hollow, bony cones lined up apex to apex into the recesses of which fit the connective cushioning that separates the vertebrae one from another. In X-rays this biconal arrangement gives healthy salmon vertebrae a distinctive 'X' appearance. Damage through handling, disease or malnutrition is readily evident in X-radiographs (Figure 1.8). In the region of the body cavity two ribs are attached to each vertebra, providing support for the muscular body wall on either side. Posterior to the body cavity, in the tail region each vertebra carries a haemal arch ventral to the septum. Within the canal formed by the haemal arch are found the caudal artery, caudal vein and caudal lymphatic vessels. The neural and haemal arches are extended into spines that support the median septum above and below the vertebral column to which the muscle blocks on either side of the fish are attached. Supports of the median fins are articulated to these spines.

The paired fins are mounted on the pectoral and pelvic girdles. The pectoral girdle is attached to the cleithral bone, which forms the posterior margin of the opercular cavity. The pelvic girdle is not attached to any other part of the skeleton but is embedded in the ventral muscle two-thirds of the way along the

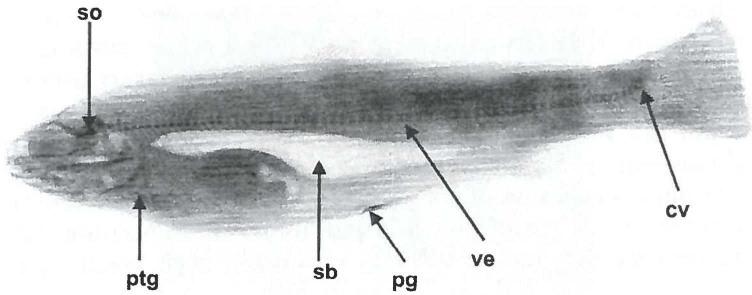

Figure 1.8. X-radiograph image of a young salmon post-smolt. so: sagittal otolith, conspictious within the skull; ptg: pectoral girdle; sb: swimbladder; pg: pelvic girdle; ve: vertebrae; cv: caudal vertebrate (note how terminal vertebrae curl upward in the tail region). (Image courtesy of Professor D.F. Houlihan, University of Aberdeen.)

body cavity. This bone obstructs the ventral incision normally used when gutting salmon.

The skull in salmon, as in most fish, is exceedingly complex with numerous bones capable of moving relative to one another to achieve the feeding and respiratory movements (Figure 1.8). The eyes are mounted in orbital sockets on either side of the cranium but are surrounded by the mobile cheekbones.

The bones of teleost fish are solid, without any marrow spaces and are acellular (once the bone is laid down it cannot be readily reabsorbed). Starved fish therefore lose muscle and fat but the size of the head and length of the body remain the same, giving a 'pin-head' appearance.

1.2.2.2 The muscles

In many respects the muscles are the most important part of the fish, since this is the part of interest to the consumer. The main muscle blocks, or myotomes, are arranged in blocks on either side of the median septum formed by the neural and haemal spines of the vertebrae. There is also a horizontal septum separating the upper (dorsal) epaxial muscles from the ventral hypaxial muscle. In a salmon steak (transverse section), therefore, the muscle falls into four main parts: the left and right epaxial and hypaxial muscles. From head to tail the muscle is divided by myosepta into segments, known as myotomes. The muscle fibres run roughly fore and aft between the myosepta, which transmit the force of contraction to the skin and backbone. The muscle fibres are conventional vertebrate striated muscle fibres as described in most elementary biology textbooks. When the meat is cooked, the myosepta dissolve away, freeing the myotomes to form the flakey appearance typical of fish meat. Swimming is achieved by a coordinated series of contractions of the myotomes in sequence from head to tail. By alternating the wave of contraction between the left and right side the body executes a bending motion, resulting in movement of the tail from side to side transmitting thrust to the water like a

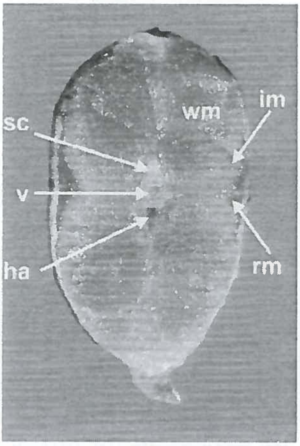

Figure 1.9. Cross-section of the tail of the salmon in the region of the anal fin. ha: haemal arch of the vertebra through which run the caudal artery, caudal vein and caudal lymph vessels; v: vertebra (centrum); sc: spinal cord; wm: white muscle fibres; im: intermediate muscle fibres; rm: red muscle fibres. The white muscle occupies most of the cross-section of the fish in this region.

propeller. A full tail beat with a movement of the tail from left to right and back again is known as a 'stride'. Typically the fish moves forward seven-tenths of the body length for each stride. Thus a 50 cm long fish swimming at two tail beats per second would be moving at 0.7 metres per second or 1.4 body lengths per second. One body length per second is a slow, sustainable cruising speed for a fish. Smaller fish can do more body lengths per second than large fish and smaller fish tend to use more tail beats per second. However, the shorter stride means that small fish cannot travel as fast as big fish. Typically speeds of 1–2 body lengths per second can be sustained indefinitely. Maximum burst speeds are about ten body lengths per second, which means 5 metres per second for a 50 cm fish.

The bulk of fish muscle differs from that of most vertebrates (e.g., beef) in that it has a poor blood supply and no oxygen binding pigment, myoglobin. This gives the muscle its characteristic pale white or creamy colour. The pink coloration of most salmon is derived from carotenoid pigments in the crustacean diet that colour the flesh, notably in the fat droplets deposited between the muscle fibres. In aquaculture, if the consumer desires pink flesh, the pigment has to be provided in the diet. The main bulk of the pale pink flesh in salmon is known as 'white muscle' and is made up of relatively large-diameter fibres capable of fast contraction but having poor endurance (Figure 1.9). This is the muscle used when the salmon leaps up waterfalls and it can generate very high power outputs, converting the sugar, glycogen into lactic acid without need for oxygen. However, this results in a build up of lactic acid in the muscle fibres and the cost of getting rid of this is the 'oxygen debt' the fish has to repay after a burst of exercise. This is what happens when fish struggle during grading or netting; it may take them 24 hours to get back to normal after exhausting exercise and it is not unusual for fish to die from acidosis associated with handling stress if they are not allowed to recover properly. If fish are allowed to struggle too much during slaughter or if CO_2 is used for killing, there is danger that such acidosis can lead to *post mortem* reduction in flesh quality. As long as they are not chilled or frozen, the fillets can recover to some extent because the enzyme systems continue to function even after death.

For normal swimming during migration or cruising round a tank the fish does not incur an oxygen debt but uses a thin strip of dark muscle (known as 'red' muscle) which lies close to the skin beneath the lateral line on either side of the fish. This muscle is rich in myoglobin and has a good blood supply feeding oxygen to the working fibres. This muscle tastes more 'gamey' than the main muscle of the fish fillet or steak. The red fibres are smaller in diameter and capable of slow contractions. The small fibre diameter aids diffusion of oxygen into the muscle, supplying the high density of mitochondria that are responsible for producing high-energy phosphates which drive muscle contraction. Between these two layers of muscle the salmon also has intermediate fibres that can be used during fast cruising without invoking the massive fast twitches of the main musculature.

It seems remarkable that the small amount of red muscle is sufficient to account for all the routine swimming activity of the fish. However, it is a characteristic of ship (and fish) propulsion systems that at slow speeds a very small motor can push a large load but for high speeds the power requirements are very high (power required is proportional to velocity cubed). White muscle is hardly used most of the time and represents the main energy store in the fish. Thus, instead of storing large lumps of fat, the fish in nature tends to store its energy as excess muscle, which is useful in emergencies for fast escape responses and to provide power for leaping waterfalls. In fact, fish fed on a high lipid diet do store fat around the guts but this does not normally occur in the wild. The power output of red muscle depends on temperature. In cold weather fish have difficulty ascending fast-flowing rivers. To some extent this power deficit can be made up for by using the sprint white muscle but this can result in rapid exhaustion. In the salmon intermediate muscle fibres lie between the red and white muscle layers; these fibres are mixed in composition and are capable of fast contraction but without the rapid exhaustion of white muscle.

The metabolism of salmon is geared to using protein as a major energy source; carbohydrate is relatively unimportant. Because white muscle is a food store its composition and quality is variable. The main components are protein, lipid (fat or oil) and water. The lipid is in droplets dispersed between the muscle fibres and contributes to the textural feel, particularly of smoked fish. A well-fed growing fish will have high protein and lipid contents and relatively low water content. If the fish starves then lipid is lost first and replaced by water. Such fish show greater weight loss in smoking and cooking. In nature, prior to spawning fish cease to feed and transfer lipid and protein from the muscles to the ova or milt in the gonads. Thus as sexual maturation proceeds, flesh quality falls and kelts (post-spawning salmon) are not normally considered edible.

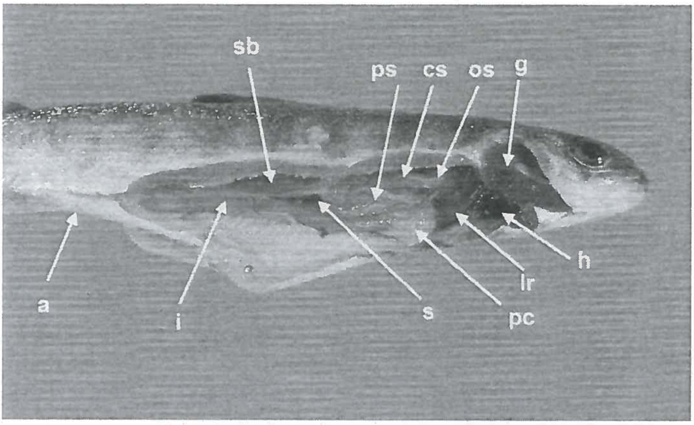

Figure 1.10. Dissection of a salmon parr showing the main internal organs. a: anus; i: intestine; s: spleen; pc: pyloric caecae; lr: liver; h: heart; g: gills; os: oesophagus; cs: stomach (cardiac part); ps: stomach (pyloric part); sb: swimbladder.

1.2.2.3 The gut and associated organs

A fish has a single main body cavity, extending from behind the head to the vent, which contains the gut, liver and associated organs (Figure 1.10). A salmon's gut is very simple. Food passes from the mouth down a very short oesophagus into the stomach. The stomach is a J-shaped bag with an exit at the pyloric sphincter, the end of the shorter limb of the stomach. Food passes into the intestine through the pyloric sphincter, which has a ring of muscle controlling stomach emptying. The first part of the intestine has numerous blind-ending side branches known as pyloric caecae. These are the main site of protein digestion. Digestive enzymes are secreted by the pancreas, which is a diffuse, pale-coloured tissue surrounding the pyloric caecae. Fat deposits also lie around the caecae and have a more translucent appearance than the pancreas itself. This part of the gut is favoured by parasitic worms because of the high concentrations of partially-digested food.

The gut beyond the pyloric caecae has a simple, straight, tubular large intestine leading to the anus. Loosely attached to the stomach is the spleen, a red-coloured organ responsible for production of blood cells. Some salmon have more than one spleen.

When the body cavity of an immature fish is opened the liver, lying at the anterior end, is the most prominent organ apart from the gut itself. In healthy fish the liver should appear dark red or brown. There is a gall bladder, which normally in growing fish should not be very visible. This stores a green coloured bile, which is released via a duct into the intestine to neutralise stomach acids as the food moves from the stomach to the intestine. The gall bladder in a feeding fish therefore empties at frequent intervals. If the gall bladder is full and distended this usually indicates that the fish has not fed for several days.

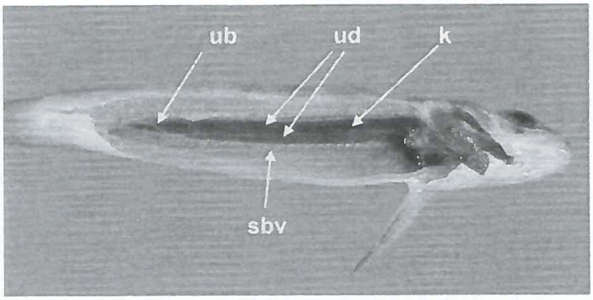

Figure 1.11. Dissection of a salmon parr with the viscera and swim bladder removed to reveal the kidney. ub: urinary bladder; ud: urinary ducts; k: kidney; sbv: segmental blood vessel.

When mature salmon return to freshwater they cease feeding and may starve for up to 12 to 14 months before spawning. The gut becomes reduced in size and the internal lining becomes keratinised and impermeable to food and water.

Above the gut is the swim bladder, a transparent air-filled sac extending along the whole length of the body cavity. The appearance is very variable according to the degree of inflation of the bladder. The bladder acts as a buoyancy organ and in salmon is connected through a pneumatic duct to the oesophagus. This duct enables fish to expel excess gas or gulp air to help fill the bladder. During harvesting fish sometimes emit a croaking sound as the swim bladder is squeezed during handling.

Above the swim bladder is a long streak of red tissue running right from the anterior end of the head region along the whole length of the body cavity. People cleaning gutted fish often think that this is a blood clot but this is, in fact, the kidney (Figure 1.11). In fish, the kidney is a multi-function organ. On the shiny lower surface two urine-collecting ducts are visible to the naked eye. These carry urine from the kidney to the bladder situated near the vent at the posterior end of the body cavity. The urine is produced in conventional kidney tubules that occupy most of the bulk of the kidney. When in fresh water, the fish continually takes in water through the gills and by drinking; this is compensated for by production of large volumes of dilute urine, almost pure water. In seawater, the kidneys virtually close down and produce very little water. In teleost fish, nitrogen is not excreted as urea but as ammonia, excreted directly into the water from the blood stream via the gills.

In between the kidney tubules, particularly in the head region, are the haemopoietic tissue and the hormone-secreting cells. The haemopoietic tissue duplicates the functions of mammalian bone marrow in producing new blood cells. The hormone-secreting cells are chromaffin tissue, which secretes adrenaline and noradrenaline (epinephrine and norepinephrine) and cortisol-secreting cells. These duplicate the functions of adrenal glands of higher animals, traditionally described as preparing the animal for flight or fight. The salmon kidney therefore combines the functions found in the bone marrow and adrenal glands as well as the kidney in the mammals.

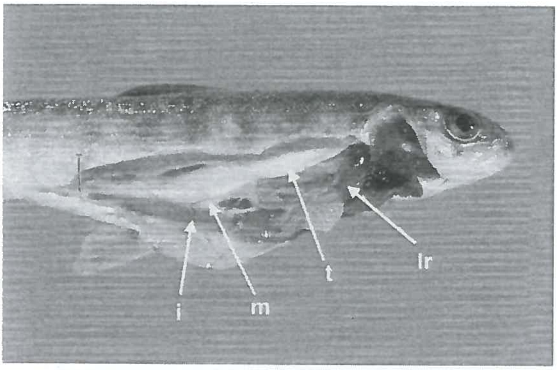

Figure 1.12. Dissection of a sexually mature male salmon parr showing the testes ventral to the swim bladder. i: intestine; m: milt (sperm) leaking out of the intestine; t: testis; lr: liver. Precocious maturation of males as parr is quite common in many wild stocks of Atlantic salmon.

The ovaries and testes lie just below the swim bladder in the salmon. In the immature fish the left and right gonads appear as streaks of tissue running from the head to tail region on the surface of the swim bladder and the two sexes are indistinguishable to the naked eye. Development starts at the anterior end and the gonad gradually thickens up and swells along its length. The ovary becomes recognisable by a bright yellow/orange yolky colour and granular texture as the oocytes develop. The testis has a smooth grey appearance. At maturity the testes are swollen and white in colour with sperm leaking out if the membranes are ruptured (Figure 1.12). In the mature female the two ovaries become unrecognisable as eggs (4–5 mm diameter) are released loose into the body cavity. There are no external sex organs-eggs and sperm are simply released into the surrounding water through openings at the vent.

1.2.2.4 The circulation system

The heart of the salmon lies in its own cavity just in front of the abdominal cavity below the oesophagus, and is protected by the bones of the pectoral girdle. The heart has four chambers arranged in sequence so that blood returning from the veins flows in the sinus venosus, the atrium, the ventricle and finally the bulbus arteriosus (Figure 1.13). The sinus venosus is a collecting chamber where the main veins from the rest of the body collect the blood before it flows in the heart; the pace-maker cells that control heart rate are situated where the sinus connects to the atrium. The atrium has thin muscular walls and contracts under the influence of the pace-maker, pushing blood into the ventricle. The ventricle has a thick wall with two layers of muscle, the inner spongy layer and outer compact layer. The surface of the heart has coronary arteries that supply oxygen to the hard-working compact layer. Blood is expelled from the ventricle in a high-pressure pulse that fills the

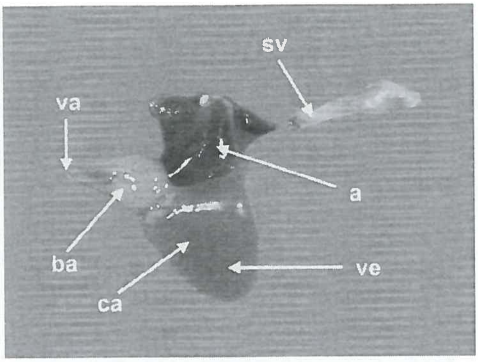

Figure 1.13. The heart. a: atrium; ve: ventricle; ca: coronary artery; ba: bulbus arteriosus; va: ventral aorta; sv: sinus venosus.

bulbus arteriosus. The bulbus is white in colour and is composed almost entirely of elastic tissue. When cut out of a harvested salmon and dropped on a hard surface, the bulbus bounces with high rebound efficiency. The elastic walls of the bulbus store the energy generated by the ventricle. The blood-filled bulbus gradually empties by elastic rebound, thus keeping a continuous flow of blood through the gills which are located just in front of the heart. The coronary blood vessel feeding oxygenated blood back from the gills to the heart is very conspicuous on the ventral surface of the bulbus.

As the heart works, it produces electrical impulses which can be recorded as an electrocardiogram very similar to that in mammals. There is an initial P wave denoting contraction of the atrium, followed by the QRS wave of the ventricle contraction and finally the T wave denoting ventricular filling whilst the bulbus maintains the blood flow. The ECG can be recorded and telemetered in wild salmon. Typical heart rate in salmon during their spawning migration varies between 10 and 50 beats per minute. In the female, heart rate is between 15 and 25 during rest and slow movements and increases to the maximum during spawning. Males tend to be hyperactive, with hearts rates between 25 and 40 for much of the spawning season (Altimiras et al., 1996). The range of heart rates is influenced by temperature, with higher heart rates in warmer water.

The bulbus arteriosus directs blood immediately into the ventral aorta which feeds blood to the gills. This blood vessel is very short and divides into four pairs of afferent branchial arteries to the gills (Figure 1.14). From the gills, the corresponding four pairs of efferent branchial arteries just below the cranium connect together to feed blood into the dorsal aorta that distributes blood to the rest of the body. Arteries branch off to the brain and the eyes and the main dorsal aorta passes back along the body immediately beneath the vertebral column to which it is closely attached. Near the liver, a major branch, the anterior mesenteric artery supplies blood to the guts and other abdominal organs. The dorsal aorta itself is flattened so that it is five times as wide as it is high and within it is a remarkable

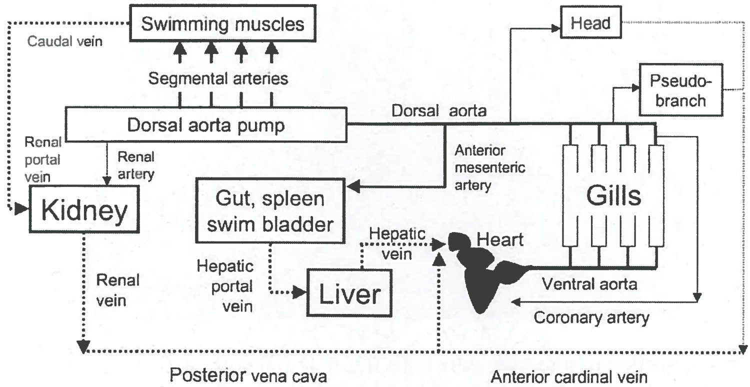

Figure 1.14. Diagram of the blood circulatory system of the Salmon. (After Smith and Bell 1976). Solid lines or arrows are arteries, dotted lines or arrows are veins. Blood flows anteriorly along the ventral aorta to the gills. The coronary artery is attached to the ventral aorta feeding oxygenated blood back to the heart.

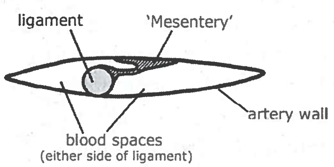

Figure 1.15. Diagrammatic cross-section of the dorsal aorta of the salmon. This blood vessel lies below the backbone and above the kidney. It is divided into two halves along its length by the ligament that automatically pumps blood when the fish is swimming (After Priede, 1975).

elastic ligament, the dorsal aorta ligament that acts as a secondary heart. As the aorta moves from side to side during the fish's swimming movements, blood is pumped back along the vessel and propelled into arterial branches to the muscles on either side (Figures 1.15, 1.16). The dorsal aorta tapers in width towards the tail and ends up as the caudal artery within the haemal arches of the tail vertebrae (Figure 1.9). Blood is returned to the heart from all parts of the body by a system of veins but also by lymphatic vessels. The blood volume of fishes is relatively low compared with mammals, and tissues such as the white muscle depend largely on lymph circulation comprised of blood plasma without red blood cells to supply nutrients and remove wastes. The blood of salmon is very similar in salt concentration to human blood but, unlike humans, the erythrocytes, or red blood cells, retain a nucleus and are rounded/oval in shape. The iron-containing pigment, haemoglobin, is present in the erythrocytes and carries oxygen. The absence of the oxygen-carrying capacity of red blood cells in lymph is no handicap to white muscle that operates only during sprinting.

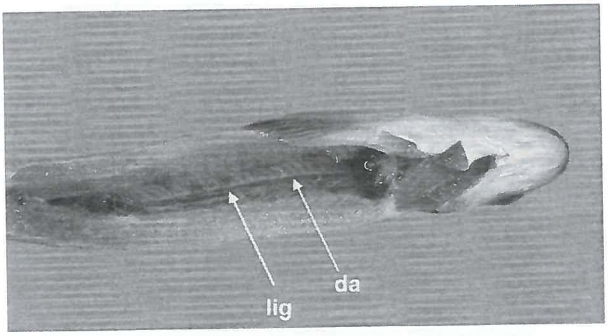

Figure 1.16. Dissection of a salmon parr as in Fig. 1.11 but with the kidney removed to reveal the dorsal aorta. da: dorsal aorta; lig: ligament visible through the transparent wall of the blood vessel. Swimming movements automatically propel blood backwards along the body of the fish.

1.2.2.5 The gills, respiration and excretion

The primary site of gaseous exchange with the environment is in the gills. Oxygen is taken up from the water and carbon dioxide is excreted.

The salmon has four gill arches on either side of the head. There is an additional 'false gill', or pseudobranch, under the operculum just in front of the gill arches (Figures 1.6, 1.7). The pseudobranch is thought to act as a sensor which monitors blood pressure, oxygen content and other parameters. The surface of the true gills is composed of very fine lamellae arranged on filaments which are hinged onto the gill arches (Figure 1.17). There are two rows of filaments on each gill arch. Blood is fed to each gill from the afferent branchial artery and a branch runs along the outer edge of each gill filament. The blood then flows through secondary lamellae located above and below each filament. The interior of each lamella is hollow, the thickness (15 μm) corresponding to the diameter of an erythrocyte. This means that oxygen can diffuse through the gill membrane into the erythrocyte from the water on either side of the secondary lamella over a distance of less than 5 μm. Pillar cells connect the membranes together on either side of the lamella to prevent swelling as blood pressure is applied.

Blood flow through the gills is varied according to the requirements of the animal. During gentle exercise the blood flows preferentially through the first (anterior) gill arches. As oxygen requirement increases, so more gill filaments are perfused until at maximum activity all the gill area is in use. The thin gill membrane allows free interchange of water between the blood and the environment by osmosis. Thus in freshwater there is an inward flow of water tending to dilute the blood and a contrary flow in seawater leading to loss of water. Avoiding blood flow to the entire gill unless absolutely necessary reduces the water loss or gain. The gills should appear bright red in healthy fish. The water flow over the gill is driven by the buccal and opercular pumps with the flow rate regulated to meet necessary oxygen requirements.

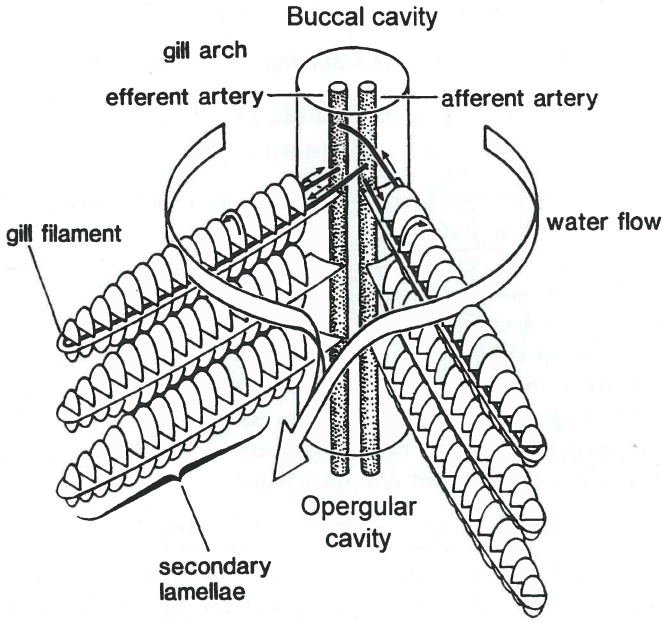

Figure 1.17. Structure of gills. This diagram shows a section of gill arch as viewed from the opercular cavity looking inwards towards the buccal or mouth cavity. Each gill arch carries two rows of filaments. Oxygen uptake occurs in the secondary lamellae, which are filled with blood and are arranged in rows on the upper and lower surfaces of each filament. Tiny muscles swivel the filaments so that they lie across the water current. Water flows through the tiny spaces between the lamellae and the blood flows in the opposite direction, thus ensuring efficient exchange of oxygen across the single layer of cells separating blood from water. (For clarity only three pairs of filaments are shown and the number of secondary lamellae has been reduced.)

Oxygen is taken up by haemoglobin in the erythrocytes as the blood flows through the secondary lamellae. In the body tissues, oxygen is off-loaded by a reverse reaction which is aided by the low pH (acidity) and high carbon dioxide concentration in actively metabolising regions of the body. It has been found that fish can alter their haemoglobins to suit different conditions and to adapt to different temperatures.

As the blood returns in the veins its pH is low and the level of dissolved carbon dioxide is high. The blood is also loaded with ammonia (NH_3) excreted by the cells as a result of protein breakdown in different parts of the body. Both the carbon dioxide and ammonia pass out into the water via the gills in a complex series of exchanges.

In the gill cell the ammonia is ionised:

$$NH_3 + H_2O = NH_4^+ + OH^-$$

The ammonium ion is then excreted in exchange for an incoming sodium ion.

$NH_4^+ \sim Na^+$ This aids maintenance of electro-neutrality.

Meanwhile the hydroxyl ion can combine with carbon dioxide:

$$OH^- + CO_2 = HCO_3^-$$

This provides a source of bicarbonate ions which are exchanged across the gill membrane for incoming chloride ions:

$$HCO_3^- \sim Cl^-$$

Thus the fish achieves excretion of carbon dioxide (CO_2) and ammonia (NH_3) in exchange for taking up salt (NaCl). Since in freshwater salt is continuously lost by diffusion as water is being gained, the ability to actively take up salt is very important. These exchanges, however, are also influenced by pH.

In the gill epithelium excess carbon dioxide in the presence of the enzyme carbonic anhydrase is transformed into bicarbonate:

$$CO_2 + H_2O = H_2CO_3^- = H^+ + HCO_3^-$$

The bicarbonate can be excreted in exchange for chloride ions but the hydroxyl ion (proton) can be exhanged for an incoming sodium ion (Na^+). As H^+ ions are excreted this provides a means of reducing blood pH so the fish can regulate pH via the gill. Thus in the gill of the freshwater fish regulation of pH, excretion of CO_2 and ammonia are all interconnected. In acid waters, where the fish may have difficulty in regulating pH if it falls too low, the haemoglobin may not be able to take up oxygen. The electro-neutral exchanges $NH_4^+ \sim Na^+$, $HCO_3^- \sim Cl^-$ and $H^+ \sim Na^+$ are all thought to be driven by ion pumps at the outer membrane of the gill; enzyme protein molecules sit in the lipid membrane. The most important of these ion pumps is the $Na^+ \sim K^+$ ATPase that excretes sodium from cells and takes up potassium. This is active on the inside of the gill epithelium transporting salt into the blood (Figure 1.18).

In seawater, the function of the gill has to be reversed so that, instead of uptake, salt is excreted. Salt transport out across the gill epithelium seems to occur mainly in chloride cells found at the base of the secondary lamellae of the gills. These cells are in contact with blood on the inner side and water on the outer side. On the outer side of each cell is an apical pit into which salt is excreted. The inner side is perforated by a tubular system that connects with the blood and branches out throughout the cell which is packed with mitochondria. The mitochondria consume oxygen and generate adenosine triphosphate (ATP) to provide energy for the salt pump, $Na^+ \sim K^+$ ATPase. The precise mode of action is not fully understood but sodium is pumped from the cell into the tubular system generating very high Na^+ ion concentrations. Where the tubular system runs close to the apical pit, sodium diffuses from the tubular system into the apical pit and thence into the surrounding water. Chloride follows by a cotransport process that is not fully understood. Salt transport is an energy-demanding process and the concentration of mitochondria in the chloride cells is greater than in any other cells in the body of the fish (Figure 1.19).

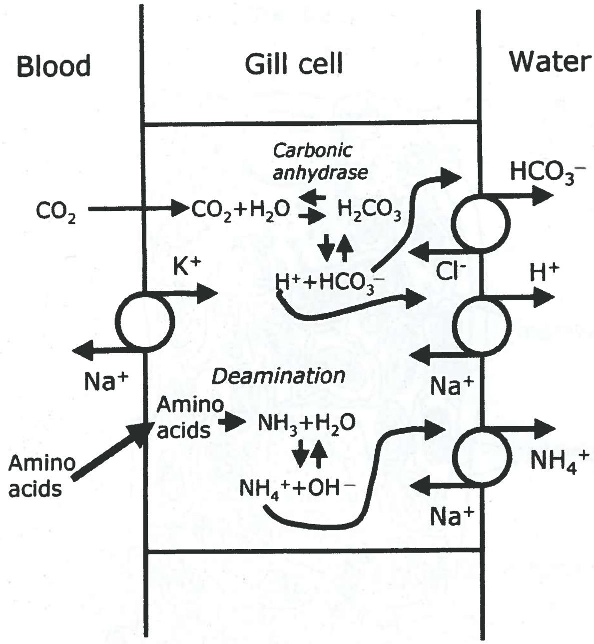

Figure 1.18. Transport mechanisms in a gill cell of a fish in freshwater. Salt uptake is linked to carbon dioxide, hydrogen ion and ammonia excretion. Circles in the cell membranes denote active exchange processes. (After Rankin and Davenport, 1981.)

1.2.2.6 The nervous system and sense organs

The salmon brain lies on the floor of a protective cranium inside the skull. It is divided into three parts: the forebrain, midbrain and hind brain. The forebrain has two main olfactory nerves that connect to the olfactory rosettes beneath the nostrils on the fish's snout. The forebrain is thus predominantly concerned with the sense of smell or chemoreception. The midbrain is dominated by the optic lobes and optic nerves from the eyes that are connected to this region on either side. The pineal stalk projects upwards between the optic lobes and the end of the pineal is attached to the underside of the roof of cranium. The pineal is sensitive to light, and a window in the skull admits light to this region. Beneath the mid brain lies the pituitary gland. The hind brain is dominated by the cerebellum and the medulla, or brain stem, which connects to the spinal cord. The lateral line nerve enters the brain in this region as a branch of the vagus (X) nerve (Figure 1.20).

The hearing and balance organs lie on either side of the hind brain and are connected to the brain via the auditory nerve. The salmon ear on each side has three semicircular canals, similar to those in mammals, which detect rotational motions in three planes. The canals are connected to a series of sacs equipped with sensitive hair-cells for hearing. Fish can predominantly hear at frequencies up

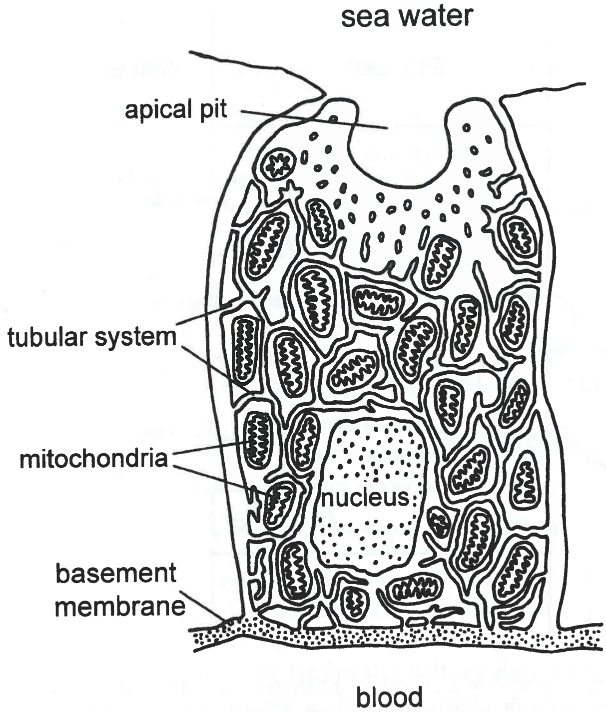

Figure 1.19. Appearance of a chloride cell in the gill of a fish in seawater. These cells occur at the bases of the secondary lamellae. Salt is excreted into the apical pit by processes involving active transport across the membranes of the tubular system using energy provided by the mitochondria. (For clarity the numbers of mitochondria and tubules are greatly reduced in this diagram). Continuous function of these cells is necessary to ensure survival. (After Rankin and Davenport, 1981.)

to about 1kHz, mostly at lower frequencies corresponding to knocks and grunts. They cannot perceive whistling-type pure tones in the upper part of the human auditory spectrum. Living in water, sound travels directly from the surrounding medium into the interior of the fish, so there is no need for the external ear, ear canal, ear drums or ossicles for impedance matching as in land animals. The presence of the swim bladder enhances hearing by converting the pressure component of the sound wave into a motion of the swim bladder wall which is transmitted to and stimulates the hair cells of the inner ear which would otherwise not detect this aspect of sound energy in water. Some freshwater fishes (e.g., the carp family) have ossicles connecting the swim bladder to the ear to enhance this effect.

In addition to the semicircular canals on either side, the salmon ear is equipped with otoliths, or ear stones, which are suspended on hair cells within the fluid-filled chambers of the ear. The largest of the otoliths is the sagitta, which lies at the base of the sacculus. There is one on either side and this is the otolith that is commonly

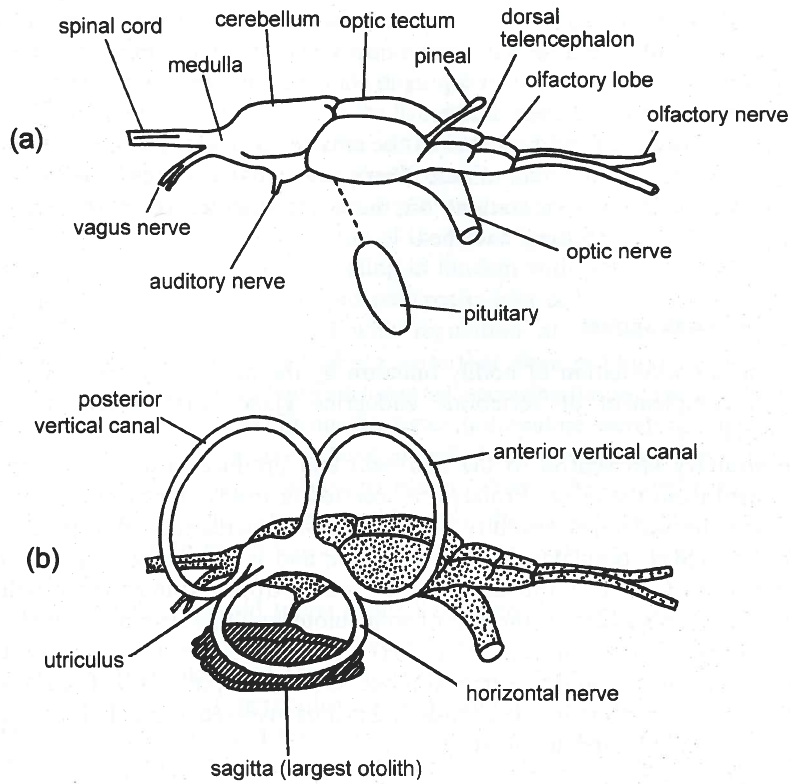

Figure 1.20. The brain of salmon. (a) Lateral view from the right hand side. The pituitary is located in a chamber in the cranium below the brain. The pineal is attached to the room of the skull. (b) The same view but showing the position of the acoustico-vestibular (inner ear) system of the right side. (After Smith and Bell, 1976 and Meek and Nieuwenhuys, 1998.)

extracted for age determination in fish. The growth of the otolith is proportional to growth of the whole fish and rings are apparent from slow growth in winter. Isotopic analysis of zones in the otolith can be used to determine the length of time the fish spent in freshwater and seawater and the past thermal history of the individual. In Atlantic salmon, scale reading is more commonly used than otolith studies but otoliths can be extracted from stomach contents and faeces of predators such as birds or seals. Identification and measurement of otoliths provides a means of assessing the number and size of salmon lost to predation. In the living fish, the otolith provides a means of detecting linear acceleration. The salmon therefore has an acoustico-lateralis system comprising semi-circular canals, otoliths, hearing region (no cochlea) and the lateral lines, all concerned with detection of sound, vibrations and accelerations.

In the hind brain, one on either side, are two very large nerve cells characteristic of teleost fish, known as the mauthner neurons. These are connected to fibres that run the length of the spinal cord and are concerned with generating fast sprint starts by stimulating the white muscle mass at maximum speed. An automatic reflex, which can be set off by a variety of alarm inputs to the mauthner cells, enables the fish to sprint forward rapidly to escape danger.

The spinal cord sends off branches to the muscle segments all the way along the body. Nerve fibres to the red muscle fibres are capable of generating graded responses but the nerve terminations on the white muscle are of the end plate type, generating 'all or nothing' twitches.

1.2.2.7 Endocrine system

In addition to coordination of bodily function by the nervous system, the salmon has a full complement of vertebrate endocrine glands that secrete hormones (Figure 1.21).

The pituitary lies ventral to the midbrain and produces a suite of hormones under control from the brain. Prolactin is secreted in freshwater and is responsible for reducing the water permeability of the skin and increasing urine production. Thyrotropin (TSH) stimulates the thyroid tissue and is thus important in growth and metabolism. Growth hormone (GH), or somatotropin, stimulates growth and manipulation of this system is the aim of some biotechnology research in transgenic fish. Adrenocorticotrophic hormone (ACTH) is responsible for stimulating corticosteroid release from the kidney interrenal tissue. Gonadotropin (GTH, I & II) stimulates sex seroid production by the gonads and is thus involved in regulation of sexual maturation, ovulation and spermiation.

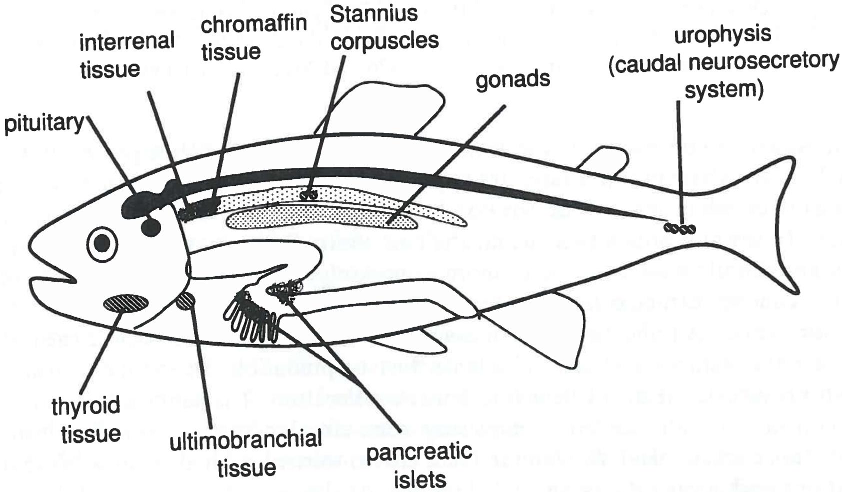

Figure 1.21. The approximate position of the main endocrine glandular tissues in the salmon. The interrenal, chromaffin tissue and Stannius corpuscles are located in the kidney.

The pineal is the site of secretion of melatonin, which occurs during hours of darkness. More melatonin is therefore secreted during the winter than in summer and it provides the means by which the day–night and seasonal cycles are transduced to the different functional systems of the fish. Melatonin therefore influences growth, activity and sexual maturation. This is the means by which artificial day-length manipulation results in changes in growth, smolting and sexual development.

The urophysis is a neurosecretory organ unique to teleost fish. It is found at the end of the spinal cord in the tail region of the fish, a kind of 'pituitary of the tail'. Its secretions influence ion regulation acting in tandem with prolactin.

The pancreas of salmon contains pancreatic islet cells. As in most vertebrates, these secrete hormones concerned with regulation of carbohydrate metabolism: insulin that lowers blood sugar and glucagon that elevates blood sugar.

In the salmon kidney are various hormone-secreting tissues; the interrenal corticosteroid-secreting cells and chromaffin tissue (adrenaline secreting, increases heart rate and increases blood glucose) have already been mentioned. The corpuscles of Stannius secrete hypocalcin that lowers blood calcium. Associated with the kidney tubule glomerulae are the juxtaglomerular cells that secrete renin, or angiotensins that are involved with regulation of blood pressure, water balance and blood electrolyte equilibrium.

The salmon has thyroid tissue located between the lower jaws anterior to the heart that secretes two main hormones known as T_4 (Thyroxine) and T_3 (triiodothyronine); molecules with three and four iodine atoms respectively. These are involved in regulation of metabolism, growth and metamorphosis.

The gonads, ovaries and testes secrete hormones concerned with regulation of gametogenesis (production of eggs and sperm), vitellogenisis (production of yolk), sexual maturation and development of the secondary sexual characteristics. Androgens—testosterone (T), 11-ketotestosterone (11-kT)—are the male hormones, and oestrogens—17β-oestrodiol, and progestins—are the female hormones.

Development of gonads is therefore controlled by release of GTHs from the pituitary gland. The hormones travel through the blood stream to the gonads. The GTH is controlled to a large extent by the pineal gland, which alters its output of melatonin in response to seasonal changes in day length. Within the gonads themselves sex steroids are released to help control gonad development and development of the secondary sexual characteristics such as the hook jaw, or kype, in the lower jaw of the male salmon. It is possible to release GTH artificially by removing pituitary glands from slaughtered fish, grinding them up and injecting an extract into other fish. This will induce these fish to spawn, and the method is often used in the management of broodstock which cannot be induced to spawn by manipulation of day length or environment. Similarly, administration of sex steroids can be used to change the sex of salmon; for example administration of testosterone to female fish will convert the ovary into a testis which will produce sperm. Use of such sperm to fertilise eggs will result in all-female offspring.

Associated with sexual maturation is an increase in mucus production and weakening of the skin. Maturation is associated with stress, and manifests itself by secretion of corticosteroids. These have the effect of suppressing the immune system and reducing resistance to disease. Sexually-mature fish tend to be more susceptible to fungal and bacterial infections.

1.3 INTEGRATED FUNCTION

1.3.1 Smoltification and transfer between fresh and salt water

One of the most important events in the life cycle of the Atlantic salmon is the transition from freshwater to life in the sea. This is not essential, since some stocks of salmon are land-locked but, generally, migration into the sea provides access to greatly-enhanced food resources and growth rate rapidly increases compared to growth performance in freshwater. If salmon parr are transferred into seawater the effect is as lethal as for any freshwater fish. It is at the smolt stage, while still in freshwater, that the salmon acquires the ability to survive in seawater. Once this stage has been attained, transfer into seawater can be instantaneous; in nature this would often occur as fish migrate through a stratified estuary with freshwater on the surface and seawater underneath. Smolts swimming deep to avoid predation would need to move from freshwater into full-strength saline water within seconds.

Seawater contains approximately 35 parts per thousand of salt, which is equivalent to an osmotic concentration of $1050\,mOsm.l^{-1}$ (milliosmoles per litre). The blood of salmon has a concentration of approximately $300\,mOsm.l^{-1}$. This means that in freshwater ($0–20\,mOsm.l^{-1}$) water is taken up through the permeable gill membranes by osmosis. To compensate for this, the parr produces large quantities of dilute urine, but loss of salt is a problem. The parr reduces water intake by not drinking and the skin is impermeable to water. Salt is taken up actively in the gills and some salt can also be absorbed from the diet. As explained in Section 1.2.2.5, the salt uptake is related to carbon dioxide and ammonia excretion and is influenced by pH. In acidic waters the fish may not be able to regulate its salt and water balance. When the salmon is in seawater the blood salt concentration is approximately the same, but the effect of osmosis across the gill now results in a continuous loss of water. The salmon in seawater is effectively dehydrated—the same as shipwrecked humans who have only seawater to drink. The salmon compensates by drinking seawater but, unlike humans, is capable of excreting the excess salt through the chloride cells in the gills. The urine flow ceases almost completely; only a small amount of urine is produced with a high concentration of particularly divalent ions such as Mg^{++} (Figure 1.22).

In the parr-to-smolt transformation the smolt is pre-adapted to the incipient transfer to seawater. Several external morphological changes occur: the body becomes more elongated and the skin looses its parr marks and becomes more silvery, an appropriate camouflage for life in the sea. Even the retinal pigments change to make the eyes more blue-sensitive to match the light in the open oceans. The fins become more transparent and acquire black margins. The scales

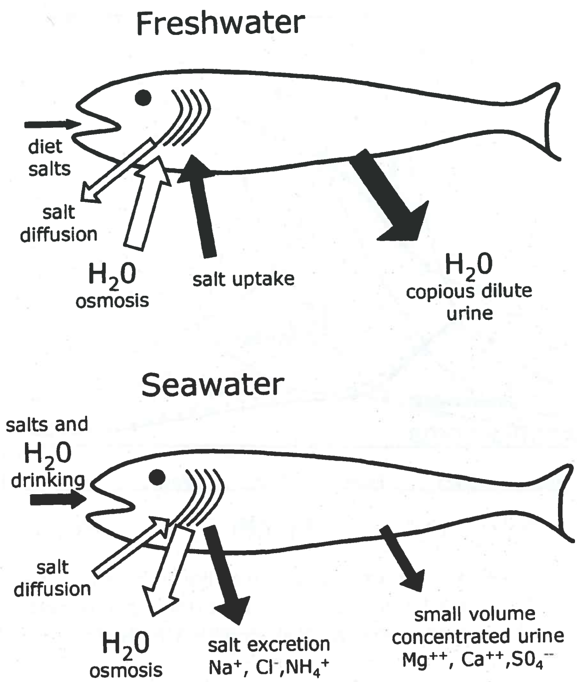

Figure 1.22. Comparison of the salt and water exchanges for salmon in freshwater and salt water through three pathways: the gut (drinking and feeding), the gills and the kidneys. Open arrows are passive processes. Black arrows are active processes.

become looser and are shed more easily, resulting in some of the problems of handling smolts during transfer. The behaviour of the fish also changes from the territoriality of wild parr to shoaling behaviour appropriate for an oceanic life style.

In Atlantic salmon, young fish in nature can spend 1–5 years in freshwater. The 'decision' whether to smoltify in a particular year takes place in the September–October prior to the fish going to sea. It seems that if, the fish has grown to a critical size and is in good condition during this time window, the smoltification sequence is triggered by the decrease in day length. For most European stocks of Atlantic salmon, the critical size is 7.5–8.5 cm, whereupon those fish destined to become smolts show a spurt of growth, reaching a size of 12 cm or more before the next spring. The remaining fish do not grow and remain as parr capable of smoltifying the following season if they reach the critical size during the following summer. The age of smolts is therefore largely determined by food supply, and in aquaculture effort is directed to producing viable smolts at the youngest possible age.

The changes associated with smoltification are almost certainly internally under the control of hormones (Figure 1.23). In measurements of changes in the blood plasma the first effect is an increase in insulin, in the December some 4–5 months before going to sea. Following the increase in insulin there is a massive increase in

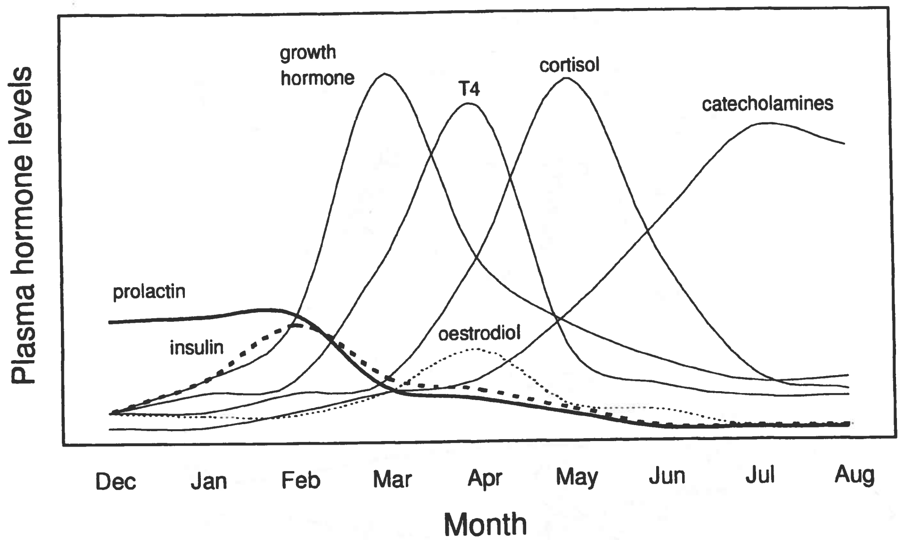

Figure 1.23. Changes in the concentrations of different hormones in the blood plasma during the process of smoltification in Atlantic salmon in the northern hemisphere under normal day length conditions. Note the sequence of hormonal surges. (After Stefanson and Hansen, 1998.)

GH, followed by T_3 and T_4 thyroid hormones. Cortisol reaches a maximum around the time of going to sea and catecholamines, adrenaline and noradrenaloine continue to increase. Endocrinologically, at the time of seawater transfer the smolt is a hyperactive, stressed fish and its suppressed immune system makes it susceptible to disease. Prolactin is the one hormone that decreases during smoltification; this is associated with the decreased need of urine production in the sea.

Amongst all the changes that take place during the smolting process the critical factor is the ability of smolts to survive in seawater. By manipulation of day length, temperature and food supply it is possible to produce smolts less than one year old, so-called 0+ smolts. However, silveriness and external smolt-like characteristics do not necessarily mean that the animal can osmoregulate in seawater, and it is possible to produce 'pseudo smolts'. Pseudo smolts can be distinguished from true smolts by a seawater challenge test. The test fish are placed in full strength seawater (35‰) for 24 h and then blood samples are taken. The plasma Na^+ and Cl^- concentrations are then measured. In a pre-smolt, typically the fish will have lost water and gained salt so that plasma chloride will increase to approximately 200 mM. A healthy smolt should be able to regulate its blood chloride to 140 mM (Figure 1.24). This can be confirmed by measurement of gill Na^+, K^+-ATPase activity, which rises tenfold at the time of smolting owing to proliferation of functional chloride cells in the gills (Figure 1.25).

In successful smolting there is a period of about a month when the fish can be transferred to seawater. The precise timing of this smolting window is dependent on temperature with higher temperatures leading to earlier transferral. If fish are not

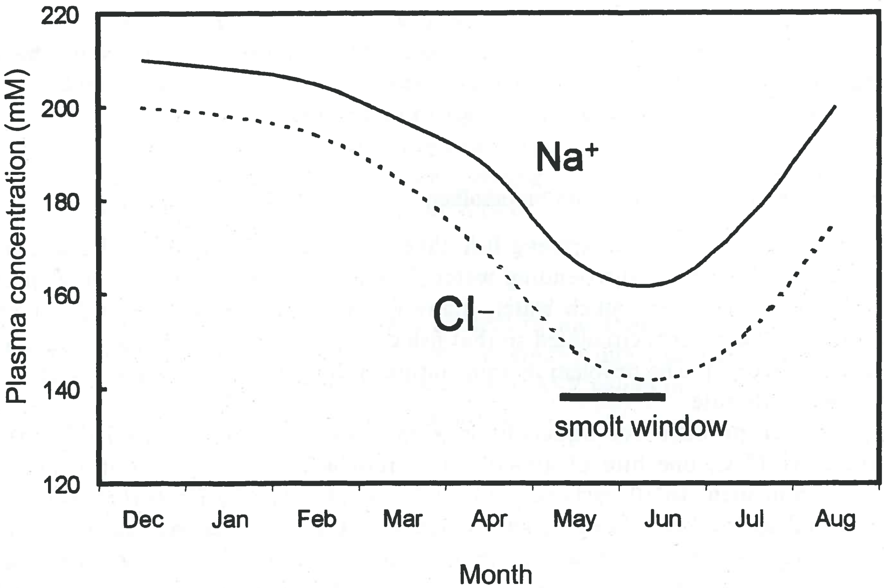

Figure 1.24. Results of seawater challenge tests on young salmon. The values given are the concentrations of sodium (Na^+) and choride (Cl^-) ions in blood plasma samples taken 24 hours after transfer from freshwater to seawater (35‰). In December the blood takes up salt but during the smolt window in May the fish is capable of maintaining low salt concentrations in the plasma and hence is fit to go to sea during this time. (After Stefanson and Hansen, 1998.)

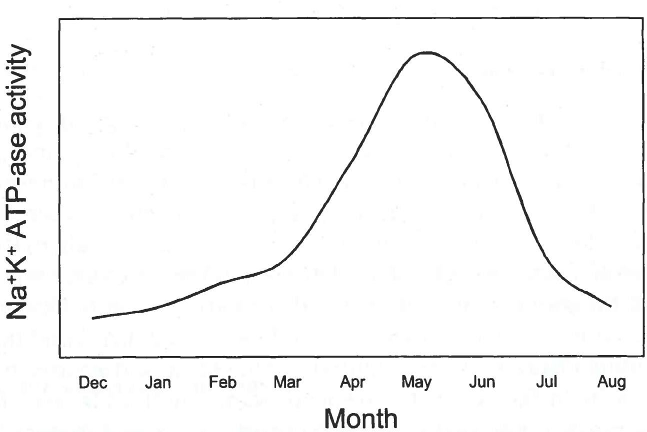

Figure 1.25. Sodium-potassium ATP-ase activity in the gills of young salmon kept in freshwater during the period of smoltification. Note that during the smolt window period ATP-ase activity is at a maximum. (After Stefanson and Hansen, 1998.)

transferred to seawater (or in nature fail to find a route to the sea) then a reverse process known as desmoltification takes place, and by midsummer the fish will have completely lost their ability to survive in seawater. Such fish can resmoltify the following year and make another attempt to find the sea.

1.3.2 Oxygen consumption and metabolism

The basic requirements for keeping fish alive are water and oxygen. Gills take up oxygen dissolved in the surrounding water. From the point of view of living space fish do not require very much water; many fish will shoal at very high densities, especially if the water is circulated so that fish can swim continuously all pointing in the same direction. The problem in aquaculture is to replace the oxygen or water at an appropriate rate.

A major problem for aquaculture is that water contains remarkably little oxygen. At 15°C, one litre of air-saturated fresh water contains about 10 mg of oxygen, equivalent to 10 parts per million by weight. The 10 mg available in one litre is sufficient to keep a 1 kg weight salmon alive for only three minutes and, since the fish gills can remove only about a third to half of the oxygen from the water, 1 kg of water is only sufficient for about one minute. A single fish requires about 1.5 tonnes of newly oxygenated water per day.

The oxygen in the water is replaced by diffusion from the atmosphere, which can be aided by agitation or aeration of the water, and from oxygen produced by algae and aquatic plants as a result of photosynthesis during daylight hours. In aquaculture the approach to supply of oxygen is either to supply water at an appropriate rate flowing through tanks and cages so that sufficient oxygen is delivered to the system or to directly inject air or oxygen into the water contained with the system.

There are several ways of expressing the dissolved oxygen concentration in water.

1.3.2.1 Partial pressure (pO2)

The Earth's atmosphere is 20% oxygen and 80% nitrogen (ignoring minor constituents). Therefore oxygen contributes 20% of the pressure of the atmosphere so the partial pressure of the oxygen in the atmosphere is said to be 0.2 atmospheres which is equivalent to 200 millibar or 0.2 bar. Expressed in millimetres of mercury the value is 76 mm × 0.2 = 152 mm Hg. Oxygen tension is also used as an alternative term for partial pressure. If a container of water is left open to the air, oxygen will diffuse into the water until the water is air saturated and the pO_2 is equal to that in the atmosphere above. This will vary slightly according to weather conditions, as the barometer reading changes. At high altitudes, the pO_2 also decreases but this is of no concern to salmon farms which, except for some smolt units, are mostly at sea level. Partial pressure is not used very much in aquaculture as a means of measuring oxygen but it is important to note that most commercial oxygen meters work on the principle of measuring the partial pressure. This is then transformed with the aid of temperature information (often using an internal microprocessor) into absolute oxygen content units. It is always worthwhile checking an oxygen meter in well-aerated water or simply waving the moist probe in air to check that it gives the expected reading. Partial pressure is also important because gasses always diffuse down the partial pressure gradient, i.e., from high partial pressure to low partial pressure, not from high concentration to low concentration. This can be important in the design of oxygenation systems and sorting out problems particularly when waters of different temperatures are being mixed.

1.3.2.2 Air saturation value (ASV)

A simple way of expressing the oxygen content of water supplies is in terms of air saturation value (ASV). If a water sample is in equilibrium with the air the water is said to be 100% saturated. Salmon can survive in ASV values of 50% and above but values of 70–80% are desirable for good growth.

1.3.2.3 Oxygen content

Unfortunately the ASV or partial pressure gives no information on the actual quantity of oxygen in water. The amount of oxygen dissolved in water at 100% air saturation varies according to salinity and temperature (Table 1.1). As temperature and salinity increase so the amount of oxygen in water at saturation decreases. Using an oxygen meter measuring percent saturation the oxygen content of the water can be simply calculated:

$$\text{Oxygen content} = \text{solubility} \times \%\ \text{saturation}/100$$

The tables are often built into the meter together with a temperature sensor so that an automatic read-out is given in parts per million (ppm) which is equivalent to $mg.l^{-1}$.

The most precise measurements of oxygen in water are achieved using the Winkler titration, the standard method used in most water quality laboratories. The true oxygen content is obtained without the need to know the temperature or salinity of the sample at the time of collection. Oxygen content is sometime expressed by volume (ml) or by weight (mg). To convert between these two systems:

$$1.428\,\text{mg} = 1\,\text{ml}$$

$$0.7\,\text{ml} = 1\,\text{mg}$$

For practical purposes, oxygen content of water in a salmonid farm should never drop below $5\,mg.l^{-1}$ whilst for good growth a minimum of $7\,mg.l^{-1}$ is essential.

1.3.3 Oxygen requirements of salmon

During their growth from newly-hatched alevin to the adult, salmon undergo more than a 1000-fold change in weight. Most bodily functions vary according to the size of an animal, for example the legs of a mouse work much faster than the legs of an elephant and the heart rate of a mouse is faster than the heart rate of an elephant.

Table 1.1. Oxygen solubility in water.

The amount of oxygen dissolved in water milligrams per litre (mg/l) in relation to salinity and temperature. Atmosphere at Standard Pressure (760 mm Hg), relative humidity 100% and oxygen content 20.94%.

Temp	Salinity (parts per thousand)							
(°C)	0	5	10	15	20	25	30	35
0.5	14.42	13.83	13.61	12.74	12.55	12.36	11.60	11.42
1	14.22	13.65	13.44	12.60	12.41	12.21	11.45	11.28
2	13.82	13.29	13.09	12.28	12.10	11.93	11.18	11.01
3	13.44	12.94	12.75	11.98	11.80	11.63	10.91	10.74
4	13.08	12.59	12.41	11.68	11.50	11.33	10.64	10.49
5	12.72	12.26	12.09	11.38	11.21	11.05	10.38	10.23
6	12.40	11.95	11.78	11.09	10.93	10.78	10.13	9.98
7	12.08	11.65	11.49	10.82	10.67	10.52	9.89	9.75
8	11.80	11.36	11.21	10.56	10.41	10.26	9.67	9.53
9	11.51	11.09	10.94	10.30	10.16	10.02	9.45	9.31
10	11.25	10.84	10.70	10.07	9.93	9.79	9.23	9.11
11	11.01	10.60	10.45	9.84	9.71	9.58	9.03	8.91
12	11.05	10.37	10.22	9.63	9.50	9.36	8.84	8.72
13	10.55	10.14	10.00	9.41	9.29	9.16	8.65	8.54
14	10.32	9.94	9.80	9.21	9.09	8.97	8.47	8.36
15	10.10	9.73	9.59	9.03	8.90	8.78	8.31	8.20
16	9.88	9.52	9.39	8.85	8.73	8.61	8.15	8.05
17	9.67	9.32	9.19	8.67	8.55	8.44	7.98	7.88
18	9.45	9.13	9.01	8.51	8.40	8.28	7.83	7.73
19	9.27	8.94	8.82	8.34	8.23	8.13	7.69	7.59
20	9.08	8.77	8.65	8.18	8.07	7.97	7.56	7.46
21	8.90	8.60	8.48	8.03	7.93	7.83	7.42	7.31
22	8.73	8.43	8.33	7.88	7.78	7.68	7.28	7.20
23	8.57	8.28	8.17	7.73	7.64	7.54	7.15	7.07
24	8.40	8.12	8.01	7.59	7.49	7.40	7.04	6.95
25	8.24	7.97	7.87	7.46	7.37	7.27	6.91	6.83
26	8.10	7.83	7.73	7.32	7.23	7.14	6.79	6.71
27	7.95	7.68	7.59	7.19	7.10	7.02	6.68	6.60
28	7.81	7.56	7.46	7.08	6.99	6.90	6.56	6.49
29	7.67	7.42	7.33	6.95	6.87	6.79	6.45	6.37
30	7.54	7.29	7.21	6.83	6.75	6.67	6.34	6.26

Values are derived from Table 4 in Carpenter (1966) by interpolation and application of the following conversions:

Oxygen at STP 1.428 mg = 1 ml
Salinity ‰ = 0.030 + 1.805 Chlorinity ‰ (Knudsen relationship, Harvey 1966)

At high altitudes or for atmospheric pressures deviating from 760 mm these figures must be adjusted. mg/l $O_2 = R \times AP/760$, R = reading from table. AP = Local barometer reading in mm mercury.

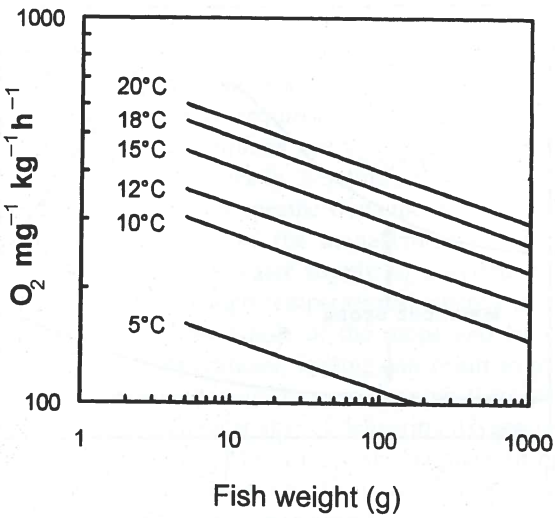

Figure 1.26. Oxygen consumption of salmonid fish (per kg body weight) in relation to fish (body) weight and water temperature. (After Liao, 1971.)

There is a general law in biology that energy expenditure (R) varies according to animal size in the following way:

$$R = \alpha W^{\beta}$$

where α is a constant, W is body weight, and β is constant with values between 0.6 and 0.75. Since β is <1 energy expenditure per unit body weight decreases with increase in body weight. Energy expenditure is often expressed in terms of oxygen consumption necessary to release that energy, and in the case of fish farming is of direct concern since engineering systems must be installed to deliver the appropriate quantity of oxygen. Thus a 200 g fish does not consume twice as much oxygen as a 100 g fish. In fact if a 100 g fish consumes 20 mg h^{-1} a 200 g fish consumes 34 mg h^{-1}. Thus a tonne of 100 g fish (10,000 individuals) will require $10{,}000 \times 20$ mg of oxygen = 200 g oxygen per hour, compared with a tonne of 200 g fish (5000 individuals) which will require 5000×34 mg = 170 g oxygen per hour. Thus a water supply just sufficient to sustain one tonne of 100 g fish will be able to hold 200/170 = 1.18 tonnes of 200 g fish. In general, therefore, the smallest fish on a farm require the best oxygenated and greatest water supply, and are most susceptible to oxygen shortages (Figure 1.26).

The other main factor influencing energy expenditure and, hence, oxygen consumption is temperature. Atlantic salmon can survive at temperatures between 0°C and about 23°C. The latter is the upper lethal temperature, which varies slightly from stock to stock and previous history of the individual. The optimum range of temperatures for growth is 12–15°C. Between 6 and 16°C is the range over which reasonable growth can be expected and a temperature change of this magnitude results in an approximate doubling in oxygen consumption. The oxygen content at

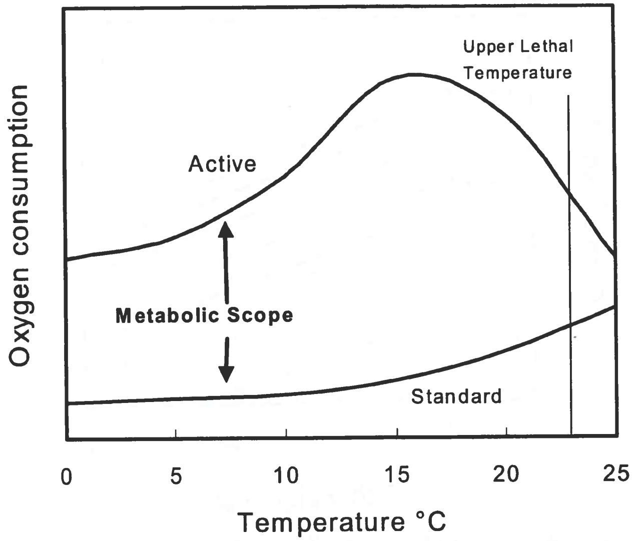

Figure 1.27. Metabolic scope of salmon in relation to temperature. Note that at 15°C the difference between standard (resting) and active (maximum) metabolic rate is the greatest. This is the optimum temperature for growth and activity. (After Beamish, 1978.)

saturation, comparing 6°C and 16°C, shows a decrease from 14 to 9 $mg.l^{-1}$ freshwater. This means with temperature increase resulting in doubling of oxygen requirement the oxygen available in the water decreases by 35%. Thus to sustain the fish over this temperature increase, the water supply has to be increased approximately threefold.

The food consumption and growth rate of fish generally increase in parallel with the change in oxygen consumption. Thus fish consume approximately twice as much food over 10°C increase in temperature within the optimum range. Small fish require more food per tonne than bigger fish.

The oxygen consumption of fish at any temperature varies between limits. Since salmon never or rarely remain static, there is a problem with defining resting or basal metabolic rate. The term 'standard metabolic rate' (SMR) is used to refer to a theoretical resting or quiescent metabolic rate. This is the oxygen consumption of a fish with an empty stomach but is not in a starved state and there is no discernible activity (Figure 1.27).

Swimming activity can increase metabolic rate so that at maximum sustained swimming speed the maximum oxygen consumption is reached; this is by convention known as the 'active metabolic rate' (AMR). The difference between the AMR and the SMR is known as the metabolic scope, within which the fish has to do all its work. In general, the SMR increases with temperature whereas the AMR shows a dome-shaped relationship. At high temperatures the gills cannot extract as much oxygen from the water which is decreasing in oxygen content, so the AMR is progressively decreased until the upper lethal temperature is reached. When the metabolic scope becomes zero the animal cannot survive. The SMR corresponds approximately to the maintenance ration energy expenditure.

In salmon and other fishes, feeding also increases the metabolic rate. During growth, synthesising new proteins requires energy and the functioning of the digestive system and so on also requires energy. Thus in a feeding and growing fish the oxygen consumption is typically 2–3 times the SMR. This post-prandial increase in metabolism is known as specific dynamic action (SDA). SDA is very important from the point of view of the management of an aquaculture unit. During feeding the oxygen and or water supply to a system must be increased. Furthermore, it is evident that at high temperatures, where the metabolic scope is restricted, SDA alone may use the whole of the scope and leave no capacity for swimming activity. At high temperatures, feeding can result in mortalities through the fish being unable to take in enough oxygen through their gills. The gills (and heart and blood system) are often incapable of delivering oxygen to supply the needs of both activity and feeding metabolism. In nature, fish have to make a choice and this may be one reason why fish ascending rivers do not feed, reserving their full metabolic scope for the energy requirements of swimming activity. In Figure 1.27 it is evident that the optimum temperature for growth is where the metabolic scope is greatest—the fish is able to swim actively and process the maximum amount of food.

Handling fish increases their metabolic rate, as does stress. If the fish also have full stomachs the combination of high temperature, SDA, stress and activity may lead to tissue hypoxia and death. In the management of a fish stock the additive nature of the different metabolic loading factors must be taken into consideration together with the limiting nature of the metabolic scope. Many diseases lead to anaemia and/or damage to the gills or the heart, which may decrease the metabolic scope of the individuals. Such impaired fish will tend to feed less in order to maintain some spare metabolic scope and, although the effects may not be directly lethal, growth rate will be reduced. An important means of reducing oxygen consumption of a stock of fish if problems arise, such as failure of water supply or fouling of sea cage meshes, is to cease feeding. This can ensure survival of a stock that would otherwise have to be slaughtered. It can be tempting to increase aeration to the extent that water becomes supersaturated. This is dangerous since gas bubbles can form in the fishes' blood vessels and internal organs, resulting in death. Supersaturation often occurs if cool water with high oxygen content is heated in attempts to accelerate growth or development rates. Supersaturation can also sometimes occur in some pumping or supply systems in which gas becomes entrained at high pressure. The gas is then rereleased when pressure is reduced to ambient in tanks. In such situations the water should be agitated to release excess gas before it reaches the fish tanks.

1.4 CONCLUSIONS

In the culture of salmon the farmer is obliged to provide a complete life-support system for the animal, supplying food, oxygen, disposal of waste, etc. Particularly in the case of the water and oxygen supply, failure can be lethal to the stock within minutes. The system needs to be in excess of 99.99% reliable, of the order required in the chemical process or nuclear power industries. The fact that this level of success is widely achieved in the industry is a tribute to the ingenuity and care with which fish farm systems have been designed and operated. It is only with intimate knowledge of requirements of the species and understanding of basic biology that progress can be made.

Acknowledgements

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2

Production I: broodstock management and early freshwater stages

2.1 BROODSTOCK MANAGEMENT

2.1.1 Introduction

In the early days of salmon farming, the industry obtained its stocks by stripping ova from wild salmon. While these stocks were adequate for a fledgling industry, a rapid expansion necessitated the development of reared broodstock to cope with the increased demand for ova. Initially the broodstock was produced from Scotland's native stocks, but in the modern industry many brood fish are of Norwegian origin and have been produced through selective breeding programmes (see Chapter 12) aimed at providing the performance needed today. The worldwide production of farmed Atlantic salmon has continued to rise steeply in recent years and is associated with a steady reduction in farm gate prices. In order to remain viable, companies have had to increase efficiency in various ways in order to maximise the tonnage of salmon produced in relation to production costs.

Although improved feeds and feeding technology have resulted in better growth rates and food conversion rates (FCR), and a better understanding of fish health combined with the availability of more effective medicines has greatly reduced the level of mortalities, careful stock selection is fundamental to achieving these benefits. By rearing individual families of fish, the performance of each family can be carefully monitored so that broodstock selections can be made for particular traits such as growth rate, late maturity (which allows larger fish to be marketed before the onset of maturation) and disease resistance.

Initial selections are made at the egg stage. Egg batches stripped early in the spawning season will produce a broodstock that will also produce early season eggs. These eggs result in early hatching and feeding fry which are essential for the production of S0+ smolts (smolts produced in less than one year) and will increase the size of S1+ smolts. Eggs that demonstrate high levels of fertility and survival are also selected. Further selections are made as the selected families are tracked through their life cycles.

Since it is desirable to obtain the highest possible growth rates, therefore maximising ova production, it is necessary to transfer the fish at the smolt stage into sea water. Fungal infections can also be a problem when salmon are held back in freshwater and this can be avoided with a transfer into sea water.

2.1.2 Vaccination

All salmon selected to become potential broodstock will have come from a certified disease-free stock and been kept throughout the freshwater stages in an environment free of any pathogens that cause diseases such as infectious pancreatic necrosis (IPN) and bacterial kidney disease (BKD). The presence of these pathogens would prevent the salmon being used as broodstock since both can be vertically transmitted to eggs. However, once the salmon are transferred into sea water there is a risk of that they can contract diseases carried from other sites or farms either via fish or in the water. Disease may be carried by fish escaping from another fish farm or by wild fish. Certain pathogens can survive for a limited length of time in sea water and can therefore be carried in tidal currents to a marine fish farm and then infect the fish.

One disease which may be carried both ways is furunculosis, caused by the bacterium *Aeromonas salmonicida*. This disease, once a major problem for the salmon farming industry, is no longer such a threat, largely owing to the development of highly-effective vaccines. Vaccination takes place at the pre-smolt stage at least six weeks before transfer to the sea, and is now a procedure carried out universally throughout the salmon farming industry. The vaccination process is carried out by anaesthetising each individual fish and injecting the vaccine intraperitoneally (into the body cavity anterior to the pelvic fins). The anaesthetics most commonly used are MS222, or benzocaine which has to be pre-dissolved in either acetone or alcohol (100 g of powder in 2.5 l). While this vaccination will protect the fish from furunculosis for its full marine growing cycle (from smolt to harvest), the process does have an adverse effect. The vaccine can cause adhesions within the body cavity. In the case of the gonads, for example, if the vaccine comes into contact with the developing ovary, a 'skin' may form over the ovary which prevents the ova being released into the body cavity at the time of full maturity, thus making it impossible to strip the eggs from the fish.

In order to avoid this problem, it is advisable to adopt a different approach when vaccinating fish destined to become broodstock. To ensure that the vaccine does not come into contact with the ovaries, a different injection site can be used, and the favoured location is the space between the muscle blocks posterior to the dorsal fin. Here there is a slight depression into which the vaccine can be injected, taking care to avoid the muscles. Since brood salmon will be kept in sea water a year or more longer than production fish, it may be advisable to give them a boost with a second vaccination. The timing of this boost will depend on the length of time for which protection is given by the initial vaccination and should give additional protection through to full maturity. It should not be done at a time when the fish are likely to be stressed easily, for example when sea temperatures are high. This operation is carried out as close to the broodstock rearing unit as possible in order to reduce unnecessary handling and transport.

2.1.3 Holding facilities and environmental conditions

Once the potential broodstock has reached the smolt stage, there are two options for the marine phase. The smolts can be transferred either into pens in the sea or into tanks filled with sea water by pumping.

2.1.3.1 Sea pens

The pens used for broodstock are exactly the same as those used for growing salmon for the market place, generally being made either of plastic or steel frames. The mesh size of the nets is increased as the fish grow, although meshes greater than 20 mm are not used in order to prevent cock fish getting their kypes (hooked lower jaw) caught. Nets are cleaned or changed as often as is necessary to prevent the build-up of fouling and therefore to maximise water flows and oxygen levels and maintain water quality.

Anti-predator devices, such as nets and scarers, should be employed to protect this valuable stock from herons, cormorants and seals (Europe) and great vigilance must be maintained regarding the presence of the sea louse, *Lepeophtheirus salmonis*. Monitoring and treatments, when necessary, must be carried out to ensure that this parasite causes no stress or damage to the fish.

It is particularly important that brood fish are reared in a stress-free environment in order to maximise the survival of the fish and the quality of the ova produced from them. In view of this, stocking density is held at a low level with a recommended maximum of $7\,kg\,m^{-3}$. The location of the broodstock pens is important: they must be safe from potential storm damage and have a good separation from any other pen sites. Ideally the site should be used exclusively for broodstock. Since salmon broodstock are normally held in the sea over either two or three winters before they reach maturity, it is necessary to have more than one generation in the sea at the same time to maintain continuity of egg supply. It is advisable not to mix year classes on the same site, so it is preferable to operate with at least two separate broodstock sites. If this is not possible, each year class should be held in a separate pen group as far apart as the site will allow.

2.1.3.2 Pump-ashore tanks

The alternative to pens are land-based tanks into which sea water is pumped. These tanks are built of concrete or glass reinforced concrete (GRC) and are very large (a minimum of 12 m in diameter and 2 m in depth) since brood salmon can weigh at least 20 kg as they approach maturity. It is important that all internal surfaces of the brood tanks are maintained to a smooth finish and that any fouling is removed regularly to prevent the risk of damage to the fish. Water flows should be maintained at a level that provides a minimum oxygen level of $6\,mg\,l^{-1}$ (continuously monitored), removes waste products through a central screen, gives the fish a degree of exercise and facilitates feeding. When making a choice between tanks and pens for broodstock, although the capital and running costs of tanks are higher, they have advantages over pens:

- a greater degree of management control;
- less possibility of cross infection;
- protection from predators is easier;
- sea lice should not be a problem;
- environmental conditions can be manipulated; and
- tanks are less affected by the weather.

While salmon can attain full maturity in sea water, there are advantages in mirroring the natural cycle, especially in that the viability of eggs and sperm is higher if the broodstock is held in freshwater prior to spawning. In terms of managing the spawning process, it is much easier to work in freshwater, especially if the fish are held close to the incubation facility. The freshwater brood site can be either pens in a freshwater loch or tanks. These pens or tanks will be similar to those used for the marine phase although, in both cases, they may be smaller since the fish will be kept in them for a relatively short time.

A significant advantage of pump-ashore tanks is that the change to freshwater can be achieved simply by switching the water supply gradually from sea water to freshwater with the fish staying in the same tanks. By the time the first fish are ripe and ready for stripping, the broodstock is in freshwater.

2.1.3.3 Transferring fish

When transferring broodstock from sea pens, great care must be taken to handle the fish carefully, thereby keeping stress levels to a minimum in order to prevent a decrease in egg quality and possible mortalities of the fish themselves.

Broodstock should be netted one at a time in soft-meshed nets and should be kept in the water as much as possible. Damage to fish may also result in *Saprolegnia* infections (fungus) before the fish can be spawned. Transfer from the sea is often accomplished using helicopters which, although expensive, speeds up the process, thus keeping stress to a minimum and reducing the risk of mortalities of very valuable fish. Transfer will normally take place no more than one month before the earliest fish are due to ripen. Any earlier and there is a greater risk of *Saprolegnia* problems since maturing fish in freshwater are very susceptible to fungal infections. Any later and there is a risk that some of the hens may have already ovulated and ova may be shed during transport. Before transfer, any immature fish can be removed as the stock is sorted and cocks and hens can be separated, although this may also be done at a later stage once the fish are in freshwater.

2.1.4 Broodstock feeding

When considering the feeding of broodstock, two aspects need to be covered: first, the choice of diet and second, the method of delivering the feed to the fish.

Since the success of the broodstock will determine the success of the next generation of stock, the choice of diet is important. Although salmon broodstock can perform adequately on ordinary grower feed, broodstock diets are specially formulated to take into consideration the increased requirements for specific nutrients during gonad development. Hence, only the highest-quality ingredients are used in the manufacture of brood diets, which contain boosted levels of vitamins, especially vitamins C and E. High levels of pigment (typically 75 ppm Astaxanthin) are also contained in the feed and give the eggs their deep orange colour, mirroring that of eggs produced from wild salmon. It is thought that pigment in the eggs helps to protect them from light. Broodstock will normally be changed from a grower to a brood diet approximately eight months before they are due to be spawned.

The feeding method has to take account of the differences between production salmon and broodstock. Since the brood salmon are held at lower stocking densities ($7\,kg\,m^{-3}$), the preferred method is handfeeding; the fish are fed slowly and carefully to ensure that they all get the same feeding opportunity and that the risk of fighting, particularly between males, is reduced. An added benefit of this feeding method is that it enables the fish to be observed and monitored daily during the feeding process with particular attention being paid to behaviour, condition and health status. Given the value of the fish, it is time well spent. Regarding the frequency of feeding, brood salmon normally require one or two meals per day.

To ensure good-quality eggs, brood salmon should be fed throughout their marine phase for as long as they are willing to accept feed. This may be until nearly the time when they are transferred to freshwater as they approach full maturity, characterised by changes in external appearance (colour and shape). However, appetite decreases as they reach this stage, and feeding rates are reduced accordingly. Salmon are no longer fed once they are in freshwater prior to spawning because they will no longer accept food.

2.1.5 Broodstock health testing

To help prevent the spread of disease between farms it is important to ensure that brood salmon and, therefore, the eggs that they produce are free from certain diseases. Indeed, under EU legislation all farms with broodstock must be inspected at least once per year and tested for viral haemorrhagic septicaemia (VHS) and infectious haematopoietic necrosis (IHN) at least once every two years. Under UK legislation, if IPN is present on a site, then all broodstock must be tested and eggs from positive fish destroyed. For internal (UK) use of eggs, the testing authority[1] recommends that testing is carried out for indigenous pathogens that may be vertically transmitted (within eggs), i.e., IPN and BKD. For export, tests need to satisfy the requirements of the importing country. For example, Chile requires certification for a list of diseases including VHS, IHN, epizootic haematopoietic

[1] Scottish Executive Rural Affairs Department, Fisheries Research Services, Marine Laboratory, Aberdeen, Scotland.

necrosis (EHN), infectious salmon anaemia (ISA), IPN, BKD and salmon rickettsial syndrome (SRS). Some of these (VHS, IHN and EHN) can be certified 'freedom as a zone' without testing.

Anyone embarking on a broodstock programme should contact their regulating body at an early stage to discuss an appropriate testing regime. A programme can then be agreed whereby the broodstock are sampled and tested throughout their lives up to and including the time when they are spawned. For both voluntary UK certification and for export, at least 150 fish—or all fish if there are less than 150 on site—need to be tested. However, in some situations all broodstock have to be tested for certain diseases. For voluntary certification the tests can be carried out by anyone who is competent to do so, whereas for statutory purposes and export it must be done by an inspector (in the case of Scotland, from the FRS Marine Laboratory). For export certification, in the case of ISA and BKD an element of testing involves visual examination and this must be done by a Marine Laboratory inspector or under the supervision of a veterinary surgeon. For IPN and SRS, a proportion of samples must be taken by an inspector but if 100% of fish are being tested, the farmer may do the majority of the sampling. Advice and training in sampling techniques can be obtained from the FRS Marine Laboratory staff in Aberdeen.

At the time of spawning, the priority regarding broodstock is to produce eggs of the highest possible quality. Nothing should be allowed to jeopardise this goal. However, health testing is also important and must be carried out correctly. Therefore it is necessary for the two operations to run smoothly without compromising one another.

Good planning is essential. In situations where all the broodstock are tested it is important to label individual fish which can be matched to egg batches. If egg batches are incubated separately from one another, then in the event of a fish coming up with a positive test, the eggs from that fish can be identified and destroyed without affecting the others. Since all test results are available within four weeks they are known to the farmer before eggs are either laid down for hatching or despatched to other farms.

2.2 STRIPPING OF BROODSTOCK

2.2.1 Assessing ripeness

As salmon approach maturity, changes in external appearance occur that distinguish males (cocks) from females (hens) and maturing from non-maturing fish. These changes can be observed from early in the summer and become more pronounced as autumn approaches. By the time the salmon are fully mature and ready for spawning in November, the differences are obvious. These visual changes enable broodstock to be sorted prior to spawning. Maturing cocks become dark in colour, develop a kype (hook) on the lower jaw and have an extended upper jaw (Figure 2.1). In contrast, the maturing hens darken, but less so than cocks, have a

Figure 2.1. A typical mature cock salmon illustrating a well-developed kype on the lower jaw and an extended upper jaw.

smaller head, develop a rounded belly caused by the increasing egg mass and become extended at the vent.

Although all the hen salmon in a particular population will mature over a relatively short time, each individual has a specific time when it ripens. It is important that each hen is stripped at this exact time in order to maximise the survival of the eggs and the subsequent fry. It has been demonstrated that this period lies between four and seven days after ovulation, when the ovarian tissue breaks down and the eggs become free within the body cavity (Springate and Bromage, 1984). Progressively poorer results are obtained if stripping is carried out further from this period in either direction. In order to strip hens as close to

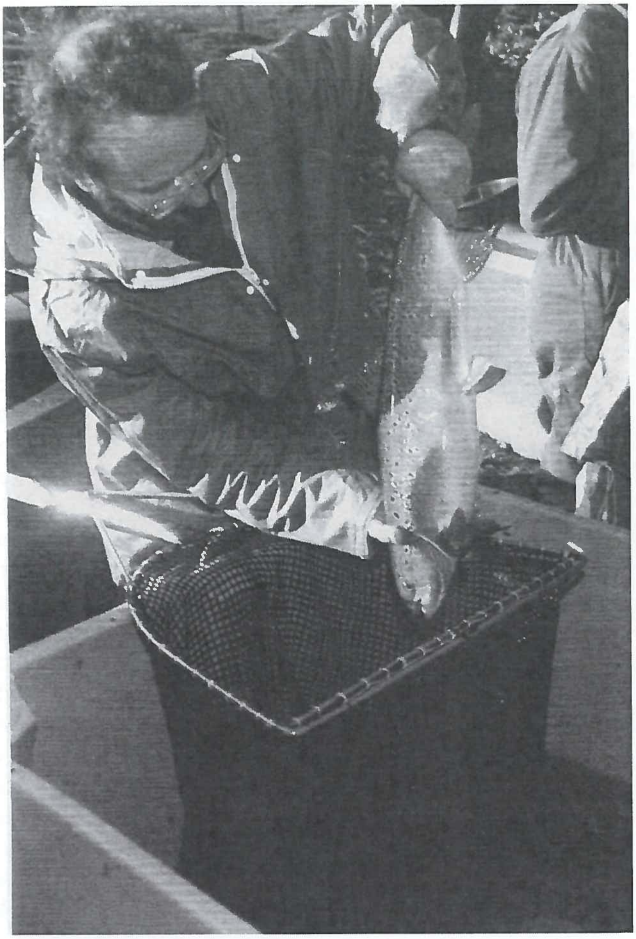

Figure 2.2. A small ripe hen. In this vertical position the free eggs drop towards the head, leaving a narrowing at the vent.

the peak time as possible, each hen should be checked for ripeness once per week. More often would cause undue stress to the fish, with possible mortalities, and less often would not guarantee getting close to the peak time. The most common method used to assess ripeness in a hen is to anaesthetise the fish before lifting her up by the tail into a vertical position with the head down. If the hen is ripe, the egg mass will drop towards the head leaving a narrowing at the vent (Figure 2.2). The belly will also be soft. While this method works well with small and medium-sized hens it is not so suitable for large hens, which are not only more difficult to lift into a vertical position but could also be damaged in the process. For these fish an alternative is to hold the anaesthetised hen on a net top (Figure 2.3), and pull the tail back with one

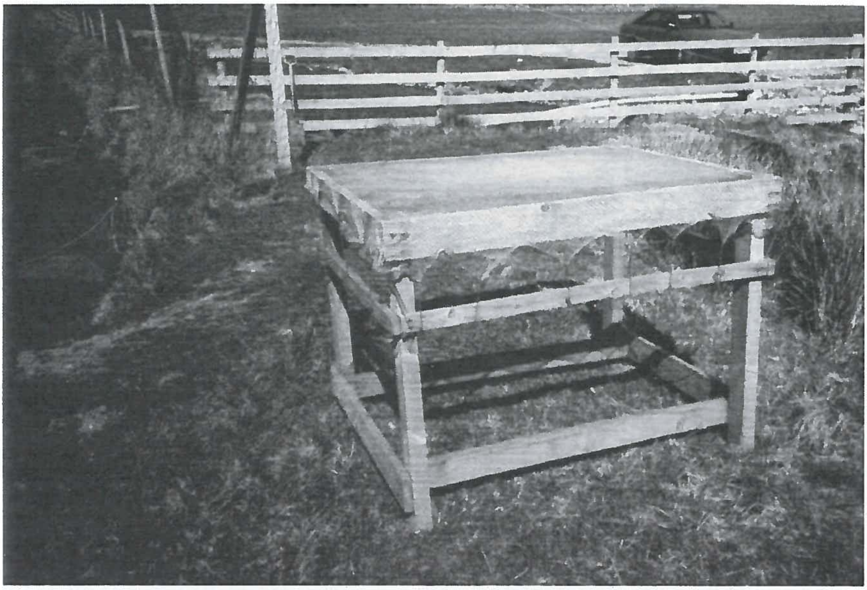

Figure 2.3. A table made of knotless netting acts as an ideal surface for checking the ripeness of large hens.

hand while applying pressure to the forward part of the belly with the other. If the hen is ripe, a few eggs will be extruded at the vent.

In the case of cocks, ripeness is easily assessed because they ripen in advance of the hens and stay ripe throughout the spawning season. They can be checked by gently rubbing their flanks close to the vent. If ripe, milt (white fluid containing sperm) will run from the vent.

2.2.2 Stripping location

Although it is possible to strip salmon (remove eggs or milt) at any one of a number of locations—such as river bank, barge or boat alongside freshwater pens, loch shore or next to brood tanks—it is most appropriate to have a location as close as possible to the site where the resultant eggs will be incubated. This reduces the transportation needed for the post-strip eggs and therefore minimises unnecessary risks to the eggs. Wherever the location, it is important that stripping is carried out in some form of shelter where environmental conditions can be controlled to some extent. The stripping season occurs at a time of year when weather conditions can be severe and, since it is not possible to choose only the fine days for stripping, precautions must be taken to protect both the eggs and the spawning operatives from low temperatures, wind and rain. It is particularly important to keep rain off the eggs (as will be explained later in this chapter) and conditions should be comfortable for the operatives. A cold, miserable operative with numb fingers cannot do an efficient job. Egg quality will suffer.

2.2.3 Stripping methods

The dry manual method of stripping is practised widely and will give excellent results if carried out correctly. It is important to establish a routine that produces consistently good results and then stick rigidly to it. Any deviation from the routine may result in poor batches of eggs. One routine that gives a consistently high degree of success (up to 99.8% to the eyed stage for wild salmon) is outlined step-by-step as follows:

1 A sufficient number of plastic basins or buckets are washed, disinfected using an iodophor, rinsed and thoroughly dried in preparation for the stripping.
2 Ripe hens are crowded within their holding unit. It is advisable to sort out ripe hens the previous day so that there are no delays on the stripping day.
3 Ripe hens are netted singly from the holding unit and placed in an anaesthetic bath.

The floor of the bath should be wide enough to allow the hens to roll over on to their sides once they are fully unconscious. The concentration of the anaesthetic should be adjusted so that the hens are completely immobilised after one to two minutes (start with a light concentration then strengthen it until the right one is reached). No attempt should be made to strip a hen which is not immobilised since this can result in damage to the hen and/or the eggs, is difficult for the operative and slows up the process.

4 Once immobilised each hen is removed from the anaesthetic and rinsed in clean freshwater to remove any anaesthetic.
5 Each hen is then taken to the operative and placed on a suitable surface (a net top is ideal) where all water is removed using paper towelling. The hen should not be rubbed too hard as this may result in skin damage.
6 The operative adopts a favoured position (sitting, kneeling or standing), holds the caudal peduncle (wrist) of the hen with one hand positioning the vent above a basin or bucket and then, keeping the hen as close to a vertical position as possible, brings their other hand or arm firmly down the hen's belly. Providing that the hen is fully ripe, eggs will pour in a steady stream from the vent (Figure 2.4). For large hens stripping might be a two-person operation, with one operative holding the hen while the other removes the eggs. During the removal of the eggs it is important not to apply pressure with the fingers near to the vent as this may result in bursting eggs. Burst eggs, which appear as creamy strands in the presence of water, greatly reduce the fertility of a batch of eggs, which can drop to as low as 60%. It is also important to prevent water getting on to the eggs since this would initiate water hardening before fertilisation can take place. During water hardening, water enters the egg through its porous shell, increasing the volume by approximately 20%. As this happens the

Figure 2.4. In a fully ripe hen, eggs readily flow from the vent when the hen is held as close to the vertical as possible and pressure is applied to the abdomen.

single hole (the micropyle), through which a spermatozoan has to enter to fertilise the egg, closes. If this occurs before a sperm can enter then the egg can no longer be fertilised.

Normally the eggs from each hen will be stripped into a separate basin or bucket, although it is possible to add the eggs from more than one hen into each container, especially if the eggs are to be batched for incubation.

With the dry method, all the eggs for a particular day can be stripped before any fertilisation needs to be done. Unfertilised eggs can be kept for several hours without any adverse effects.

Figure 2.5. Milt is easily squeezed from a ripe cock salmon into a basin of eggs.

7 Two approaches can be adopted for the fertilisation process. Either milt (white fluid containing sperm) can be squeezed from at least two cocks directly on to the batch of eggs (Figure 2.5); or the milt from several cocks can be extracted in advance and kept chilled before being used (with great care to avoid contaminating the water). The second option is preferred in modern broodstock units because it allows a sample of milt from each cock to be checked for sperm motility before being used. To check motility, a small sample of milt is placed under a raised coverslip on a microscope slide. When a drop of water or ovarian fluid is introduced to the edge of the coverslip the spermatozoa are immediately activated and, when viewed through the microscope, should show a high level of activity for up to one minute. Milt showing poor activity can be discarded. This option also enables milt from several cocks to be pooled before being used and a precise amount to be added to each batch of eggs (2 mls/10,000 eggs).

Once the required amount of milt is added to a batch of eggs, the eggs and milt are mixed thoroughly using a clean hand. This operation must be done quickly since the sperms only remain active for about one minute. After mixing, the eggs are left to stand for exactly one minute.

8 The fertilised eggs are then added to an equal volume of clean fresh water and left to stand for a further 1.5 minutes.

Excess milt is washed off quickly using no more than one bucket of clean

Figure 2.6. After fertilisation and washing, the eggs can be added directly into an incubator – –in this case a basket – for water hardening.

water. It is important not to prolong this washing operation as there is a danger of moving eggs which are starting to water harden.

9 After washing there are two options. The eggs can either be added directly to an incubator (Figure 2.6) or left in a full bucket of clean water for water hardening to take place. The choice depends on whether it is possible to lay them down in an incubator in advance of water hardening and whether there is the necessity to disinfect the eggs before they are incubated to prevent the possible transfer of pathogens. Whichever is chosen, under no circumstances should the eggs be moved during water hardening. Even the slightest movement can result in heavy losses. The hardening process takes up to one hour to complete; at the

end point the eggs can be moved freely whereas before they adhered to one another and the surfaces of the bucket or incubator during the process. Once water hardening is complete, if not already in an incubator the eggs should be moved to one as soon as possible. If eggs are added to an incubator for hardening, account must be taken of the 20% increase in volume when deciding on how many eggs to put in.

To prevent the possible transfer of pathogens carried on the external surface of eggs either into the hatchery or between hatcheries, it is important to disinfect the eggs at the appropriate stage. A buffered iodophor (such as Buffodine™ in which the active ingredient is iodine) is used to disinfect eggs either as newly fertilised, water hardened or eyed. The buffering is essential since an iodophor with a low pH will kill eggs. Plastic basins or buckets are suitable containers for disinfecting eggs and should contain ten times as much diluted iodophor by volume as the volume of eggs to be treated (i.e., 1 l of eggs in 10 l of disinfectant solution).

To disinfect newly-fertilised eggs, the stripping and fertilisation procedure is followed to stage 7, at which point the milt should be washed from the eggs using a 0.9% solution of sodium chloride (i.e. 90 g to 10 l).

The clean eggs are then immersed in disinfectant solution made up of 90 g sodium chloride and 100 mls Buffodine™ in 10 l of water. The 0.9% sodium chloride prevents the iodine solution passing through into the egg (i.e., prevents water hardening).

After ten minutes' immersion, the eggs should be washed four or five times in a solution of 0.9% sodium chloride before being transferred to an incubator. Some mortalities may be expected when newly fertilized eggs are disinfected. For water hardened and eyed eggs the disinfection procedure is the same but without the necessity of sodium chloride.

Diluted iodophor may be used to disinfect successive batches of eggs provided it does not become exhausted. To check on exhaustion, keep a full (white) cup of the original iodophor dilution on one side and compare this with the used disinfectant after every batch of eggs. As long as the disinfectant colour remains similar to that in the cup, it may be used.

Although the manual method of stripping is widely practised and gives excellent results, there are two other methods which can be employed. Since almost all salmon broodstock are used for only one season they are killed at stripping time (the exception being wild broodstock which are generally released after stripping). Instead of anaesthetising these fish they may be immobilised by killing them prior to stripping. It is obviously of vital importance that ripeness is confirmed before this is done. Incision spawning may then be employed where the abdomen of the recently-killed hen is cut from the vent to the pectoral fins while she is held vertically with the vent positioned over a dry basin or bucket. The eggs are allowed to pour out. Any contamination of the eggs with blood has no significant effect on fertility and the blood can be removed when the eggs are washed after fertilisation. This method of stripping is considered to be faster than the manual method and produces more eggs from each hen. Once the eggs have been stripped, subsequent procedures are the same as for the manual method described above.

If very large brood hens are being stripped, a third method may be considered. This is air spawning where compressed air at relatively low pressure is passed through a hypodermic needle into the body cavity of a ripe hen. The pressure forces the eggs from the vent. With this method the hen does not need to be lifted into a vertical position for egg removal.

2.3 THE HATCHERY

Once the salmon eggs have been stripped, fertilised, water hardened and disinfected they are carefully transferred to the egg incubation facility at the hatchery. Although salmon hatcheries in some shape or form have existed for more than 150 years, modern units are increasingly sophisticated. Traditional hatcheries were small and used to handle wild eggs for restocking rivers, whereas most hatcheries today are designed to service a salmon-farming industry which is becoming ever more demanding in terms of stock requirements. These units are larger (the largest caters for more than 30 million) and make full use of available materials and technology to produce the stock at the time and the size required. The hatchery comprises incubators for the eggs and alevins, and tanks for growing-on the fry normally through to the smolt stage, and must be supplied from a reliable source of high-quality freshwater.

This water supply can be one or more of four types: spring, borehole, river/stream or loch; some hatcheries use both ground water and surface water to get the benefits of both. Ground water is often used for eggs and alevins since it has a higher, more constant temperature in the winter than surface water, is little affected by spates caused by heavy rainfall (no suspended solids) and is unlikely to contain pathogens.

However, to get good fry growth rates in the summer, a higher temperature and more water are required, so surface water is the preferred option. Whatever the water supply, it is advisable to carry out a full analysis before it is used to ascertain whether or not it is suitable for incubating eggs and rearing fish. Of particular importance are

- pH (eggs will fail to hatch at a pH of less than 5.5);
- the presence of heavy metals which can be toxic to fish; and
- the levels of dissolved gases (ground water is usually high in dissolved nitrogen and low in oxygen).

While little can be done if heavy metals are present, both pH and dissolved gases can be modified. pH can be raised by dosing the water with calcium carbonate while the balance of gases can be improved by vigorous aeration (nitrogen is blown off and replaced by oxygen). To prevent the risk of introducing pathogens, many hatcheries treat the water either with UV light or ozone and filters are commonly used to remove organic matter. It is particularly important to have high-quality water for eggs and alevins.

2.3.1 Egg incubation and development

Before introducing eggs to the hatchery, it is important to disinfect thoroughly all equipment and facilities to ensure that there is no risk of an infection being passed from a previous stock to the new stock. Iodophors are the most commonly-used disinfectants with iodine as the active ingredient. Since disinfection is not carried out merely as an exercise, procedures must be adopted which will ensure that any pathogens present are killed. Equipment should be fully immersed for ten minutes in a dilution of iodophor which has an iodine concentration of 200 ppm. Larger equipment, incubators and tanks should be thoroughly wetted with an iodophor dilution at the same iodine concentration, using either a sprayer or brush. Foot baths (200 ppm iodine) should be used at the entrance to the hatchery and within the hatchery where cross-contamination is to be avoided. Any organic material must be washed off the equipment before disinfection otherwise the procedure is not effective. This is particularly important with boots. Although iodophors can be used on eggs, they are highly toxic to fish and therefore must be disposed of responsibly after use. The best method of disposal is via a soak-away.

At the time when eggs are laid down in incubators it is desirable to obtain an approximation of their number and size so that correct stocking densities can be used and an estimate made of production. Egg size is a function of age, with the size increasing as the fish get older (i.e., eggs from grilse are smaller than eggs from MSW salmon). Normally eggs are measured by volume and, since there is a direct relationship between egg diameter and volume, by measuring the mean diameter of a sample of eggs the number of eggs per unit volume can be calculated. In practice this is done using the Brofeldt's scale (Table 2.1) where a sample of water-hardened eggs is spread along a ruler and the number per 25 cms recorded. From the table the

Table 2.1. Brofeldt's scale. Relationship between egg diameter and egg number per unit volume.

Egg volume (litres)	Number of eggs per 25 cm								
	37	39	41	43	45	47	49	51	53
0.10	390	450	520	600	680	780	880	990	1120
0.20	780	900	1040	1200	1360	1560	1760	1980	2240
0.30	1170	1350	1560	1800	2040	2340	2640	2970	3360
0.40	1560	1800	2080	2400	2720	3120	3520	3960	4480
0.50	1950	2250	2600	3000	3400	3900	4400	4950	5600
0.60	2340	2700	3120	3600	4080	4680	5280	5940	6720
0.70	2730	3150	3640	4200	4760	5310	6160	6930	7840
0.80	3120	3600	4160	4800	5440	6240	7040	7920	8960
0.90	3510	4050	4680	5400	6120	7020	7920	8910	10,080
1.00	3900	4500	5200	6000	6800	7800	8800	9900	11,200

number of eggs per litre can be obtained. For this exercise dry volume is used (eggs only with no water). Atlantic salmon eggs normally lie between 4000 eggs l^{-1} for large eggs to 6000 eggs l^{-1} for small eggs.

Although hatchery operators prefer to obtain eggs as large as possible, there is no difference between large and small eggs in terms of survival either at the egg stage or later fry stage. However, large eggs result in larger fry at the first feeding stage than the equivalent from small eggs and therefore gives them a better start.

Although eggs can be incubated in a variety of ways, certain environmental conditions (which should be continuously monitored to identify any fluctuations) have to be met to achieve a good level of success:

- Water must be chemically suitable and have a low level of suspended solids. While a thin layer of sediment on eggs in an upwelling system has no adverse effect, excessive siltation may suffocate the eggs.
- The pH of the water should be as close to neutral (7) as possible and not below 6 (low pH may prevent hatching).
- The oxygen level at the incubator outflow should be a minimum of $7\,mg\,l^{-1}$.
- The incubation temperature should be chosen to achieve the desired result from the eggs. Since the rate of egg development is controlled entirely by the water temperature, then by altering the temperature, the rate of development and hence the duration of incubation can be controlled. It comes down to a balancing act since, on the one hand, eggs incubated at 6°C will have few mortalities and a high success rate in terms of development at the alevin stage, while on the other, eggs incubated at much higher temperatures (up to 12°C) will have more mortalities and a poor rate of successful development combined with a higher level of abnormalities in later life. However, by incubating at a higher temperature the incubation period can be dramatically shortened, resulting in first feeding taking place much earlier.

The knock-on effect is that a higher percentage of bigger S0+ and S1+ smolts can be produced. Since most hatcheries require the water to be heated to achieve this result, it is most economical to accelerate development at the egg stage when relatively low water volumes are required. A good all-round result is obtained by choosing a temperature of 8°C.

- Water flows must be high enough to provide oxygen and remove waste products, but not so high as to disturb the eggs during the sensitive green stage.
- Flow patterns must be achieved to ensure that water flows evenly through all the eggs. Air bubbles must not be allowed to accumulate below eggs because they create dead areas and disrupt water flows, thus reducing the oxygen to the eggs above.

Premature hatching is often indicative of the presence of air bubbles (low oxygen levels stimulate hatching). Bursting air bubbles can also disturb and kill eggs.

- Light levels must be kept very low (sunlight kills eggs). Egg incubation is normally carried out in total darkness either by blacking out the hatchery completely or by using well-fitted covers on the incubators. Subdued daylight or artificial light can be used when working on eggs with no adverse effects.

- Incubator materials manufactured specifically for use in hatcheries should be used. Glass-reinforced plastic (fibreglass; GRP), plastic and aluminium are the materials used in modern incubators.

Commercial incubators fall into four basic types, with the particular design resulting in water flowing either vertically or horizontally through the eggs:

2.3.1.1 The hatching silo or cylinder

The hatching silo or cylinder (Figure 2.7). This incubator is used to take eggs through to the eyed stage but, despite its name, it is not suitable for hatching

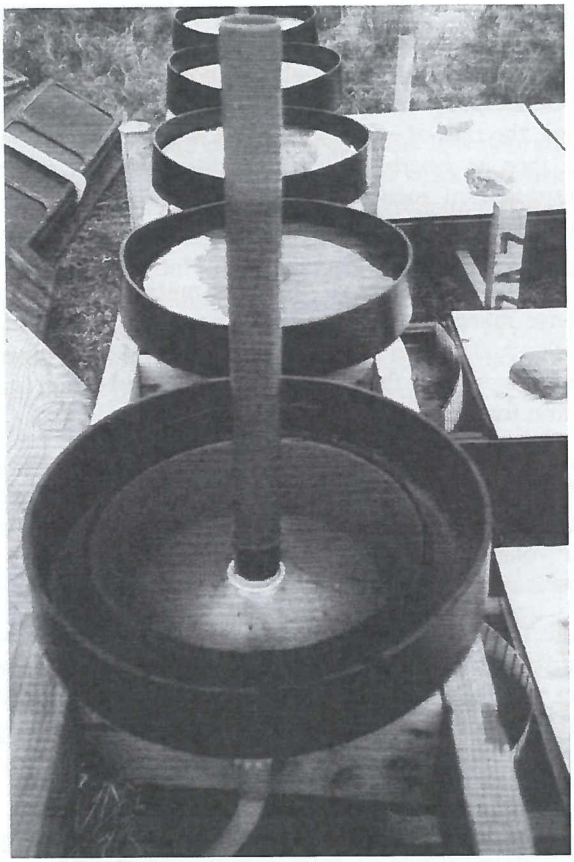

Figure 2.7. The hatching silo. The silo in the foreground shows the egg mesh attached to the air pipe in a raised position. When pushed down to the bottom the silo can hold 30 litres of eggs.

eggs. It is ideal for the production of eggs that are then passed on to other hatcheries for hatching. The incubator is:

- cylindrical in shape,
- normally made of plastic,
- can be free standing or supported round the collar,
- can hold up to 30 l of eggs in a column; and
- is very economical both in terms of water and space.

Water enters at the bottom of the silo and flows up through the column of eggs which are supported by an angled stainless steelmesh. A pipe running from the mesh up through the centre of the silo is designed to prevent air bubbles forming under the mesh. With this design all of the water entering the silo has to pass through the eggs; however, it is important that, on entering the silo, the water is firstly directed downwards using a 90° bend before it rises through the eggs, otherwise an uneven flow will be produced and the eggs may be disturbed. Although a water flow of $8\,l\,min^{-1}$ is recommended, in practice the flow should be set by turning it up until the eggs start to move and then turning it down enough to let them settle. This is then the maximum flow which can be used and should not be altered throughout incubation. For this type of incubator it is important that egg quality is high with few mortalities and that the water supply is well filtered to prevent any solids becoming trapped under the egg mesh. Eggs can easily be removed from the silo using a siphon. A smaller version of the hatching silo can be used when batches of eggs need to be kept separate for health testing purposes. Five-litre buckets with a capacity of four litres of eggs can be set up, each with its own water supply. With this system, if a broodfish comes up positive, only a small number of eggs need to be destroyed.

2.3.1.2 Trough and basket

In the trough and basket (Californian principle) system, egg baskets are set up in a GRP trough so that water flows up through each basket of eggs in sequence before leaving the trough. Each basket comprises a small mesh floor, an alevin grid or equivalent form of substrate and an egg tray (Figure 2.8). Troughs are generally from 2–4 m in length. When inserting the baskets, it is important that the front fits tightly into the trough to force all the water up through the eggs, otherwise water will by-pass the eggs and be wasted. This flow pattern can be checked using a dilute solution of malachite green as a tracer dye. To reduce the risk of air bubbles forming under the baskets, the inlet pipe should be positioned under the water surface to avoid splashing. With tight-fitting baskets a flow of $12\,l\,min^{-1}$ is recommended. The stocking density of these baskets depends on the developmental stage of the egg. For incubation only, eggs can be stocked up to three layers deep, while for hatching they must be reduced to a maximum of a single layer. This relates to the alevin density once the eggs hatch. If the density is too high the alevins may suffocate one another, resulting in very high mortalities.

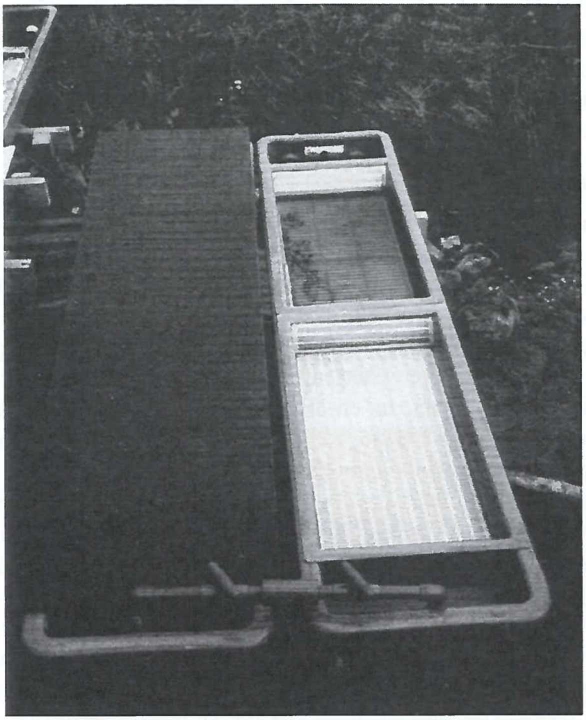

Figure 2.8. Californian-style trough and basket incubator. The near basket has an egg tray in position, while in the second basket the egg tray has been removed to show the alevin grids below.

2.3.1.3 *Trough and flow (horizontal flow)*

Although similar to the previous system, in this case the baskets are made entirely of perforated aluminium with the water passing horizontally through the eggs. Since all the water flowing down the trough does not pass through the eggs, water flows need to be higher than for the Californian system. A minimum of 15 l min^{-1} is recommended. Stocking densities need to be lower, with a maximum of two layers for incubation and less than a single layer for hatching (41 eggs m^{-2}). Alevin grids or equivalent substrate are positioned on the floor of the trough below the baskets.

2.3.1.4 *The hexhatch*

This system comprises a hexagonal frame with slotted aluminium egg grids which fits inside a two-metre diameter tank. With the tank full of water and the frame pivoting around a central stand-pipe close to the surface, water passes through the eggs before leaving the tank via the stand-pipe. Each hexhatch can incubate 100,000 eggs or hatch approximately 30,000 eggs. Once hatched, the alevins drop through the egg grids, either to the bottom of the tank or into baskets (if a silt build up is likely). Once again, alevin grids or substrate should be employed. This system has the advantage of combining egg incubation and fry rearing in the same unit but is not recommended when a water supply has a high level of suspended solids.

2.3.2 Further development

Once laid down in an incubator, the eggs develop through three distinct stages before they become feeding fry, with the duration of each stage—and hence the rate of development—being controlled entirely by temperature. Therefore development can be expressed as a function of temperature and time. This is referred to as day-degrees (or degree-days) which is the number of days after fertilisation multiplied by water temperature (°C) over a particular period (when dealing with a constant temperature). If the temperature varies, the day-degrees are recorded by tallying the temperature for each day. An egg incubated at 5°C for ten days has a developmental stage equivalent to 50 day-degrees, which is almost the same as an egg incubated at 10°C for five days. It should be noted that the day-degrees for a particular stage decreases slightly if the incubation temperature is higher, and vice versa.

During the first stage of development the eggs are referred to as green eggs. This stage commences approximately 24 hours after fertilisation and water hardening. While it is possible to handle and move eggs gently for up to 24 hours after water hardening without suffering losses, the same cannot be done during the green stage. Even the slightest movement can result in mortalities, especially in the period immediately after 70 day-degrees. For this reason, green eggs should be left completely undisturbed apart from daily inspections to check on mortalities and water flows. Dead eggs are easily recognised because they turn white (albumen precipitates as a result of the yolk membrane rupturing). If dead eggs are left in the incubator, fungus (*Saprolegnia*) will soon grow on them and, if the fungus is allowed to spread, this can result in substantial losses of healthy eggs (good eggs are suffocated and water flows are disrupted). It is possible for a full incubator of eggs to be lost if fungus is not controlled.

Two approaches can be taken to prevent fungus problems. First, if only small numbers of eggs are involved and are well spread in a basket, dead eggs can be removed daily using a rubber pipette bulb and tube. This must be done carefully to avoid touching live eggs. Clumsy egg picking will result in an increased number of dead eggs the next day. Second, when either large numbers of eggs make daily picking impractical or silos are being used, chemical treatments must be employed to control fungus. Malachite green (for which a discharge consent must be obtained), at a concentration of 2 ppm should be administered as a one-hour flowing treatment by drip feeding the chemical into the water intake. Treatments should be given as often as is judged necessary (every second day in bad cases) but should not be overdone. The green stage lasts for 245 day-degrees (at 6°C) and finishes when the black eyes can be clearly seen by the naked eye. The eggs are then referred to as eyed eggs.

Although eggs can be handled and moved before fertilisation and immediately after water hardening, it is during the eyed stage that most work is carried out on them since at this stage they are most robust and not easily damaged by movement. Unless eggs need to be handled early in the eyed stage, they should be left until midway through the stage before being removed from the incubator and sorted. They are removed either by pouring them from the basket into a bucket containing about four litres of water, or by using a siphon (a short piece of garden hose is ideal). A siphon needs to be used in silos.

Next, the eggs are stirred by hand for a few seconds. This, combined with the pouring or siphoning, will result in any infertile or poor eggs turning white, the result of the delicate yolk membrane rupturing from the movement. This process is known as addling or shocking the eggs. After addling, the eggs should be returned to the incubator for at least one hour to allow all the poor eggs to turn white before they are removed either manually or, in the case of large batches of eggs, by using an egg-sorting machine. This machine uses photocells to detect dead eggs, because light will pass through a live egg but be reflected from a white one, and can handle at least 100,000 eggs per hour. Up to 5% of good eggs may turn white during the addling process.

Once the eggs are sorted, the eyed eggs can either be laid down for hatching or be dispatched to another hatchery. In both cases they need to be counted, which can be done either with the use of an automatic counter or, more commonly, by calculating the number of eggs in one litre and then measuring out the eggs by the litre. A counting spoon or plate (a plastic plate with a known number of perforations) can be used to accurately count one litre of eggs (Figure 2.9).

Polystyrene boxes with a capacity of either 8 or 15 litres of eggs are used to transport eyed eggs. Trays in the boxes are filled with eggs (no water) and the top tray is filled with ice to keep the eggs cool and moist. Small holes in each tray allow water from melting ice to trickle down through the eggs. A compartment at the bottom of the box allows water to collect because, if eggs are allowed to sit in static water, they will suffocate. Provided the egg boxes are kept reasonably cool, a journey time of 24 hours has no adverse effect on the eggs.

Although eyed eggs are robust, all handling operations should be carried out gently, and they should be kept in water as much as possible. After 265 day-degrees at 6°C from the time the eyes are first visible, the eyed stage is completed.

2.3.3 Hatching

As the end of the eyed stage nears, all egg handling should stop and they are left undisturbed for hatching. At this stage the shells become soft and the eggs can easily be burst if handled. Hatching begins with a few premature fry appearing. These fish are of poor quality and normally die. The bulk of the eggs will hatch over a 2–3 day period, leaving a few late eggs which are also of poor quality and should be discarded. The higher the temperature, the shorter the hatching period and vice versa. Once hatched, the small fry, known as alevins or yolk-sac fry, drop down through the slats of the egg tray and lie in the substrate below. At this stage empty

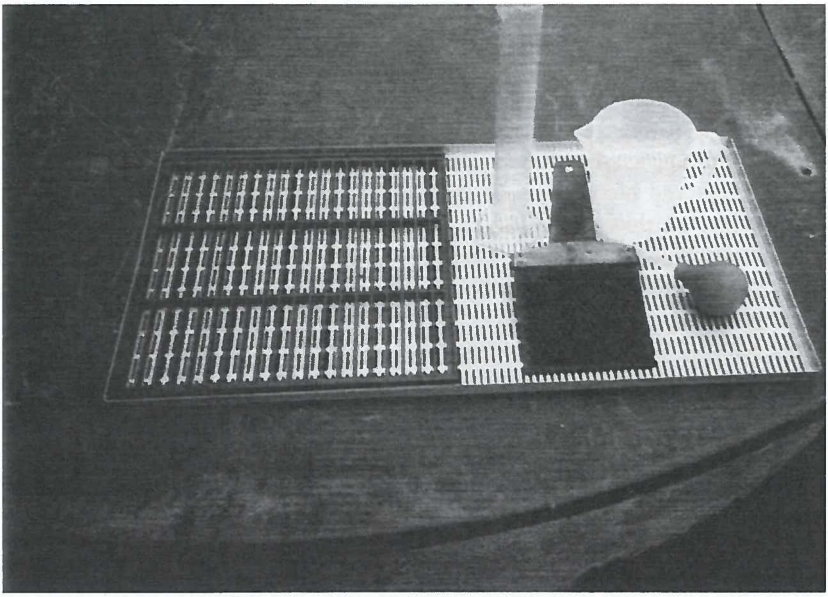

Figure 2.9. Equipment used for counting and measuring eggs. In addition to the measuring cylinder, measuring jug, counting plate and egg picker, an egg tray and alevin grid are shown.

shells will accumulate on the basket screens with the risk of blockages. Although the shells dissolve, it is advisable to brush them off the screens to avoid the risk of troughs overflowing.

A substrate for the alevins is particularly important since it prevents bunching and reduces activity. Alevins like the comfort of solid surroundings (they are surrounded by gravel in natural redds), and if there is no substrate they can only get this comfort from each other by crowding into corners. Activity levels are high, which results in the yolk-sac being wasted on activity and not going into growth. Mortality levels amongst alevins can also be high, especially at elevated temperatures. Examples of substrates are:

- plastic grids;
- rubber spikes on mats;
- modified astro turf which has every second row of fronds cut out; and
- gravel.

Other conditions for rearing alevins are the same as for incubating eggs, including the absence of light, although it is advisable to increase the water flow gradually as the alevins grow. Dead alevins, which turn white, should be removed daily to prevent the risk of fungus. After 290 day-degrees (at 6°C), the yolk is almost completely absorbed and the fry are ready for feeding. This makes a total of 800 day-degrees from stripping to feeding.

2.3.4 First feeding

Unlike rainbow trout, which actively move up into the water column when they are ready to start feeding, young salmon do not display the equivalent swim-up behaviour. Instead they remain on the bottom within the substrate. Although they display a slight increase in activity, there is little behavioural change to help indicate when feeding should commence. Instead physical appearance has to be used as the indicator, with the decision being made when no less than 10% of the yolk-sac remains. In practice, this can be judged by putting a few alevins into a glass jar with water and viewing them from below. In this way the amount of yolk-sac can be examined easily.

The timing of first feeding is important. If the young fish are put out too early, they will bunch together (usually around the central screen) and can suffer from gill problems associated with uneaten food. If they are put out too late, they may fail to start feeding, resulting in starvation and eventual death as pin-heads.

Normally first feeding is carried out in GRP tanks. The size of the tanks varies depending on the policy of the individual hatchery. While it is easier to manage early feeding fry in small tanks (up to two metres in diameter) it is more cost effective to use larger tanks that can be used to take the stock right through to the smolt stage. In view of this, three and four metre diameter tanks are popular. These tanks are set up with small mesh central screens ('top hat' type that has a large surface area), with an inlet pipe or spray bar either above or below the surface. Initially young salmon sit on the floor of the tank so there is no advantage in having deep water, and indeed mortality removal and cleaning are accomplished more easily in shallow water. A depth of 10 cm in small tanks and 30 cm in large tanks is appropriate. Deeper water is necessary to allow adequate flushing time during cleaning in larger tanks. The stocking density of early fry relates to tank floor space and therefore is expressed as $kgs\,m^{-2}$. An initial high density of 10,000 fry m^{-2} is recommended since it encourages feeding through competition and by example.

First feeding is a critical time for young salmon because they have to learn how to feed under a new set of environmental conditions. If these conditions are not met, mortalities can be high. The important aspects of the environment necessary to encourage fast growing, healthy fry are:

- **Water quality**. It is important that the water is free of anything, such as heavy metals or suspended solids, which would have an adverse effect on the delicate gills. Damage to gills can encourage bacterial invasion followed by hyperplasia of the gill filaments and eventual death. Rapid and high mortalities can result from gill damage. Another aspect of water quality involves the maintenance of high standards of hygiene. Mortalities, uneaten food and faeces must be removed at least once every day and the internal surface of the tank and screen should be brushed regularly. Each tank should have its own mortality removal net and brush to minimise the risk of cross-contamination, especially from parasites.
- Ideally the **pH** should be between 6 and 7.

- **Water flows** are important for the removal of waste products but perhaps less important for the provision of oxygen since most modern hatcheries employ sophisticated oxygen injection systems whereby oxygen levels are monitored and maintained within set limits. However, attention has to be paid to flow patterns, which should be adjusted so that the fry spread out over the floor of the tank and are not swept backwards towards the screen.They should be able to hold their position with little effort. The water current can be adjusted by altering the angle of the intake pipe or spray bar. A flow of 20 l min^{-1} is adequate for up to 30,000 first feeding fry.
- **Water temperature**. Under natural conditions salmon fry reach the feeding stage in April or May when the temperature is starting to rise. They will come on to feed slowly at temperatures between 8°C and 10°C. However, with the desire to produce S0+ and large S1+ smolts, hatcheries accelerate development through the egg stage by raising the temperature and have fry ready for feeding as early as January when ambient temperatures can be close to freezing. Therefore the temperature has to be raised substantially for feeding and will normally be set as high as 14°C. While it is expensive to heat the water to such a degree, the benefits are great: fry come on to feed rapidly, and rise quickly to utilise the whole of the water column with few mortalities as a result of pin-heads. The temperature is maintained artificially until the ambient reaches the equivalent. At this stage the volume of water to be heated is still relatively small compared with that required for later freshwater stages.
- **Light** acts as a stimulus for growth and should be utilised fully to encourage maximum growth rates in early fry. When fry are put out for feeding they are normally given 24 hour lighting at a level of 1,000 lux (normal daylight but not as bright as sunlight). This can be achieved using strip lights close to the water surface. When positioning the lights, care must be taken not to create any shaded areas that would attract the fry. Even distribution throughout the tank is important.

Since successful smolt production depends on fry getting off to a good start, great attention has to be paid to starter diets and feeding regimes. While modern diets are formulated to give rapid growth, the mechanics of feeding must be correct to reap the benefits. Small quantities of food should be delivered continually (or at least every five minutes) for the full 24 hours of light as soon as the fry are put out. This spreads feeding activity out and prevents fish becoming hungry. Initially feeding response is poor with most of the food finishing on the floor of the tank but, after a few days, fry can be seen feeding actively. At this early stage fry only take particles of food that come to them as they sit on the tank floor, so it is important that a slight current is created to carry the food slowly round the tank.

Gradually, as the number of feeding fry increases, they swim up into the water column and actively pursue their food. As this happens the water depth should be increased gradually. Feeding is carried out using automatic feeders, an example of which is a clockwork feeder (Figure 2.10). The feeder should be positioned as close to the water surface as possible (without the risk of wetting the food) and in front of the

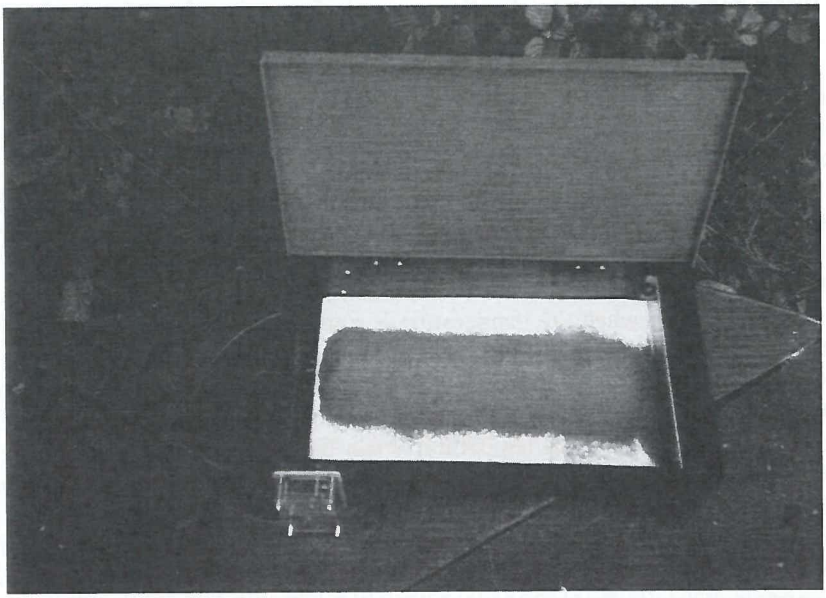

Figure 2.10. Clockwork feeders require no external power source. The clockwork motor is wound up by pulling the belt back. As the belt slowly recoils (up to 24 hours), food is continuously tipped off into the tank.

spray bar if in use. This is to ensure that the food sinks slowly and is carried round the tank, giving all the fry an opportunity to feed.

Although feeding tables can provide a useful guide for feeding rates, at this early stage they are of limited use since it is impossible to calculate the biomass of feeding fish until they are all feeding. In practice, feeding rates are determined in relation to the amount of uneaten food accumulating on the floor of the tank each day. The feeding rate is correct if a small amount is left each day. Too much may lead to hygiene problems and too little may result in some fry starving.

2.3.5 Fry and parr

Once established on feed, the young salmon are known as fry. With favourable conditions, from a starting weight of approximately 0.2 g, growth is rapid. The tank water is increased to full depth, which automatically increases the water volume and therefore reduces the stocking density (expressed as total biomass of fish in $kgs\,m^{-3}$).

Water flows are established to give a good flushing effect and create a current that allows the fish to hold position without having to work too hard. This is best judged by spending some time observing fish behaviour. Oxygen levels are maintained (minimum level of $7\,mg\,l^{-1}$ at the outlet), either by adjusting the throughput of water or by adding oxygen, and 24-hour lighting is provided to maximise growth.

Feeding should be continuous by automatic feeder, with feeding rate being determined partly from feeding tables and by observation of waste food. In large tanks it is advisable to use at least two feeders to give a better distribution of food and ensure that all fish get an opportunity to feed. Visual observations of feeding behaviour should be made at regular intervals throughout the day so that any necessary adjustments can be made.

Hygiene must be maintained by daily removal of mortalities, flushing to remove waste products and regular cleaning of screens and tank surfaces. Health checks should be carried out regularly, particularly for the presence of ectoparasites such as *Costia*, with particular attention being paid to the gills. Early diagnosis and early treatment will greatly reduce the likelihood of losses.

In all fish populations fish grow at different rates; therefore, relatively soon after first feeding, a variation in fry sizes becomes apparent. If nothing is done the dominant fish will get larger at the expense of the smaller fish. This situation is rectified by regular grading which can begin when the fry are 1–2 g in size. Grading is achieved by placing the fish on grids where the bars have a particular spacing enabling small fish to fall through while large fish are retained on top. Graders may be simple boxes with interchangeable grids to automatic grading machines which can grade three to four sizes at the same time. Some large hatcheries have grading stations to which fish are piped from their holding tanks, passed through the automatic grader, batch weighed and then the different grades are pumped back to particular tanks. Grading should be carried out as often as is practicable to keep each population as uniform as possible. This results in a better overall growth rate, reduces fin damage, eliminates cannibalism, enables better feed management and has the combined effect of increasing the overall percentage of smolts. However, grading should be avoided at times of high temperature since handling may cause the fish undue stress and any skin damage may lead to fungal infections. The final grade will normally be carried out when the pre-smolts are vaccinated. At this time any fish which have not made the required size limit can be rejected. These fish are of little value and are normally destroyed using a strong anaesthetic. As fry grow quickly, the biomass in a tank will also increase quickly and has to be carefully monitored to prevent stocking density becoming too high. This is achieved by sample weighing batches of fish every week. Sample weights also enable feeding rates to be calculated and give an indication of when it is appropriate to move to a larger food size.

The changeover to a larger feed should be done over the period of a week so that the smaller fish in the population are still catered for. In terms of stocking density, the traditional maximum figure for parr and smolts was considered to be 30 kgs m^{-3}; however, in modern hatcheries where environmental conditions can be controlled totally, this figure tends to be much higher to optimise the use of the facilities. A common figure is 60 kgs m^{-3} and in some cases the density may well be over 100 kgs m^{-3}. It must be considered, however, that although fish will survive and can grow well at these high densities (providing they can be adequately fed), fin condition is likely to suffer and disease outbreaks can have catastrophic effects. The decision on density may come down to customer requirements in terms of smolt quality.

There is a choice of holding facilities for fry and parr. At approximately 2 g in size, the fry can be transferred from tanks to freshwater pens. Transfer will normally be in May in Scotland and northern parts of Europe and is often accomplished using helicopters, which enables otherwise inaccessible lochs to be utilised. Loch culture of smolts has its advantages, including high water volumes and good growing temperatures, especially in the winter. It is not unusual for cage-cultured smolts to be well over 100 g at transfer time. Fry can be reared through to smolts in large tanks (3–7 m diameter). For S0+ production, fry are reared on 24-hour light until they reach a length of 8 cm in the summer, at which time they are given an artificial winter of short days to trigger smolting in the autumn. For S1+ production, fry and parr are reared on 24-hour light until the end of September, after which time they are given natural light for the remainder of the freshwater cycle. These fish will smolt in the spring.

2.4 HATCHERY PERSONNEL

All the work associated with broodstock management and the rearing of young salmon requires a high level of both practical skills and knowledge. Each is of limited value without the other. As with the care of any livestock it must not be considered as merely a job. Staff must be reliable, conscientious and show a high level of dedication towards the fish in their care. They must understand the consequences of any deviation from normal and the importance of accurate record keeping. Any losses should be regarded as a personal loss and not simply a loss to the company. As hatchery systems are becoming ever more complex it is important that every staff member not only has all the husbandry skills but also the technical ability to manage all the equipment. In the case of emergencies everyone must know how to respond to avert potential disasters.

Staff training programmes should be in place to fill in any gaps, either in skills or in knowledge. These programmes can take advantage of existing courses or training can be provided in the workplace and should be on-going. Courses can deliver both the practical skills and the underpinning knowledge needed to carry out these skills successfully. No one in salmon farming is likely to reach a stage when some form of training would not be an advantage. A well-trained, efficient staff is essential for the production of high-quality young salmon.

3

Production II: From egg to market size: onrearing in freshwater and marine environments

3.1 INTRODUCTION

The production of salmon in intensive aquaculture requires, at its most basic, that the conditions ensuring completion of the species' life cycle are created in the farming environment. Thus, salmon farming consists of both a freshwater and a marine phase.

In salmon farming, fertilised eggs obtained from broodstock must be incubated in a hatchery phase (as fertilised wild eggs occur in gravel redds), then the hatched young must be reared through the fry/parr stages (as juveniles are found in lotic habitats) and they must grow and complete smoltification all in the freshwater environment. Similarly, following successful transfer of smolts to the marine environment (as they naturally migrate to sea), they must be onreared to market size and harvested as marine produce for the markets.

Over the decades of active cultivation of the species, the collective knowledge derived from both research and the practical experience of the farmers themselves have ensured that the basic processes can be enhanced, thereby developing a more efficient and effective system for delivering quality assured premium produce to the consumer. In the wild, the time from fertilised egg to smolt can take from 18 months (Southern European salmon rivers) up to several years (Arctic conditions), while in the farmed situation this can be reduced to between 9–15 months. Likewise, wild salmon may spend one or more winters at sea, returning as grilse or multi-sea winter salmon, respectively, while in the farmed situation they can be reared until the desired market size.

Through these various phases, the objective of the farmer is to optimise the process and maximise use of resources and, given the wide geographic area of salmon culture, this has resulted in local adaptations to the basic rearing scheme. These adaptations, therefore, require specific arrays of equipment, materials and skills to complete the life cycle.

Moreover, it is logical that all phases of the culture cycle interact with each other, in sequence, and the overall quality at any point is dependent on the implementation of appropriate control and assurance protocols in each successive phase. The failure or poor performance at any individual step adversely affects the continuity to successive steps and negates the benefits of all previous elements.

Reflecting the natural cycle, the contents of this chapter are divided into a series of major sections:

- hatchery phase (egg to fry): Section 3.2;
- freshwater onrearing: parr to smoltification: Section 3.3;
- marine onrearing (smolt to market size): Section 3.4; and
- the final intervention, harvesting: Section 3.5.

The basic processes are described in the following sections and thereafter any manipulations/enhancements are discussed. As innovations in production techniques are constantly being explored and implemented, it is important to view these within the context of the potential tolerances and fundamental limitations of the natural cycle.

3.2 HATCHERY PHASE

3.2.1 Overview

Fertilised eggs may be considered as the start point of this phase of the rearing cycle: the production of eggs from broodstock is dealt with in Chapter 2 since it may be regarded as a more specialised portion of the overall production cycle.

The basic stages in the hatchery phase include the eggs being incubated from fertilisation and their development, the hatching of eggs to give the alevin stage when first feeding occurs and, finally, the transfer of fry from the hatchery to the freshwater ongrowing units. The objective of this portion of the cycle is to maximise the yield of quality fry for onrearing to smolts with a survival rate of more than 90% being the norm in today's production units.

In many ways, the hatchery phase, while short lived, is probably the most technically demanding and a high degree of organisation and planning is required to achieve such maximal performance levels.

3.2.2 Fertilised eggs and initial incubation

Until they reach the eyed-egg stage, fertilised eggs during the incubation phase are extremely sensitive and should be handled with special care at all times. Every effort should be made to ensure that they are not over-exposed to air or mechanically damaged, or subjected to varying/extreme environmental conditions during this initial developmental phase. Even when it is possible, or if it proves necessary, to manipulate eggs, they should still be handled gently under water. There are, however, periods when the eggs can tolerate a certain degree of handling. This is true of the period immediately post-fertilisation and again once they have reached the eyed-egg stage, i.e., when the major organs have been formed and the primordial eye has developed. The greatest sensitivity to any form of shock is directly linked to those periods of rapid cellular differentiation and organogenesis in the developing embryo. The most sensitive stage of early development in salmon, at optimal temperatures, would appear to be days 3 to 14 (approximately 20–120°C days).

The sensitivity of eggs increases dramatically post-fertilisation but there is a short window (from 6 up to 36 hours) for movement/manipulation of the ova. During this interval, the newly-fertilised eggs, often referred to as 'green' eggs, must be transferred to the incubation facility, disinfected immediately on arrival and all packaging materials destroyed. At the 2-cell stage, approximately 100 hour-degrees after fertilisation, the eggs can be checked to determine the levels of fertilisation success. Because of the particular requirements of eggs at this early stage, the incubation facility is normally a dedicated space and a high quarantine area. It is recommended that an accurate assessment is made of the total volumes and numbers of eggs (sub-sample estimates) that are being incubated. There are several standard egg counting methods, using sub-samples, based on, for example, volume displacement, mean 'dry' weights and egg diameter measurements (as described in Chapter 2): though automated egg counters are also available they can only be used with later stages (post eye-up). As a rule of thumb, it can be taken that there are roughly 5000 ova per litre.

The success rate can also be assessed between 6 and 20 days after fertilisation. A sample (n) of eggs (minimum, $n = 100$) is treated with a clearing agent (e.g., acetic acid) and they are examined under a microscope to confirm the numbers (and percentage) that show development: a viable, developing, embryo is visible as a white streak. Ideally, batches with very low fertilisation rates should be discarded as there is some evidence that ongoing problems may occur through the cycle with such batches. If such batches are retained it is good farming practice to check their subsequent performance through the entire production cycle to see if they incur higher-than-normal mortality rates or display poorer growth.

In most broodstock/egg production systems, the parental animals are culled and/or tested for transmissible diseases following egg stripping. Consequently, the fertilised eggs will be in the hatchery for some days before the findings of laboratory tests are available. If disease conditions are detected in the broodstock, it is preferable and often required by law that the eggs are destroyed (Table 3.1).

Salmon eggs are placed in special incubation units and normally allowed to develop without disturbance until the eyed-egg stage (250–300°C/days). There are only a limited number of incubation equipment designs, including stacked troughs/trays, upwelling columns/baskets and moist incubation systems (as noted in Chapter 2). As the eggs are surviving on their internal reserves there is no requirement for food during this period. The primary objectives of the farmer in the incubation unit are to maintain the eggs in a clean, aerated water flow, in darkness and with a stable temperature regime, thereby providing optimal growing conditions. Eggs are very susceptible to damage from UV light in sunlight and from fluorescent (blue) tubes. Ideally, there should be minimal agitation or handling of the eggs to avoid mechanical damage.

Table 3.1. Listing of some common notifiable diseases*

• Infectious pancreatic necrosis (IPN)
• Infectious hematopoietic necrosis (IHN)
• Viral haemorrhagic septicaemia (VHS)
• Enteric red mouth disease (ERM)
• Gyrodactylosis (*Gyrodactylus salaris*)
• Myxobolosis (Myxosomiasis)

* Specific national legislations may require notification of different disease conditions.

The quality and flow of water is crucial to optimal development and overall survival. Sufficient oxygen must be supplied and metabolic wastes must be removed. In general, the oxygen (O_2) saturation of the inflow water should be at or above 100% while the O_2 content of effluent water should not fall below a critical level of c.7 mg l^{-1} or 80% saturation, whichever occurs first. Particular care should be taken in adjusting flow rates and patterns to ensure that there are no 'dead spots' of low oxygen, which could lead to localised mortalities. Trays can be carefully tilted at a slight angle to allow air pockets—often the source of reduced water flow—to escape. The levels of suspended solids (especially finer particulate matter) in the rearing water have a dual impact on developing eggs as this material can prevent trans-membrane oxygen uptake and eventually may suffocate the egg; in addition, a high organic load implies a higher biological oxygen demand (BOD) requirement and greater oxygen utilisation within the rearing unit. In units where particulate matter occurs in the water, a very effective flushing regime must be implemented daily to ensure that any settled deposits are removed. The flow rates of water should be fixed at the desired level and checked regularly. Standard trough/tray systems require roughly 12 l min^{-1} per four tray/trough unit of about 20,000 eggs (approximately 0.5 l/min/5000 [1 litre] eggs). An excessive water flow through the unit causes increased mechanical agitation and resultant mortalities.

The temperature of the water is extremely important and should be kept within a specific range generally 8–10°C for salmon: development rate is temperature dependent and the progression of the egg development is expressed as degree-days (°C /days). Degree-days are calculated as the sum of the average (maximum and minimum) daily temperatures. Outside of the optimal range, development is slowed at lower temperatures down to 4°C and below this development may cease. At higher temperatures, there is some evidence that deformities may result while values greater than 16°C can cause direct mortalities.

Clearly, within and around the optimal range development will be delayed at the lower and enhanced at the upper end. For example, the time taken to reach the eyed egg (250–300°C days) and hatching (475–500°C days) stages at 7°C is 43 and 68 days, respectively, but this is reduced to 30 and 47 days at 10°C. Another important factor is the variability of the temperature regime as a stable regime ensures synchronisation of hatching. If there are temporal (daily or weekly) variations in temperature then there will be differential development among the individual eggs and development will be variable over the egg batch. Thus, there will be greater predictability and maybe greater efficiency and use of resources by having a relatively stable temperature environment.

Accelerated egg development and early hatching also produces alevins/fry very early in the season, thereby allowing greater time for growth and larger sized smolts in the freshwater phase (this is considered in greater detail below).

Ambient freshwater sources (riverine and lake sources) generally tend to have variable conditions in the spring during egg incubation periods, with significant fluctuations in temperature. Rapid and large fluctuations in water temperatures are not tolerated by eggs and this may result in mortality or oedema (water absorption into the yolk sac leading to distended sac) of the developing embryo. To provide stable water quality conditions, it is common to provide heated, treated, filtered water to these units: of a specific temperature, free from particulate matter and with sufficient oxygen. Very often, stable cold (>5 and <10°C) groundwater sources are used as the supply for the hatchery phase. If using such spring sources, it is also necessary to ensure that there are no heavy metal contaminants (e.g., iron and zinc) or elevated gas pressures, particularly nitrogen and carbon dioxide. If there is gas supersaturation in the rearing medium, the excess gasses may be absorbed by the egg, giving rise to gas bubble disease, characterised by the occurrence of gas emboli in various tissues. Ideally, all hatchery units, but especially those using groundwater, should have a de-gassing system in place to ensure there is gas equilibration with atmospheric levels.

Healthy eggs maintain their orange-red colour, but once they are infected or die the proteins turn an opaque whitish colour and can be readily identified. The most commonly encountered disease condition is the fungus *Saprolegnia*, which can progress rapidly if left unchecked. The incubation units must be monitored on a regular basis and any infected or dead eggs removed by hand (tweezers or suction pipettes). A helpful husbandry practice is to use hand lights (in red/yellow colour range), on low-voltage supply, when monitoring and picking eggs during this phase. In addition, it is usual to treat the eggs, via the flow through supply water or by dip, on a regular basis with a suitable fungicide to protect against such potential disease problems. Any damaged, infected or sub-standard eggs should be immediately removed. Removing dead eggs may, however, become a self-defeating process as damage to healthy eggs may induce further mortality, in particular during sensitive periods of development. Care must be taken to avoid disturbing healthy eggs, and it may be better to limit removing dead eggs during the more sensitive developmental periods. It is not possible to remove dead eggs from cylinder-type incubators.

The secret of success in this first phase of the cycle would appear to be the provision of a stable aquatic rearing medium with careful ongoing monitoring rather than relying on ambient conditions with dramatic intervention. At a minimum, the farmer should pick eggs and flush trays as well as checking egg status, water flow, oxygen concentrations, and temperatures on two occasions (morning and afternoon) per day. The optimal conditions and water quality requirements for successful egg rearing are listed in Tables 3.2 and 3.3.

Table 3.2. Summary of key rearing conditions for salmon egg incubation.

Rearing conditions	Considerations for development
Steady flow of clean, aerated, water	Laminar flow giving low agitation; avoids mechanical damage and provides high O_2 levels needed for development.
Temperature in the range (6–10°C).	Optimum for development with lower (4°C) and upper (16°C) lethal limits.
Negligible particulate matter/chemicals	Egg test is particularly sensitive and particulate matter clogs membrane.
Ova held in darkness.	UV light hinders development and kills eggs.
Stability of environmental conditions	Temporal variations (daily/long term) disrupt development and offset synchronisation.
Routine checks and regular treatments	Minimise agitation/handling/movement and prophylaxis.

Table 3.3. Summary of water quality requirements for salmon ova.

Water quality parameters	Recommended levels
Oxygen	100% saturation (minimum $6\,mg\,l^{-1}$)
pH	6.5–8.5
Ammonia	<0.005 ppm (unionised)
Iron	<0.3 ppm
Suspended solids	$<3\,mg\,l^{-1}$

Table 3.4. Treatment systems that affect critical physico-chemical parameters.

System	Function
Physical filtration (mesh to 10 μm)	Removes particulate matter/debris.
UV sterilisation	Kills bacteria/pathogens.
Gas tower	Strips excess gasses (nitrogen/carbon dioxide).
O_2 injection	Raises oxygen to desired levels.
Heating/heat recovery systems	Maintains the temperature in the optimal range.
pH regulation/dosing	Maintains in the range 6.5 to 8.5.

In choosing the location for siting a hatchery unit, the water quantity and quality should be checked through all seasons of the year. To stabilise and improve the quality of water to the hatchery, it is possible to install a number of treatment systems that affect critical physico-chemical parameters (Table 3.4).

If these systems are to be used then it is essential that an integrated monitoring/control unit is present with appropriate standby units, backup supports (e.g., generators) and linked (internal and external) alarm systems.

The benefits and drawbacks of using the two major different incubator types (trays versus upwelling basket vessels) are debatable. It is often a matter of management choice or may be dictated, to a certain extent, by site/plant characteristics. The tray type has a large surface area and requires a large floor working area, though there is ease of access to all eggs at all times since they are only one or, at most, two layers deep. More importantly, the eggs can be kept in these systems through to the first feeding stage. With the upright cylinder types, greater numbers of eggs (e.g., 20 l vessel or 5 × 4 l baskets) can be held in a smaller floor area but if there is a problem, either technical or biological, then the entire batch is likely to be affected. However, these upright containers are large enough to contain the eggs from a single female fertilisation and an entire batch can be held separately from others while disease screening of the parents takes place post-fertilisation. If the parents are found to be infected then that specific batch of eggs can be identified and culled. On the other hand, with these 'vertical' units the ova must be moved to troughs/trays at the eyed-egg stage to allow hatching to progress.

The end of this first phase is reached when the eggs show signs of the early developing eyes (as dark spots) on the egg surface. At this point, to separate fertilised developing eggs from unfertilised but living eggs, it is normal for the eggs to be subjected to a 'shock' treatment prior to transfer. Eyed eggs are very robust at this stage, hence traditional shocks include pouring them into a container of water from a height of 30 to 70 cm and then stirring vigorously, or removing the trays and striking them heavily on a solid surface and then keeping them in air for a few minutes. This process is a very effective quality-control procedure as it ensures that weak and unfertilised eggs are ruptured/killed and can be easily removed while only viable healthy eggs are passed on to the next stage. Egg shocking should be undertaken some days before scheduled transfer to allow all resultant mortalities to be detected and removed by hand or machine. Egg-sorting machines are available that separate on the basis of light transmission: transparent (live) versus opaque (dead) eggs.

In practice, it is normal for the broodstock hatchery/egg producers to keep eggs until the eyed-egg stage and then move them to the destination freshwater farms. Full quarantine procedures with disinfection should be exercised on transfer of ova from one site to another and, as before, the numbers should be verified by determining total volumes and sub-sample egg counts.

A useful rule of thumb in predicting development stages is 250 (to eyed-egg stage) + 250 (to hatching) + 250 (to first feeding)°C days (Figure 3.1).

3.2.3 Hatching to first feeding

Having reached the eyed stage, the developing eggs are normally held in (or transferred to) tray/trough type systems and should continue to be kept in darkness. Ongoing maintenance should include regular picking to remove dead or infected eggs and appropriate treatments against infections. As before, environmental monitoring should include checking water flow, oxygen concentrations and temperatures

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Alevin                                                        ------------------| fry
Eyed eggs                          -------------| hatched alevin
Green eggs                 -------------| eye up
°C days 0          100      200      300      400      500      600      700      800
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Figure 3.1. Summary of developmental stages and °C days.

twice daily (morning and afternoon). Development will continue for a further period until the eggs begin to hatch at c. 475–500°C days.

At hatching, the egg test cracks to release the yolk sac fry, or alevin, which are characterised by a fish-like body but with the yolk sac protruding underneath. Hatching enzymes cause a weakening of the egg case and the flexing movements of the alevins themselves allow splitting of the egg case and their final release. At this time, special care should be taken to ensure that the waste egg cases do not occlude the outflows of the trays and that they are not allowed to accumulate and function as a focus of infection. The released alevins will make their way down through the base mats/grills of the hatching trays and, usually when the majority of eggs have hatched, these mats/grills can be removed. There is a tendency for the alevins to aggregate in groups on the tray bottoms and it is common to have artificial substrates which can be added to the trays at this time to prevent overcrowding. These artificial substrates (e.g., matting, astro-turf) support the developing fry and limit activity. Over the coming days and weeks, the yolk sac continues to be used as the endogenous food resource. The alevin stage lasts for approximately 250°C days.

Again, temperature has a significant influence on hatching and yolk sac absorption rates and the optimum for first feeding would appear to be c. 10–12°C. At higher temperatures, the entire batch may hatch over 3–5 days and the yolk sac phase will be accelerated although the emerging alevins may be smaller. At lower temperatures, hatching is slowed and can take in excess of a week but, in these conditions, yolk sac absorption is extended and the fry tend to be larger and more fully developed. In general, greater synchronisation of hatching, more complete yolk sac absorption and better first feeding is promoted by stable optimal temperature regimes. In terms of cost-benefit analysis for the farmer, however, it may be better to accelerate development, within limits, at this early developmental stage as biomass and water consumption are low, hence energy use is low.

Higher oxygen levels are required during the hatching phase and the hatched alevins can be held at higher flow rates than eggs; however, the flow rate of the trays should be checked regularly. Indicative flow rates for alevins in standard trays are in the range 15–20 l $\min^{-1}$, i.e. 25–50% greater than the rates for ova incubation. Again, a useful rule of thumb is 1 l/min per 5000 alevins, i.e., initially approximately 1 litre of eggs. Unnecessarily high flow rates have a particularly adverse effect on these yolk sac alevins since they are more active and have to expend energy on maintaining position in the tray matter rather than on development. These conditions will result in smaller fry and may also give rise to deformed yolk sacs or even mortalities. Similar problems are encountered if a substrate is not used, forcing the alevins to swim or else they fall over sideways. Again, as a matter of good farm practice, any malformed alevins or those with coagulated yolk sacs should be routinely removed when found.

Careful attention should be paid to alevins during development to ensure that some common problems are not encouraged, namely, yolk sac damage due to excessive swimming/activity, blue (yolk) sac due to presence of elevated ammonia levels and gas bubble disease from gas supersaturation.

Over time, and as the yolk sac reserves are used up, the alevins become more active and a few may begin to swim to the surface in search of food. At this point, it is common to begin adding small quantities of a selected dry diet to the trays. Alternatively, the fry can be transferred to the first feeding unit even if some (30%) of yolk remains. Failure to commence early feeding gives rise to a stunted alevin/fry with a markedly larger head, referred to colloquially as 'pin head' condition. Once transferred to standard rearing tanks (e.g., 2–4 m side and 20–30 cm working water depth) the fry can be weaned fully on to dry diets. These fry, averaging <0.25 g, are well developed and physically robust in comparison to most marine fish. A useful rule of thumb is to stock approximately 10,000 fry per m^2 of tank floor. Thus, a 2 m square tank could easily hold 40,000 fry (of 0.25 g) at an initial stocking density of 2.5 $kg\,m^{-2}$ floor space. Substrates (mats or even stones) may be added to these tanks on initial transfer as they allow the smaller/weaker fry to find refuge from currents. However, these substrates must be monitored carefully to avoid build up of organic matter and potential pathogens. As the fry grow, they will naturally stay in the water column and orientate themselves in the currents, making these substrates redundant.

Water flows are dictated by the size and state of development of the fry but indicative rates are 20–25 $l\,min^{-1}$ for 2 m tanks. A practical guideline is to gradually increase flow rates to 1 l/min per 1000 fry. It is vitally important that the fry are not subjected to excessively strong currents across the effluent pipe mesh/grid, so it is recommended that a large sieve area with round openings is used.

During the first feeding to weaning phases, food should be administered as small quantities virtually continually during daylight hours. Research has shown a positive effect of constant light during first feeding, which stimulates growth and development in its own right and also allows continuous feeding. This is recommended and standard practice in most commercial units. In most hatcheries, automated feeders are used to provide this constant supply of food particles to the fry; however, as the alevin gain in size, their feed requirements and feeding behaviour should be checked by giving intermittent, supplementary hand feedings.

Finally, during this first feeding period, particular attention should be paid to the health status of the fry in relation to levels of wastes and tank cleaning. Since surplus feed is being continually added to the tanks, it is probable that there will be a high organic load both in the water and as sediments on the tank floor, resulting in poorer water-quality conditions or directly giving rise to gill clogging and opportunistic infections. Consequently, tanks should be regularly flushed and any mortalities removed. As ever, mortalities and moribund fish should be carefully checked to ensure there is no ongoing problem and appropriate treatments should be considered if the situation merits. The highest mortalities of the freshwater phase are found during this first feeding stage.

3.3 FRESHWATER ONREARING: PARR TO SMOLTIFICATION

The fry are now entering the major freshwater growth phase. As they continue to eat and gain weight, at roughly 1–2 g they develop the typical 'banded' markings ('parr marks') on their sides and are referred to thereafter as parr.

3.3.1 Rearing units

In this portion of the cycle, as the parr grow they can be held in increasingly larger rearing units, either tanks on land or cages in freshwater lakes. Tanks are more commonly utilised and these are normally constructed of glass reinforced plastic (GRP; fibreglass), although concrete, galvanised steel and plastic units can be employed. The tank units are either circular, hexagonal or square with round corners, and sizes vary from 1–12 m in diameter/side and corresponding depths of c.0.5–3.0 m. The floor of the tank will have a slight gradient that facilitates movement of particulate wastes to the centre. Water enters the tank at the surface, at a single point, and this is angled to give a circular flow through the tank, conferring a self-cleaning effect which carries wastes to a central drain point provided with a screen mesh. In most cases, there is a single inflow pipe but two (at diametrically opposing positions) may be preferred with larger tanks. In addition, farmers sometimes make use of a sparge bar on the inflow which is intended to encourage more uniform flows and provide additional aeration to the water. The screen mesh is normally removable, allowing the pore size to be increased (e.g., 2–10 mm) depending on the tank volume and size of fish, with the dual objectives of ensuring rapid discharge of water while retaining the fish. The water level in a tank is governed by an external level control pipe which allows the internal operating level to be raised/lowered as this external pipe is moved.

In any rearing unit, there should be an array of different sized tanks to cater for the numbers and sizes of fish progressing through the facility during the year. For example, there should be a limited number of small tanks (1–2 m diameter/side) to cater for fry as they are released from the hatchery; there should be a corresponding number of medium sized tanks (2–4 m diameter/side) for ongrowing parr and, lastly, there should be a majority of large tanks to accommodate the fish up to smoltification. Optimal use of the tanks is promoted by efficient feeding and routine grading, thereby ensuring that larger, growing fish are moved on in turn to the next largest tanks when they reach a particular size. The combination of types and sizes of tanks in use is essentially a matter of practical management choice but there are some basic rules which cannot be ignored. First, larger tanks require larger flow-through rates to maintain oxygen levels and to promote self cleaning, so smaller fish will not be able to cope with the higher currents in such tanks. Conversely, larger fish perform better in larger tanks where there is sufficient rearing space. From a practical and operational standpoint, under a traditional production regime for spring smolts (see below), it is clear that the larger tanks will not be in use at the start of the season with small parr while smaller tanks will be redundant at the end of the freshwater cycle when smolts predominate. Thus, a careful balance must be achieved in the installation of different sized tanks on a farm to ensure that operational needs are served such that the levels of capital investment are not excessive.

3.3.2 Water flows

The overall water flow requirements of the farm are dictated by the biomass and size range of the stocks on site at any particular time in the production cycle. Typically, the largest volumes will be required in the period leading up to and during smolt movement. Tank size is an important determinant of flow rate since higher biomass and stocking densities also imply higher oxygen requirements and, therefore, require greater water flows. Indicative flow requirements are c. $1\,\mathrm{l\,sec^{-1}}$ in 4 m diameter tanks and $3\text{–}4\,\mathrm{l\,sec^{-1}}$ in 7 m diameter tanks. In terms of stock performance, there is evidence to suggest that there is an optimal water current speed related to body length of fish. At current speeds of 1–2 body lengths per second, the parr appear to show better growth and lower food conversion. In this matter, a certain degree of caution needs to be exercised in relation to larger fish in large tanks where higher speeds can create centrifugal forces that result in physical abrasion of the fish.

3.3.3 Stocking densities

In relation to the stocking of parr in tanks, the densities can be raised as the fish size increases up to a maximum for the largest fish (smolts). Thus, for the different sizes, it is common to hold fish of up to 5 g at densities $<5\,\mathrm{kg\,m^{-3}}$, 5 to 15 g fish at $<10\,\mathrm{kg\,m^{-3}}$, 15 to 35 g fish at $<20\,\mathrm{kg\,m^{-3}}$, and thereafter stocking levels should not exceed $30\,\mathrm{kg\,m^{-3}}$. Experimental data suggest the fish will tolerate much higher densities than these; however, the safety/security margins in case of a water failure become progressively shorter. Furthermore, distributing feed to high numbers of fish in a heavily stocked tank is difficult. Hence, the above figures are conservative suggestions for stocking densities based on practical experience. In freshwater cage systems, these values tend to be significantly lower, often depending on the site topography, but an upper limit of $15\,\mathrm{kg\,m^{-3}}$ is common. In reality, the maximal limit used is that normally stipulated by insurance companies for standard tanks without supplementary oxygenation/aeration. In rearing systems with supplementary oxygen supplies to the tanks, it is possible to increase densities to much higher levels, and values approaching $60\,\mathrm{kg/m^{-3}}$ for larger fish are common in some recirculation units.

It must be remembered also that very low stocking densities tend to promote and increase social interactions, as territories become large enough to be 'worth defending'. Thus, one must choose an optimal stocking level that achieves a balance between the social and the physical environment.

Within the particular production schedule, the farmer should always aim to optimise stocking levels in an effort to promote efficient feeding and growth and lessen the likelihood of negative social interactions and infections. Excessively high stocking densities can easily lead to deterioration of water quality, decreased feeding efficiency, depressed growth and increased stress and may also result in aggressive behaviour causing physical damage to fins, eyes and opercula in stocks. In reality, however, the maintenance of lowered stocking levels needs to be offset against the need for separation of different cohorts/size groups within the limitations of farm disposition (sizes and numbers of tanks).

3.3.4 Feeding regimes

The fish are normally fed a formulated dry diet and it is critical to ensure that there are sufficient feed particles present in the water to satisfy the demands of the growing parr. Equally important aspects of correct feeding are the need to provide feed of an appropriate particle size and that the feed is, indeed, available to all the fish in the tank.

As the parr increase in size, their mouths grow and, consequently, the size (diameter) of particle that can be consumed increases with time. In freshwater, it is common to use a succession of different sized pellets, e.g., 0.25, 0.4, 1.0, 2.0, 3.0 and 4.0 mm diameter. At all times, one needs to ensure that fish are receiving the optimal pellet size: fish cannot physically swallow a pellet that is too large while at the other end of the scale, searching for many small pellets is inefficient energetically. Thus, it is crucial that fish size is monitored and pellet size changed appropriately to ensure continued optimal growth is achieved. Table 3.5 shows examples of recommended pellet sizes for different fish sizes. As a practical husbandry technique, it is strongly recommended that mixtures of two feeds are used to bring fish through any transition period from one pellet size to another. Informed selection of pellet sizes and mixing of different feed sizes also prevents the development of a large size range within a cohort of fish since it allows optimal feeding behaviour; the smaller particles are available for the lower size classes and the bigger for the upper size classes.

The quantity of feed to be delivered to the stocks is primarily a function of the size of the fish and the ambient temperature. The optimum temperature for onrearing of parr to smolt is taken to be the range 16–18°C although adequate but diminishing growth rates are found above and below these values. Food consumption rates of fish are normally calculated and expressed as percentage body weight consumed (% BWC) per day and in salmon two basic principles underlie the interaction between fish size and temperature. As body size (weight) increases, it is clear that the relative amount consumed (% BWC) per day at any given temperature decreases rapidly. For example, in the optimal temperature range, 5 g fish will consume c. 5% of body weight (BW) while at 50 g this will decrease to c. 2% BW. Secondly, for any given BW, with increasing temperatures the relative amounts consumed increase steadily through and beyond the optimal range, e.g., for 10 g fish, feeding rates go from c. 2% BWC at 8°C to c. 4% BWC at 16°C. Higher

Table 3.5. Feed table showing recommended pellet sizes for different sized fish reared in freshwater. (By permission of Trouw Aquaculture.)

Product name	Guidelines (g)	Pellet size (mm)	Protein (%)	Oil (%)	Ash (%)	Moisture (%)	N.F.E. (%)	D.E. (mj/kg)
Nutra Salmon Fry 00	<0.2	00 crumbs	55	14	9	8	14	18.32
Nutra Salmon Fry 01	0.2–1.1	01 crumbs	54	18	9	8	11	19.22
Nutra Salmon Fry 02	1.0–5.0	02 crumbs	51	22	8	8	11	20.06
Nutra Salmon Fry 03	4–25	03 crumbs	51	22	8	8	11	20.06
Nutra Salmon Fry 04	25–80	04 crumbs	51	22	8	8	11	20.06
Nutra Parr 1.2	2–7	1.2 pellets	51	21	10	7	11	19.63
Nutra Parr 1.5	5–20	1.5 pellets	51	21	10	7	11	19.63
Nutra Parr 1.8	15–40	1.8 pellets	51	21	8	7	13	19.87
Nutra Smolt 2.3	30–80	2.3 pellets	50	22	9	7	12	19.91
Nutra Transfer 2.3	30–80	2.3 pellets	49	22	10	7	12	19.70

temperatures, in excess of the optimal, will elicit an even greater feeding response/demand in salmon, although extreme caution has to be exercised above 20°C due to the natural limitations of the oxygen-carrying capacity of the water. As the temperature approaches the lower tolerance limit of salmon, feeding will decrease and all available energy will be used to maintain homeostasis, i.e, growth will be zero or negative.

It is standard practice to have feed available during the daylight hours, as salmon are visual feeders. In the late fry/early parr stages, food should be available virtually on demand (several feeds per hour) but as they grow in size and stomach capacity increases, the feeding frequency diminishes such that there are greater time intervals between each feeding occasion. Therefore, it is common practice in the early stages to use automated feeders that deliver small amounts continuously, and then in the later stages to have feeder units that can deliver a given amount at preset time intervals (e.g., every hour). Moreover, as the parr grow, it becomes apparent that the greatest feeding response is at dawn and dusk, so the feeding regime should be adjusted to ensure there are more feeding occasions and more feed delivered at these times. One useful husbandry technique is to undertake additional hand feeding at dawn and dusk, thereby providing a useful opportunity for farm workers to observe the feeding response and status of the stocks. A significant change in feeding levels or fish behaviour is often the first sign of stress which can be due to infection or deteriorating environmental conditions.

To promote optimal growth in parr it is necessary to ensure that the fish receive the correct feed sizes, in appropriate quantities, at the right time and frequency. Regular and thorough tank cleaning is probably one of the most important husbandry procedures at this time, coupled with appropriate treatments as needed. Day-to-day monitoring protocols should include careful checks of mortalities, feeding levels and environmental conditions. At less frequent intervals (every week, initially), the growth (length and weight) and general performance—survival, food conversion rate (FCR) and condition indices—of stocks should be checked for all tank groups and cohorts. There are no absolute or prescriptive values for either FCR or condition index (K), but the underlying trend for the fish described by successive samplings will provide a useful indication of fish performance. Ideally, FCR values in freshwater should not exceed 1.5 and should approach 1 and K values should increase steadily from 1, but the overall trend across a cycle is as relevant from a management perspective. Some of these latter parameters require that a careful record is kept of, and data collated for, daily mortalities, growth and feeding rations.

Such biological monitoring is particularly important in the early stages of parr development due to the rapid growth rates that can be achieved. At optimal temperatures, 5 g fish can double in weight to 10 g in about 14 days and double in weight again to 20 g in a further 21 days. Such growth rates are reflected in tank biomass/stocking densities and necessitate changes in pellet size with a recalculation of feeding rates and quantities. An efficient monitoring programme during this period allows the farmer to modify and adjust conditions on an ongoing basis to maximise performance. Commercially-available software packages can be used to model growth, and a simple computer spreadsheet can be constructed to project growth of stocks using key data such as mean weight and specific growth rate as estimated from actual feeding rates and an historical site FCR.

3.3.5 Size variation and grading

Very early in the freshwater phase, it becomes evident that the individual fish within a given cohort (or tank) display differential growth rates and a clear range of sizes emerge. This variation in size has been attributed to a variety of factors, both intrinsic (e.g., genetic, physiological) and external (e.g., feeding regime, stocking density). While certain practices (e.g., lowered stocking densities, improved feeding conditions) minimise and limit the level of variation, there is ample evidence that over time the variation increases naturally and, if unchecked, a significant gap will emerge between the smallest and largest individuals. A further discussion of the growth pattern leading to the natural formation of two size modes in relation to smoltification is found in Section 3.3.8. The smaller fish of a cohort, or tank population, are incapable of competing for food and gradually fall behind the group mean size, while the larger fish will continue to gain size advantage.

To limit and counter these tendencies, it is necessary to grade the stocks into different sizes using a grading machine/device. Graders separate the fish on the basis of body width, giving at least two and possibly more size grades depending on the device used. Typically, the parr will be graded on a number of occasions throughout the freshwater phase to give narrower size ranges and, ultimately, yield groups of smolts of similar size for transfer to sea. The optimal grading occasions are when the mean weight is 2 g, to separate smaller from larger parr at the beginning of the summer, again in the average range 10–20 g to separate smaller fish from larger potential smolts and, finally, before spring to give groups of relatively uniform smolts. Grading is a necessary intervention and, if possible, the occasion should be used to undertake other procedures on the fish, e.g., some treatments may be administered and the fish can be vaccinated and counted.

Grading intensity is, however, a matter of management choice reflecting the intrinsic composition of the stocks (growth rates and size ranges) and the operational capacity of the farm (numbers and sizes of tanks). One practical grading strategy works on the 'top-down' principle: the largest fish are removed and, if they comprise a relatively uniform size range, are left to grow undisturbed while further and subsequent gradings focus on the smaller stocks that have been provided with an opportunity to grow.

Most importantly, the dangers of excessive or over-frequent grading should be emphasised. The need to grade fish frequently suggests that growing conditions are not optimal. Improving rearing conditions, stocking density, feeding, etc. may reduce the need for grading. Of itself, grading can be an extremely rigorous procedure for fish, and it is known to interrupt feeding and growth. To minimise stress on the stocks it is desirable that: i) they are starved for an adequate period beforehand; ii) they are not crowded into, through and out of the grader; and iii) they are moved under water at all times.

3.3.6 Health status

It is imperative that the health status of the parr is maintained and stocks should be routinely monitored for disease conditions. Producers should endeavour to vaccinate fish stocks where a specific disease pathogen is routinely or continually encountered at a particular site. Commercially-available vaccines exist for several bacterial diseases including furunculosis (*Aeromonas salmonicida*), vibriosis (*Vibrio anguillarum*), cold-water vibriosis (*Vibrio salmonicida*) and enteric red mouth (*Yersinia ruckeri*). Vaccination should be undertaken by competent, trained operatives with strict adherence to manufacturers' instructions at all times. There are a number of different routes for vaccination—either bath/dip, injection or even orally in-feed—but the chosen procedure should ensure minimum stress to fish stocks.

3.3.7 The smoltification process

The natural life cycle of salmon and other related species includes a complex metamorphosis from a freshwater-dwelling juvenile to a seaward-migrating smolt. The parr changes into a more streamlined, silvery and actively pelagic individual, referred to as a smolt, which is physiologically adapted for life in the sea. This overall phenomenon or process is known as smoltification. In the wild, this transformation occurs in the spring following one or more years of freshwater life: in Europe smolts generally range in age from 1+ to 4+ years.

The parr-smolt transformation involves a series of inter-related morphological, physiological, biochemical and behavioural changes which are expressed at a specific time in the life cycle of the fish and are under internal (nervous and endocrine) and external (primarily photoperiod and temperature) synchronisation. Smoltification should be considered a pre-adaptation for life in a marine environment and must be effectively completed to allow fish to transfer and thrive in the sea.

3.3.7.1 Rapid growth and critical size of parr

While the smoltification process occurs in spring, it has its roots much earlier in the cycle during the previous year. Under natural environmental conditions, through the late summer months into autumn, it will be observed that the stocks of parr exhibit differential growth patterns, splitting into two distinct groupings: a larger upper mode growing at a fast rate and a smaller and slower growing lower mode (see Figures 3.2 and 3.3). This can be observed as a bimodal length distribution or, alternatively, if individual length and weight data for fish are available, then a simple scattergram (length × weight) analysis will reveal two distinct clusters. This dichotomy represents the natural separation of the (larger) potential one-year smolts (S1s) from the (smaller) potential two-year smolts (S2s) even at this early stage. There appears to be a critical minimum size of 7.5 to 8.5 cm (c 5–7 g) that must be reached by the end of summer to ensure entry to the rapidly-growing class and concluding with smoltification as an S1 the following spring. Once this minimum size has been attained, the fish will continue to grow until smoltification is completed (50 g+) whereas the smaller fish will remain at a much smaller size (10–15 g) through to spring. Indeed, fish smaller than the threshold size when the daylength goes below about 12 hours per day do not appear to grow over winter. In nature, these lower

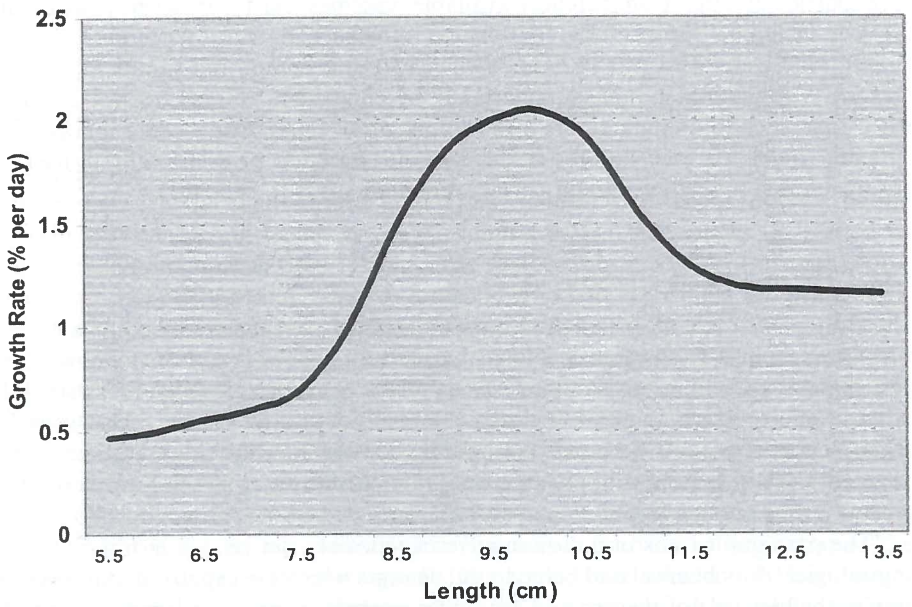


Figure 3.2. Rapid growth phase of Atlantic salmon parr.

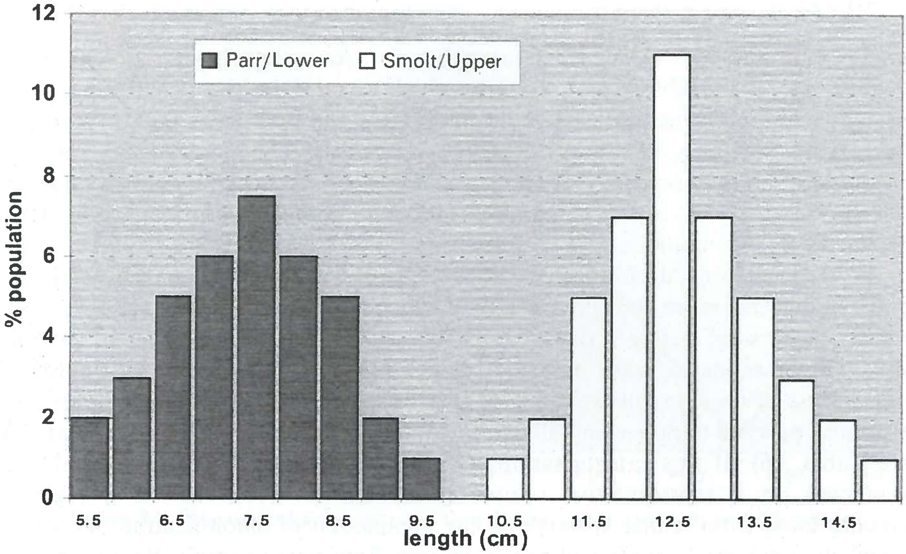


Figure 3.3. Typical bimodal length distribution of Atlantic salmon parr and smolts.

mode fish will seek out shelter or even bury themselves in the gravel or under rocks in the river bottom. They will not expose themselves to predation and they will hardly feed during winter. In farming situations, the numbers of upper mode fish can be maximised (90%+) by careful application of enhanced temperatures, extended day length and efficient feeding, which in combination will encourage earlier egg/fry development and promote faster growth through the early parr stages. Nevertheless, regardless of external manipulations, a certain proportion of fish will not achieve the critical limit and will persist as lower mode fish.

3.3.7.2 Characterisitcs of the parr/smolt transformation: smoltification

In the spring period, having received the appropriate cues, the larger parr—which have exceeded the critical size, entered the upper mode and continued to grow—will undergo major physical and physiological changes to become smolts. These changes mark the transformation from a freshwater parr to a seawater fish, the salmon smolt. The smoltification process implies the expression of changes in most organ systems but to yield a fully or properly smoltified fish these must occur contemporaneously and in synchrony. Normally, this occurs in the spring over a relatively short period, an opening termed the 'smolt window', when fish can be transferred to sea. As a corollary of this, it must be remembered that this opening will close in finite time.

3.3.7.3 Morphological changes

Several morphological or physical changes occur during smoltification. The most obvious sign is the silvering of the fish, which arises from the deposition of the crystalline purines, guanine and hypoxanthine in the epidermal layers, covering the parr marks which remain in the deeper skin layers. The scales themselves also become very loose during this period. While this silver colouring does not guarantee that smoltification has occurred, the absence of such changes is a firm indication that the fish have not smoltified.

At the same time, during the parr–smolt transformation, the fins become lighter in colouring and more transparent with darker, black margins. A visual scale of smoltification stage has been developed which can be a useful tool, in combination with other assessments, when monitoring the progress of fish during the smoltification process. Using the following listing, fish are ascribed a value on a scale from 1 (a salmon parr) to 6 (possessing all external, morphological, signs of smoltification) (see Table 3.6). If this categorisation scheme is used, the assessments should be conducted on a representative sample (minimum n = 100) and on a regular, ongoing basis from winter through to the completion of smoltification. This will permit the sequential progress of fish to be seen from parr to smolt. Because of the relatively subjective nature of this evaluation, it is advisable to have the same operatives conduct the ongoing assessments, and also that the same light and other conditions are used throughout. Natural (outdoor) light is much more revealing than most indoor light sources when undertaking this procedure.

The general shape of the body changes during smoltification with the smolt becoming longer, more slender and fusiform. These changes in body form are caused mainly by a loss and restructuring of fat tissue within the body and in some salmonids by a disproportionate increase in growth of the caudal peduncle. Collectively, these latter physical changes produce a leaner fish and result in an increased length and a consequent reduction in the weight/length ratio as

Table 3.6. Visual assessment of smoltification status.

Smoltification status/visual description:	
1	Light brown to yellowish overall colour. Yellow/brown fin colour. No silvering of scales. Parr marks very dark and clearly evident.
2	Yellowish brown overall colour. Some silvering of scales on dorsal surface. Parr marks distinct.
3	Some silver on flanks and parr marks partially obscured. Fin colour becoming clear.
4	Parr marks still visible but almost completely obscured by the silvering of the scales on the flanks. Fins clear.
5	Silvering on dorsal and flanks and difficult to distinguish parr marks. Grey margins on fins.
6	Silvering colour dominant. Parr marks completely absent. Fins clear with intense black pigment on the margins of the dorsal and caudal fins.

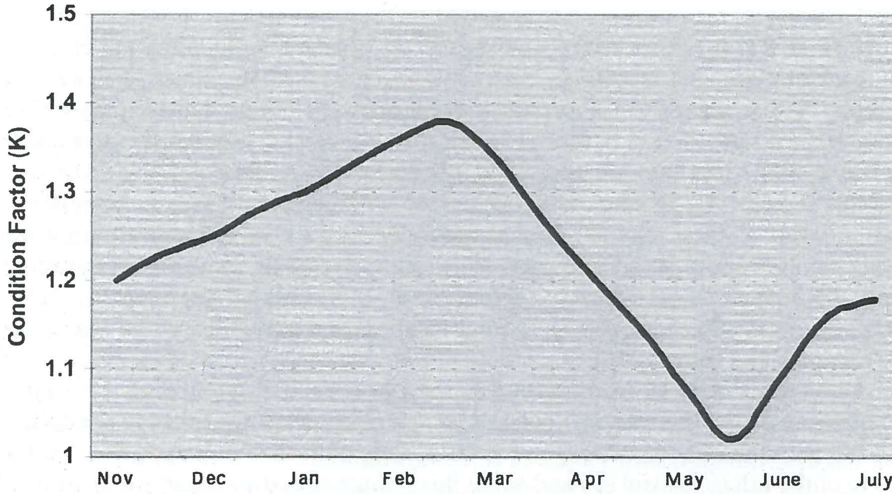


Figure 3.4. Seasonal changes in condition factor associated with smoltification.

expressed by condition factor (K). Thus, at this time, there is normally a decrease in mean K values of the stocks (see Figure 3.4).

However, as noted above, these morphological changes should not, in isolation, be used to confirm that smoltification has occurred. For example, it is common to observe extensive silvering in larger smolts towards the end of the year, well in advance of spring and the initiation of full smoltification. Very light tanks can also create a light coloured, silvery fish that may be mistaken for a smolt.

3.3.7.4 Behavioural changes

In the farming situation, the behavioural changes that occur with smoltification are less evident than in the wild, but with regular and careful observation they can also be seen in farmed stocks during smoltification. In the wild, salmon parr exhibit a marked territoriality, occupy fixed positions faced into the current flows and can be highly aggressive. However, with the onset of smoltification, these behaviours are markedly altered as fish show a schooling behaviour with downstream orientation and swimming with the currents. Similar behavioural patterns, associated with increasing restlessness, can be observed in tanks on farms during smoltification. At the same time, appetite is stimulated and the fish begin to feed much more intensively.

3.3.7.5 Physiological changes

Virtually all organ systems are implicated in the physiological changes, often mediated through various hormonal changes, that occur during smoltification. Numerous workers have studied seasonal variations in the levels of a variety of hormones, most notably growth hormone (GH), thyroxine (T_4), prolactin (PRL) and cortisol, and their impacts on associated/target organ systems. For example, it is known that GH increases hypo-osmoregulatory capacity, stimulating gill chloride cell proliferation and increasing Na^+, K^+ -ATPase activity which enables salt secretion across the gills in hyperosmotic (marine) conditions. Other studies have demonstrated that cortisol is central in regulating several aspects of the parr-smolt transformation since cortisol stimulates gill Na^+, K^+ -ATPase activity. Likewise, T_4 levels increase up to and peak during the smoltification phase in springtime. Plasma levels of these three hormones naturally all peak in succession during the spring smoltification period and then decrease in succeeding months. On the other hand, PRL (prolactin), which is described as a freshwater adapting hormone, decreases during the final phase of smoltification and on exposure to sea water (see Chapter 1, Figure 1.23).

Among their several functions in fish, these hormones also influence the osmoregulatory ability of the fish. The greatest physiological challenges during smoltification rest with the osmoregulatory status or capacity of the fish. It is apparent that the ability of the fish to control ion and water fluxes must alter dramatically to cope with the demands of contrasting freshwater and marine environments. In freshwater, parr are continuously losing ions to and passively absorbing water from the ambient environment. To counter these tendencies, fish in freshwater drink little, actively take up ions from the water and excrete large volumes of a dilute urine. By contrast, in the sea, water is continually lost to the ambient environment over the body surface and there is a passive influx of ions. In this case, fish must replace the osmotic loss of water through drinking seawater and subsequently excrete the excess salts via the gill and in a very concentrated urine.

Thus, in the period up to and during smoltification, the hormonal profile of the fish is such that it promotes its hypo-osmoregulatory capacity, thereby facilitating transfer to the marine environment.

3.3.8 Desmoltification

If fully smoltified fish are unable or prevented from going to sea then, over time, the specific smolt-related ability to cope with a hyperosmotic environment diminishes steadily and is lost. This loss of smolt status, both in osmoregulatory capacity and other smolt-related changes, is known as desmoltification. Although poorly described and understood, evidence shows that it involves loss of several of the characters listed previously. Most notably, the osmoregulatory capacity of the gills is lost and the silver livery of the smolt lessens and turns more into 'oxidised aluminium' though the parr marks will not return. It should be emphasised that this is an unstable physiological situation, as the fish is adapted to seawater but still remains in freshwater. Under unfavourable conditions, such as poor water quality, high mortalities are often recorded in these fish due to the osmotic imbalance, loss of scales and increased incidence of infections.

3.3.9 Regulation and control of smoltification: size, temperature and photoperiod

From the foregoing account, it is apparent that smoltification is a complex process occurring over a period of time but, intrinsically, only a limited number of factors control and regulate the process.

As noted above, for successful smoltification it is a prerequisite that fish achieve a minimum size by a critical time: this is taken to be about 8 cm by end of summer. Parr that have not achieved this threshold size will not respond to or be stimulated by subsequent environmental cues that govern smoltification.

Once the critical size has been reached, then temperature and photoperiod are the prime factors controlling the rate of growth of juvenile salmon and the timing and synchronisation of smoltification. The complexity of inter-linkages between these two factors can be best appreciated in the context of feeding, where the amount eaten will depend both on the photoperiod and on the water temperature. However, in the context of smoltification, it is necessary to distinguish between their distinct roles. High temperatures will accelerate overall growth rates and produce more potential (upper mode) S1 fish and larger smolts. It has also been demonstrated that higher temperatures advance the timing of smoltification in spring but may shorten the 'window' for successful transfer to seawater, whereas a lower temperature profile will delay but lengthen the period for transfer. This can be demonstrated by the differences in gill Na^+, K^+ -ATPase activity for groups of fish reared at different temperatures (see Figure 3.5). In certain circumstances, where constant elevated temperature is used, the fish may be exceptionally large and silvery very

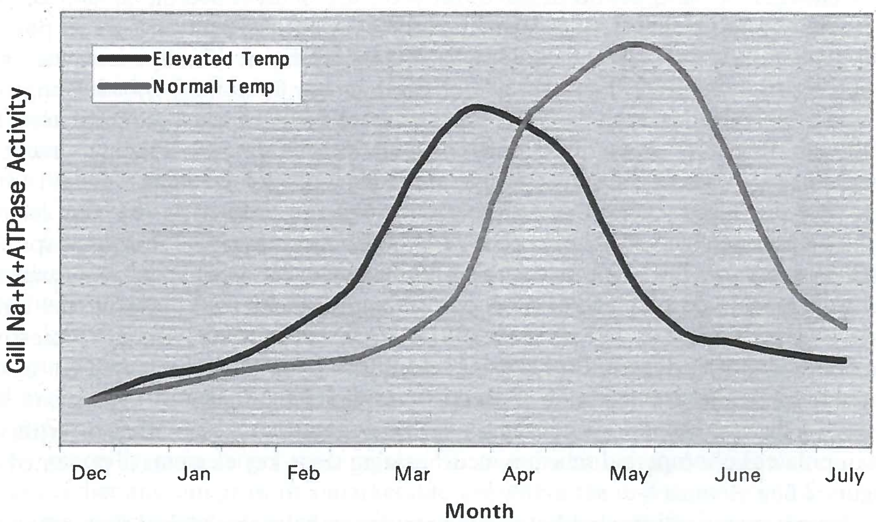


Figure 3.5. Differences in gill Na^+, K^+ -ATPase activity for groups of Atlantic salmon reared at different temperatures.

early in the year but may still have poor salt tolerance. In fact, the long-term directive cue for smoltification rests with the changes in photoperiod over winter and spring. Thus, temperature should correctly be considered both as a mechanism for governing the proportion and size of smolts (accelerating or retarding growth) and also as a factor controlling the pace of the developmental processes driven by the changes in photoperiod, and hence the timing and duration of the smolt window.

Undoubtedly, the single most important environmental cue for the synchronisation of the parr–smolt transformation is photoperiod: in its simplest form, the natural changes and seasonality of daylength. In the absence of a changing photoperiod regime (i.e., in a constant light environment), it has been noted that individual characteristics of the smoltification process may occur (e.g., silvering in 'pseudo-smolts'), but there is an overall lack of synchronisation (e.g., changes in external characteristics not corresponding with changes in salt water tolerance). This practice of keeping fish on an unchanging photoperiod, e.g., constant light, was common in the farming industry in the past, in the belief that with large smolt size came osmoregulatory capability.

Numerous studies on both sides of the North Atlantic have, however, clearly demonstrated that signals from the environment are needed to synchronise the process, and that the salmon primarily detect and respond to changes in day length. In general, studies of temperate and arctic animals, including fish, have concluded that photoperiod is the most important signal for the animals to adjust their physiology, behaviour, migration, etc., to maximise survival and performance. These changes in day length occur year after year and are more predictable than any other environmental cues, including temperature. Earlier, it was believed that changes in photoperiod acted directly on the neuroendocrine system of the fish, thereby regulating development in a direct way, often referred to as photo-stimulation. However, recent findings have concluded that photoperiod acts as a 'zeitgeber' (German, 'time-giver'), i.e., changes in day length act by adjusting the internal biological rhythms of the fish, often referred to as 'biological clocks'. Although this may seem quite theoretical, it does have wide-ranging practical implications in smolt farming, which are addressed below. Thus, there is the extended day length period of spring/summer leading into a shorter day length experienced over winter which is followed by the increasing day length of spring. This increase in day length synchronises the endogenous rhythms, causing all the independent developmental processes to coincide with each other at the right time and giving rise to a fully-smoltified salmon. The three essential, successive elements of the photoperiod cycle can be identified as: a long day length (to reach critical minimum parr size); a distinct short day length winter signal: and an extended day length as a spring signal. A diagrammatic representation of artificial (manipulated) photoperiod schemes incorporating these key elements is presented in Figure 3.6.

Recent investigations on photoperiod regulation have emphasised that it may be the regularity of changing daylight that acts as a synchroniser of the internal timing process rather than as a direct causative factor.

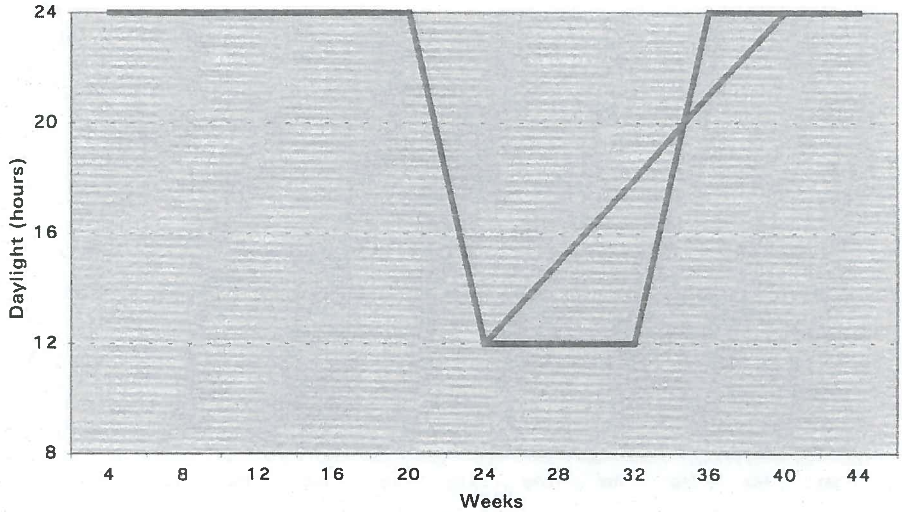


Figure 3.6. Artificial (manipulated) photoperiod schemes.

3.3.10 Types of smolts and manipulation of smoltification

Freshwater hatcheries must aim to optimise their output of smolts in a given growing season. From a practical farming viewpoint, the first decision relates to potential S2s. Under 'natural' farmed conditions, most smolts will be S1, although a smaller proportion of potential S2 fish will be produced. The decision to continue with these fish for a further year is questionable. While they tend to be much larger on transfer than their S1 counterparts, there are presently few other arguments for maintaining them on site. Indeed, most farmers will cull these fish in the autumn of their first year for a number of reasons but primarily because of the unit cost of production which will extend over further years in freshwater. In addition, S2s in their second spring/summer in freshwater appear to be extremely susceptible to a variety of disease conditions and may require an inordinate amount of husbandry care. Likewise, they may exhibit a high incidence of precocious males (identified as smaller dark fish) during their second autumn in freshwater. Under optimal growing conditions these males may become smolts next spring, but the resources (temperature, husbandry) necessary to stimulate this development may be too high. One acceptable option may be to produce manipulated S11/2 smolts (see manipulations below) to be transferred in the autumn, from these potential S2s. Nonetheless, these large S2s may represent an interesting option to reduce rearing time in seawater. They generally grow larger than regular S1s, can be transferred to seawater a few weeks earlier and can grow to a marketable size within the first summer and autumn.

The exploitation of salmon by aquaculture techniques has been increasing steadily over the past decades and, for obvious economic reasons, special attention has been given to the possibility of reducing the duration of the freshwater

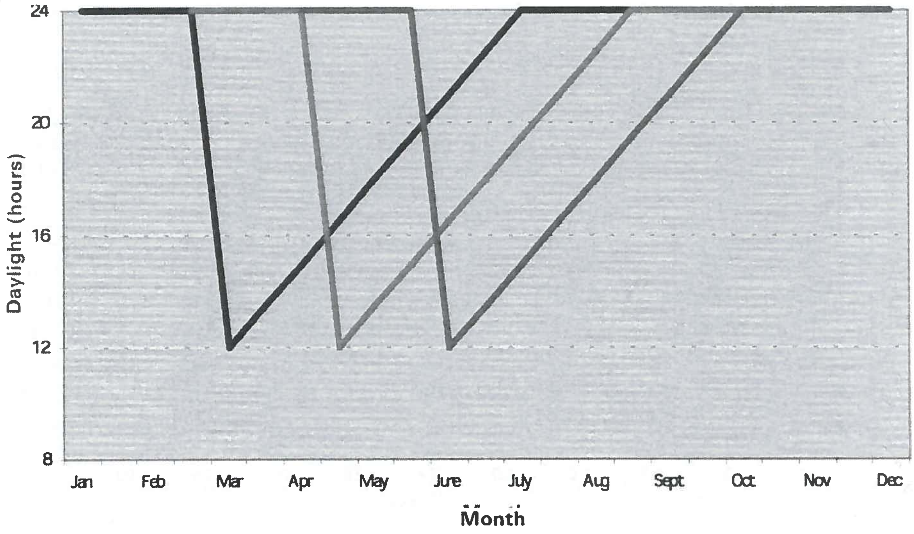


Figure 3.7. Photoperiod manipulations to produce successive cohorts of smolts.

phase in order to reduce the cost of the smolts and increase throughput, thus raising asset utilisation. More importantly, under standard conditions, smolts will be available only in spring (as either S1 or S2) and, in the case of any individual marine site, the farmer is faced with the decision of keeping the fish growing at sea for barely one or else nearly two full years. The knock-on effect of such a limited production strategy will be gluts of production at particular times or seasonal availability of specific sizes, depending on the rearing strategy utilised in the marine phase.

From the knowledge base on the factors controlling smoltification, it is now possible to strategically control and manipulate environmental conditions (temperature and specifically photoperiod (Figure 3.7) in order to produce out-of-season smolts capable of being transferred to seawater in the autumn of their first (or even second) year. These smolts are referred to variously as 'half-year', 'underyearling', 'S0+s', 'S$\frac{1}{2}$s' or '0+' smolts if in their first year or S1$\frac{1}{2}$ smolts if in their second year. Indeed, through judicious use of the two environmental control factors, it is theoretically possible to produce successive cohorts of smolts, say two months apart, throughout most of the year. In this scenario, specific temperature regimes can be used to either accelerate or delay growth while photoperiod can be used at the appropriate time to provide the necessary winter/spring signals to initiate and complete smolting. The result will be a fully controlled, season-independent smolt production.

The following is a practical example of a production schedule that could easily be implemented by a freshwater producer to maximise output using the natural cycle and a series of specific manipulations. Two tranches of eggs are taken into the hatchery, one earlier and one later in spring (Figure 3.8). The first grouping can

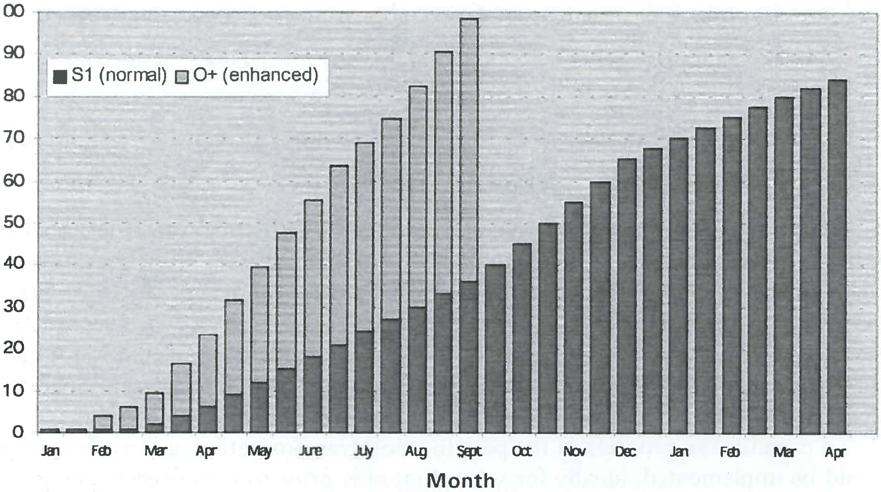


Figure 3.8. Production schedule of two tranches of eggs and smolts per annum.

be rapidly brought through the hatchery at elevated temperatures well in advance of the second; thus the same equipment is used to produce double the number of juveniles. With this first grouping, extended or continuous daylength is used to promote fast growth thereby ensuring that a large proportion of these parr make it past the critical minimum size. Once the critical size for smolting (as described earlier) has been exceeded, a shortened day length (winter signal, LD12:12 or shorter) photoperiod is instituted for a minimum period of eight weeks. Thereafter, day length is increased to LD 24:0 (spring signal) which is maintained until smoltification. Alternatively, a reduction to LD 12:12 (winter signal) can be followed by a gradual increase in day length, stimulating the natural increase in spring. This production regime has been used successively in commercial operations, and represents a less artificial photoperiod regime (see Figure 3.7). Both of these manipulations are sufficient to complete smolting of underyearling salmon. In total, these photoperiod manipulations will take 14–18 weeks. These fish should be ready to go to sea in late September of their first year as S0+s. Meanwhile, the relatively slower growing second grouping of eggs will be reared under ambient conditions and smoltify as normal S1s in the spring of the next year. In theory, virtually double the number of smolts can be produced using the same facilities.

By using out-of-season smolts, it is possible to spread freshwater production across the year, allowing greater annual output of smolts and better utilisation of plant equipment and human resources. Likewise, in the marine environment, the salmon industry has greater flexibility as smolts can be put to sea on at least two occasions per year, with input timing, intervals, smolt size, etc., being determined by the specific production plan on the site. Hence, the peaks and troughs in production can be reduced. For example, it is possible, even within a single marine site scenario, to use alternating S1 and S0+ smolt inputs, giving a marine production phase of up to 15 months and a fallowing period of some three months between final harvest and next smolt input.

3.3.11 Monitoring of smoltification and transfer to sea

3.3.11.1 Monitoring of smoltification

In the wild, migrating smolts can use the estuary to gradually acclimatise to the seawater environment. In culture, however, smolts are usually transferred directly to salt water rearing structures and this can be a very traumatic phase in the life cycle. Consequently, it is very important to know about the physiological state of smolts in order to assess their potential for adaptation to the marine environment. The dangers are twofold: on the one hand, the fish may not be fully smoltified and, on the other, they may be too far advanced and have begun desmoltification.

To monitor the progress of the parr to smolt transformation, a sampling regime should be implemented, ideally for several months prior to the expected smoltification time. It is possible to monitor all aspects of the transformation, including morphological and physiological characters. In the latter case, under laboratory conditions it is possible to monitor, for example, Na^+, K^+ -ATPase activity, T_4 levels and even growth hormone (see Figure 1.25, Chapter 1). For the farm situation, more pragmatic solutions are often required and regular monitoring should include: i) size (length, weight) frequency distributions; ii) estimation of mean condition factor; and iii) visual appraisal of smolt status (1 = parr to 6 = smolt). In addition, as smoltification approaches, a practical test for salt tolerance is needed. In these later stages, both ion regulation tests (using 35% salinity) and or high salinity challenge/survival tests (using 40% salinity) can be employed.

In the ion regulation test, representative samples of fish are tested for their ability to regulate blood (plasma) ions (sodium and chloride salts) levels following their transfer to 35% sea water for 24 hours. A fully smoltified fish has the ability to actively osmoregulate blood sodium down to physiologically acceptable limits, whereas elevated values will be recorded with parr. Blood plasma concentrations of 160–170 mM l for sodium and 140–150 mM l for chloride after 24 hrs at 35% shows an ability to osmoregulate in sea water, i.e., indicative of a 'true' smolt. For parr, values of sodium in the range 170–190 mM l and sometimes in excess of 200 mM l, will be recorded and very often the fish will die. In practice, as the fish grow and develop they will show decreasing levels of blood sodium/chloride as larger fish have a greater osmoregulatory ability (Figure 3.9). Therefore, it is necessary to undertake successive trials and test a range of sizes from the potential smolts. All analyses of plasma sodium/chloride levels should be undertaken by an experienced and reputable laboratory. Alternatively, if blood salt levels can not be checked, a high salinity tolerance test (survival at 40% salinity for 96 hours) may be carried out on a representative sample. The underlying concept of this test is that only fully smoltified fish will be able to survive while parr or pre-smolts will die during the extended trial period. Survival of good quality smolts should be 100%. This test,

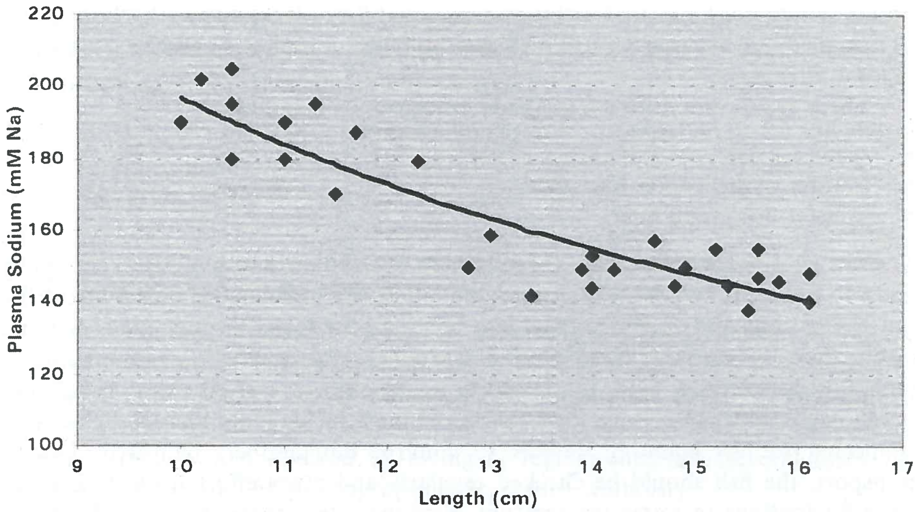


Figure 3.9. Plasma sodium values for a group of salmon parr and smolts.

though useful, is far less sensitive than the ion regulation test, places a very significant salinity load on the fish and raises issues of animal ethics.

Recent investigations have shown that seawater temperature is critical for the acclimation process and even interpretation of seawater challenge test results. As mentioned above, temperature is the primary rate controlling factor in fish. In the present context, at low temperature, in the range 4–7°C, the increase in blood ion levels takes place at a slower rate than at higher temperatures (10–15°C). Furthermore, the subsequent acclimation to seawater, seen as a gradual reduction and stabilisation of plasma ion levels, is again delayed at low temperatures and may take as much as 1–2 weeks at 4–5°C, whereas the process is completed in 2–4 days at optimal temperatures. Consequently, seawater challenges aimed at assessing the seawater adaptability of smolts should preferably be performed at a standard temperature throughout the testing period. If the test is carried out at low temperatures, one may consider extending the test period for 2–4 days, if conditions permit. This is also relevant when transferring smolts to seawater cages at low temperatures, as care should be taken to avoid excessive disturbance of the fish for the first week or two of seawater acclimation.

3.3.11.2 Transfer to seawater

If fish are confirmed as having the ability to osmoregulate effectively, i.e., they are true smolts, then they can be transferred to sea. The transport of smolts requires a degree of planning to ensure that all logistical requirements are in place, resulting in the minimisation of stress and avoidance of subsequent problems of poor performance, damage and mortality. It is also essential to ensure that all regulatory certifications and permits relating to the transfer are in place. Prior to transfer, the smolts should not be treated with any compound for at least one week, they should be arranged into transfer groups of known numbers and they should be starved for at least three days.

There are several different methods of transport including:

- road transport using tanks;
- transfer by helicopter bin; and
- transfer using well boat.

Transfer should take place with the minimum of handling and preference should be given to transport and delivery systems that allow fish to be loaded directly from the freshwater units and discharged and into holding pens at sea through pipes or tubes rather than by excessive hand netting. Extreme care should be observed if fish-pumping devices are used for transferring smolts: excessively long hoses and rough edges may cause stress or damage and must be avoided. Fish pumps can be connected to fish counting devices to confirm the numbers delivered. During transport, the fish should be checked regularly and every effort made to prevent large fluctuations in water temperature. Well-insulated transport tanks should be used.

Transport tanks should be completely full with no ullage space and the interior should be smooth and dark. Oxygenation, rather than aeration, should be provided as air bubbles may create too much turbulence. Dissolved oxygen should be continually monitored to avoid both low and supersaturated conditions. The stocking density of smolts in tanks will depend upon the length of time of transport and the water temperature. As a general rule, stocking density should not exceed 120 kg m^{-3} at temperatures below 10°C and journeys should take no longer than eight hours. However, most operators will generally move fish at lower stocking levels.

3.4 MARINE ONREARING: SMOLT TO MARKET SIZE

3.4.1 Quality of smolt intake

The cost of smolts may represent 20% of the total production costs in the sea and the quality of the smolt stock for ongrowing on a sea farm will determine the final quality of the harvested salmon to a large extent. If the smolts transferred to sea are of less than the highest quality, this will result in extended periods of poor feeding, reduced growth performance, increased stress and possible disease outbreaks and, at worst, heavy mortalities. This is particularly true of smolts moved very early or late in the 'smolt window'.

The smolts should be in excellent physical condition and the following must be avoided:

- shortened opercula (gill covers);
- one or both pectorals severely damaged or missing;
- spinal or jaw deformities;
- fish with damaged eyes;

- scale loss: excessively loose scales may be a sign of desmoltification;
- clinical external symptoms/gross pathologies of disease, e.g., lesions, swelling, reddening, bruising, residual fungal marks.

Fish exhibiting any of these conditions should not be accepted on to the site and, in practice, smolt quality can only be guaranteed by carefully examining the fish in freshwater prior to transfer.

3.4.2 General stock maintenance at sea

While it might seem axiomatic, it must be stressed that cages for ongrowing should always be sited where there is sufficient water exchange to provide a constant supply of clean, well-oxygenated seawater and sufficient current flow to minimise accumulation of wastes. In the case of established sites, the benthic conditions should be sampled annually and checked by diving at regular intervals (several times per year), or as stipulated by the appropriate regulatory authority.

The net mesh should be sufficiently large to allow maximal water exchange while containing the fish and the nets should be changed regularly to negate the effects of fouling. The dangers of build up in fouling are particularly insidious since it can occur very rapidly. These dangers are at an engineering and biological level. First, fouling places undue physical stresses on the cage infrastructure which can lead to engineering problems, shortening the life of the cage or causing total failure. Second, and more significantly from a biological perspective, fouling impedes/reduces water exchange through the cage while the increased organic loading takes valuable oxygen from the ambient water. The combination of heavy fouling and high water temperatures is a situation that must be avoided as it can lead to mortalities. When nets are being changed there should be a minimum of disturbance to the stock.

Nets should be sufficiently weighted to prevent reduction of cage volume in strong currents, as such reductions effectively increase stocking densities and heighten the risks of abrasion and net rash. The threat of damage from predators should be minimised by using predator nets both above and below water. On occasions when a cage must be moved, the nets should be provided with additional weights to prevent distortion and the towing speed strictly limited.

In the sea, best farming practice aims to minimise interventions and reduce stress while optimising feeding and growth to produce a quality product. To achieve these aims a number of recommended standard practices have emerged. For example, fish can be carried through in the same cage from smolt to harvested fish; thus, when being transferred to sea they should be stocked at a rate to generate a final maximum stocking density of no greater than $15\,\mathrm{kg\,m^{-3}}$. If interventions prove necessary, the fish should be crowded slowly and carefully to prevent panic and the procedure should not take too long.

Though used less frequently as sea, it is sometimes necessary to grade fish and, in such circumstances, passive handling/grading techniques are recommended where the fish are allowed to swim through a mesh, thus separating the larger from the smaller. Grading at sea will ensure that size at harvest is also more consistent, reducing post-harvest grading and allowing easier production planning. Handling stress caused by summer grading and stock splitting must be avoided at all costs to reduce the risks of disease outbreak. For farms operating production cycles of greater than 12 months, it is better that grading is carried out in the early spring or late autumn.

Disease and treatment of disease can have a major effect on product quality. Moreover, in the marine situation with large fish in large cages, the problems of administering an effective treatment are immense. For example, the impracticality of handling individual fish for injection is obvious. Likewise, ectopic treatments are problematic, requiring at least skirts or bag nets to contain the compound, thus leaving oral delivery (of antibiotics or anti-sealice treatment) as the only feasible treatment route in many cases. It must be remembered that if antibiotics are used, an appropriate withdrawal period prior to harvest must be exercised. Thus, vaccination of smolts prior to transfer is imperative and, in the sea, the health status of the fish should be monitored diligently.

To minimise health risks, mortalities should be removed from cages regularly and accurate records of losses maintained. Mortalities destined for disposal should be kept in sealed containers, away from the main fish farm operations. There are a number of methods available for disposal of mortalities, including ensiling in formic acid, rendering and composting. The choice of disposal route will depend upon the number of mortalities, their freshness and the disease status.

There should also be a contingency plan in place to deal with a catastrophic loss situation which would result in very large numbers of mortalities. These plans should be compiled in liaison with the local/regulatory authorities.

The following practices are recommended for the operation of the larger volume cages, e.g., Bridgestone. Mechanised handling systems should be available to allow easy changing of nets and handling of stock, resulting in the minimum of disturbance to stock. These large-volume cages should be accompanied, where appropriate, by a conventional cage unit into which fish can be transferred for specific husbandry procedures such as treatments and grading.

A stock monitoring programme should be instituted to ensure that relevant data both on stocks and ambient conditions are collected and collated on an ongoing basis.

3.4.3 Feeding in the marine environment

Feeding of fish is probably the most important operational activity on marine farms. Feed could represent up to 40% of the production costs of a marine salmon farm and feeding efficiency largely determines growth of fish and is therefore likely to be the crucial factor in overall profitability. The feeding strategies employed on a farm have direct consequences on food conversion efficiency, growth rate, environmental impact (via benthic wastes) and the final quality of harvested salmon.

As in freshwater, feeding rates are determined by fish size and ambient temperature. However, the recommendations for feeding in the marine environment are for guidance only and much greater emphasis must be placed on the actual feeding response. Fish should be fed *ad libitum* through observations of feeding behaviour at all times. If it is necessary to reduce feeding rates (during lower temperatures) then it is best that the number of feeding occasions are cut back. This will ensure that there are consistently sufficient numbers of pellets to provide for all fish in the cage. Feed should be evenly distributed on the water surface in sufficient quantity so as to reduce fish crowding. Crowding can lead to eye and fin pecking and results in large variation in fish sizes, with the smaller fish performing poorly. This, in turn, has direct implications for grading interventions. Hand feeding can be used for smaller cages but mechanised feeding systems are needed with large cages to ensure efficient and uniform feed delivery to the entire cage surface. It is now common practice to use in-cage fish monitoring devices (either direct video or scanning) to follow the feeding behaviour of the salmon. Thus, the operator will continue to feed until the feeding response and behaviour changes indicate satiation among the majority of stock.

Good husbandry practice requires regular visual checks of fish behaviour and feeding habit which may indicate early symptoms of disease leading to early control. Similarly, accurate feed records will permit the feeding efficiency to be calculated and reviewed on an ongoing basis.

To achieve a quality finished product, it is necessary to provide in the diet a pigment source to colour the flesh. Two carotenoids are currently permitted under EU legislation as fish feed additives, notably canthaxanthin and astaxanthin (see Section 4.13.3, Chapter 4). The level of pigmentation required is often a subjective decision of the consumer, although an even pigmentation of the salmon flesh is always desired in a quality product. Research has shown that it is best to feed pigmented diets at lower levels and over a longer time period. In current practice on farms, it is almost standard to administer pigmented diets from the time the smolts have adjusted to transfer. A misguided strategy of using higher levels of pigment towards the end of the growth cycle tends to give poor pigment levels in the flesh and produces large variations in colour both within a cage population and within individual fish. As part of quality control procedures, the pigmentation of the flesh should be regularly checked during the growth cycle.

3.4.4 Salmon cage technology

Cages have been used in fish production for many centuries. Original designs were simple floating structures. The first cages used for the rearing of salmon in Norway were developed by the Vik brothers in the 1950s (Myrseth, 1993). These were very small (approximately $10\,m^3$) floating wooden collars with a net containing the salmon suspended below. Although the technology was basic in relation to what is available today, the initial development and success of the Norwegian salmon farming in the 1970s can be attributed to the development of these simple structures. Some land-based tank sites with pumped seawater were also developed, but by the early 1990s such systems had almost completely disappeared from Norway.

As the salmon industry expanded, the early cage and onshore systems were replaced by larger sea-cage systems, and although some farmers still use large cages in sheltered fjords, most production takes place in larger offshore systems. Advantages of moving farms offshore include the availability of unpolluted waters, increased area for waste dispersal and opportunity for increased cage and farm size. Increased cage size for salmon has been shown to offer greater scope for growth and increased efficiency of feed usage: feed retention time is longer in larger, deeper cages. The continued increase in cage size through time has allowed salmon farming to operate more efficiently, and technological advances together with an increased understanding of environmental requirements, feeding and health have benefited the growth of the industry.

3.4.4.1 Principles of cage design

The primary aim of a cage or pen is to provide a barrier to prevent fish from escaping and through which water exchange can take place freely. There are three basic types of cage available currently for fish culture:

- floating: supported by a frame or collar;
- fixed: supported by posts driven into the sea bed;
- submersible: the entire cage structure can be lowered below the water's surface (Beveridge, 1984).

Cage frames may be either flexible or rigid or a combination of both. Flexible structures are generally less expensive to purchase and install and consist of a conventional bag-shaped net which retains the fish and allows clean water to flush through. A variety of mechanisms are employed to provide and maintain the shape of the nets. Gravity cages use weights or floats while other types tend to use pre-stressed ropes to provide shape. Semi-rigid cages use a combination and pre-stressed ropes. Rigid cages have the highest start-up costs, but have a longer life span and these use solid beams to define the net shape. All cage types tend to have a floating collar that often supports a walkway for ease of access during routine feeding, monitoring and maintenance (Huguenin and Ansuini, 1987). To prevent abrasion, knotless netting is used for the cage bag; mesh size is a compromise to ensure that the smallest fish are retained but water can circulate freely. Biofouling of nets poses one of the main problems in marine salmon farming, increasing both their weight and the drag effects of currents. Although the extent of fouling can be controlled by careful site selection and by cage submersion, it is not removed completely and methods have been developed for fouling removal in order to minimise maintenance costs. To prevent fouling, nets may be treated with approved antifouling paints, changed frequently or used in rotation, allowing exposure to air and drying out, thus killing attached organisms.

The type and particular design of the cage are based on considerations of local oceanographic conditions at individual sites in addition to economic, biological and engineering factors. It is particularly important that the design of cages does not impose unnecessary stress on the fish as stress reduces disease resistance and growth performance (Pickering 1990). Many processes involved in the commercial rearing of fish, such as grading and weighing, are unavoidable and do induce stress, making any further impositions of stress by sub-optimal holding facilities undesirable. Stress is also induced by poor water quality, unfavourable social interactions within fish groups and conditions of overcrowding as found when cage volume is reduced because of wave action (Sumpter 1993).

Ideally cages should provide for the following conditions (from Kuo and Beveridge, 1990):

- stable temperature and salinity;
- steady current speed;
- sufficient dissolved oxygen (near saturation);
- even distribution of feed;
- minimum vertical movement;
- avoidance of parasites, toxic algae and pollution.

Other factors influencing cage design are economic and engineering considerations, ease of installation, operation and maintenance (Linfoot *et al.*, 1990). Therefore, before a cage is selected for use a site must be chosen and the cage design matched specifically to the requirements imposed by site and species selection. Provision must also be made for corrosion, fouling and impact on the seabed and the following physical loadings must be considered (Milne, 1970):

- weight of structure (gravity forces);
- maintenance and operational loads;
- dynamic loads (wind, waves and tidal currents);
- collision and mooring forces.

As noted above, the first aquaculture cages had wooden frames. Today, however, most marine salmon cages have galvanised steel or plastic frames; plastic is often favoured because of the lower cost. Plastic cages are strong, resistant to marine corrosion and have the ability to withstand strong winds and rough seas (Svensson, 1993). Steel cages have more commonly replaced wooden cages in near shore sites (Linfoot *et al.*, 1990). Cage size has increased over the decades as a result of health and financial considerations (Myrseth, 1993). Volumes are now likely to be several thousands of m^3, compared with less than 100 in the early days of salmon culture.

3.5 OFFSHORE SALMON FARMING

3.5.1 Automation of fish farming

Initially, the most sought-after sites for fish farming were sheltered fjords, lochs or bays where there was little movement of water. In such locations, floating sea cages have the advantage of being easy to operate, require a low capital investment and rely on proven designs and husbandry practices. The first offshore salmon farming system was installed in Norway in the early 1960s (Balchen, 1990) and, by the late 1980s and early 1990s, it was commonly considered that the future of salmon farming was offshore, in spite of the obvious problems associated with the technique. Offshore sites are exposed to harsher environmental conditions, particularly large waves several metres high and swells, and currents greater than traditional near-shore sites, presenting very different environments in terms of water movement and structure of the water column (Gowen and Edwards, 1990). The movement to offshore salmon farming allowed a dramatic increase in the quantity of salmon produced which would never have been possible had the industry remained an inshore operation. Results show that when using large volume cages (5–10,000 m^3) and low stocking densities (5–10 kgm^{-3}) it is possible to obtain faster growth with lower food conversion ratios, less loss of feed, fewer injuries and mortalities and greater disease resistance, together with an improvement in flesh quality (Dahle and Oltedahl, 1990; Oltedhl, 1990; Guldeberg *et al.*, 1993).

In addition to the opportunity for increased volume a range of other advantages of offshore cage locations have been identified and are summarised below:

- more available sites for farms;
- availability of unpolluted waters (Balchen, 1990) and improved water quality (Rudi and Dragsund, 1993);
- increased water movement carrying fresh oxygen (Loverich and Gace, 1997);
- increased cage size (Balchen, 1990);
- increased area for dispersal of farm waste (Balchen, 1990);
- lower salinity and temperature fluctuations (Gowen and Edwards, 1990);
- higher stocking densities possible due to increased water movement (Loverich, 1998);
- improved fish health and quality;
- less conflict with tourism and fisheries (Fearn, 1990).

Many of the problems encountered by open water aquaculture can be overcome by minimising the forces reaching the cages by using breakwaters or altering the design of cage frames and moorings to make them better able to withstand open ocean conditions. In response to the offshore move of salmon farming a number of advances have been made (Willinsky and Huguenin, 1996):

- bottom mounted: submerged cages and barrier systems;
- surface operated/bottom moored: nested cages or submersible cages;
- surface operated, moored and flexible systems: barges or ships.

Floating breakwaters can be employed to reduce the effects of waves on cages in exposed areas. The technique is based on using barriers, generally made from rubber, to break up the wave action before it reaches the cages. While this type of system has been successful in some areas, its use is limited to sites that are relatively near to the shore and where the wave action is moderate.

Cage collars developed specifically for offshore use are generally made from flexible materials such as plastic or rubber and are available throughout the world from a number of manufacturers. Articulation of components within the cage structure is frequently used to counteract these forces and prevent damage to the structure of the cage. Due to the lack of suitably sheltered inshore sites, salmon farming in Ireland must be undertaken in deeper offshore waters; the first and largest rubber Bridgestone cages for salmon farming were used in Ireland. These cages were originally developed for use in the Japanese aquaculture industry and the flexibility of the rubber allows them to withstand the wave action in the open ocean (Gunnarsson, 1993). They have a flexible rubber support collar with no moving parts, and the nets used in the pens are designed not to use their shape in severe wave conditions. These and similar systems do not support a walkway and therefore all routine maintenance must be carried out from boats by experienced, well-trained staff. Polar Cirkel Nova cages use the flexibility of the floating structure to allow the system to withstand offshore conditions. These are made from flexible plastic and none of their parts are susceptible to marine corrosion.

Steel cages are generally less resistant to damage from the ocean than plastic ones (Myrseth, 1993) but are generally employed in more inshore sites. In the development of steel cages for use in exposed locations, engineering problems of hydrodynamics and strength as well as biological and economic problems must be addressed. Linfoot *et al.* (1990) produced a comprehensive report on the factors influencing cage design and site selection for offshore farming. The conclusions drawn from this review included:

- Breaking waves with wavelengths comparable with the cage component length can cause worst vertical load cases for multi-component hinged steel cages.
- Horizontal forces on cages, mooring lines and nets increase with increased severity of storm loading.
- If the development of offshore cages is to be a commercial success there is an overwhelming need for the validation and improvement of existing analytical tools.
- Important biological factors such as the motion tolerance of fish also require quantification. Information about fish feeding response in waves could be used to optimise feeding with consequent benefits both to the environment and to the economics of the farm.
- Cage designers must protect the fish from the effects of solar UV-B radiation.

In addition to the importance of the design of the cage collar for use in offshore systems, when cages are moored in offshore sites the moorings, which were simple and straightforward in sheltered sites, become complex (Myrseth, 1993). While strong materials allow cages to withstand rough weather conditions, much of the energy is then transferred to the moorings. Damage to sea cages and losses caused by storms and bad weather are often the result of weaknesses in the fabric of cages and/or their moorings. An important aspect of the considerable research carried out on cage moorings is the reduction of the mooring area required for cages. Developments include the use of grid moorings to moor two or more cages using the same anchors and submerged mooring grids to reduce the area required.

Although some offshore farms are manned full time with accommodation modules moored alongside production systems, most are not and must be automated to a degree with respect to monitoring, servicing and maintenance. Examples of equipment used to manage offshore systems include underwater vehicles for cage inspection, automatic feeders and feeding systems, sizing devices, monitoring systems for fish and cages and alarm systems. Size measurements of fish, including nose to fork length, width, girth, thickness and mass are useful in the planning of salmon farm management and recent advances in the technology of cage culture include the measurement of fish size using video techniques (Petrell *et al.*, 1997; Shieh and Petrell, 1998). These methods are generally less disruptive to fish populations than traditional dip netting methods and have been shown to be as effective. Feed usage, and particularly feed waste estimates, are vital to the efficient operation of the fish farm and methods have been developed for the detection of feed wastage in cages (see Section 4.10, Chapter 4). Fish weight can also be estimated automatically using a permanently installed frame where light beams are interrupted as fish pass through it (Heyerdahl, 1993).

3.5.2 Submersible sea cages

While cage design and component materials can protect the cage under some conditions the offshore environment can adversely affect the fish within cages. Fish may experience stress due to the physical disturbance and stop feeding during storms (Bugrov, 1996). In addition to the physical disturbance caused to fish by high waves, a decrease in volume of up to 80% is widely reported under high wave conditions, resulting in a poor environment (and increased effective stocking density) for the fish held within. A fixed cage volume is beneficial as it allows for consistent and predictable fish production; this can be provided using a taut netting system. Taut nets have the advantage that they do not cause the physical damage to fish that traditional nets do when they move. Many farms have used the underwater positioning of cages to avoid areas of high wave action completely, leading to the development of an array of submersible cages for fish production in offshore sites. Submersible cages are designed to eliminate the problems encountered near the water surface by being positioned below the area of wave action, and were first developed in Japan by Bridgestone for the production of yellowtail and red sea bream. These traditional floating structures were only submerged during storms and the fish were not fed during this period. Advantages of permanently submerged cages over traditional surface cages include reduced marine fouling and corrosion in deep waters (30–50 m). Stress on fish is also removed when cages are submerged due to reduced wave action and selection of optimal temperature zones (increased growth during cold winter surface temperatures). Stock may also be kept below the level of plankton blooms. Dahle and Oltedal (1990) provided a proposed design for a prototype offshore submersible cage for salmon farming.

3.5.2.1 Commercially-available offshore cages

Offshore cage fish engineering underwent considerable development in the 1990s in Europe and the USA. Some of the designs were optimal in engineering terms but economic advantage was removed by the complexity: commercial operation often represents a compromise. Some of the commercially-available designs are described below.

Ocean Spar Technologies (USA) designed a system capable of avoiding wave action completely rather than withstanding it. Their designs use an internal framework to maintain the shape of the net and hence the cage volume. The mainstay of the design is the floating spar buoy strong enough not to be affected by the waves; four of these buoys support a cubic net, keeping it taut even in very high currents. Such cages are normally limited in use to depths of less than 35 m and all servicing must be done from boats as there are no walkways.

This company went on to design the Ocean Spar^{R} Sea Station based around one central spar buoy. A circular steel ring is suspended from this buoy and radiating lines between the rim and the buoy provide tensioning for the netting. The vertical position of this cage can be altered using the specially designed ballast unit. Currents exceeding predetermined values cause the sea station to automatically sink below the wave action zone. The taut netting keeps the fish safe from predators and is easy to clean using mechanical cleaners. Such cages were introduced to the west coast of Ireland for offshore salmon production in 1999.

The first semi-submersible system was developed by Farmocean in Sweden during the 1980s. This was made up of a rigid reinforced steel framework and normally operated in a semi-submerged position. The framework is mounted on a ballast unit normally located 3 m below the surface of the water. Because the main ballast unit is located below the wave action the effect of rough weather conditions is minimised and cages can withstand waves up to 10 m. Feed storage is incorporated in the cage, reducing requirements for daily visits because fish can be fed even under conditions where boats cannot reach the cage.

The Tension Leg Cage was developed by Marintek in the early 1990s for rearing fish in waters where high wave action occurs (Midling *et al.*, 1998). This is the only gravity cage that retains its volume in high currents and also sinks automatically in high wave conditions. This design was based on research into wave kinematics in depth, drag and buoyancy forces and the flexibility of the pen. The cage design resulting from consideration of these factors is 'upside down' with the bottom part rigid and the top part flexible. Most of the buoyancy is located at the bottom part of the net pen where the wave forces are lower than encountered at the water surface (Rudi and Dragsund, 1993). The sides of the pen are stretched upwards from the base by a number of buoys.The cage is moored by six anchor lines that can stretch, without slackening, to allow for horizontal movement of the cage while not disturbing the vertical position of the cage base. This type of mooring system significantly reduces the sea bed area required to moor these cages compared to more conventional mooring systems. This cage can be submerged beneath the wave action when weather conditions are bad. The forces on this submerged construction are reduced because the wave velocities and accelerations are reduced and the displacement is constant. The mooring module consists of a submerged ring moored to the sea bed. A number of vertical anchor lines are used and no individual line goes slack at any time.

Research and technical improvements in cage design and operation in the salmon industry are ongoing. Myrseth (1993) reported that technological advances in fish cage design have led to cage systems that, although technologically brilliant, are too costly for application to commercial aquaculture. He pointed out that as the cage is the most important capital investment in farming fish at sea, improving sea cage design is the key to lowering production costs. The requirements of an open production system are summarised by Myrseth as follows:

- Price:
  affordable in relation to expected profitability and longevity
- Strength:
  certified for use on the site
  easy to check strength
  easy to repair
- Workability:
  control of fish and nets
  easy feeding, grading, harvesting and mortality removal
  easy predator control
  easy control/removal of fouling and changing of nets
- Biological requirements:
  vary from species to species
- Health and safety:
  fulfil the requirements set by the relevant authorities

3.6 HARVESTING

This is the final step in the rearing process and the objectives are to prepare fish for harvest, to kill them efficiently and to move them to the packing station as quickly as possible, whilst ensuring minimal stress, careful handling to avoid damage, and rapid chilling to maintain product quality.

Prior to slaughter the fish must be starved for an adequate period, to void the gut. The duration of starvation may vary (from about 7–20 days) depending on factors such as fish size and condition, water temperature, diet composition and feeding regime. Starvation of fish is important as it ensures that the gut is free of digestive enzymes and bacteria which can accelerate spoilage and cause tainting.

All structures coming into contact with fish should be of a material and construction that allow easy cleaning, i.e., food grade stainless steel and plastics. During slaughter every effort should be made to limit crowding and reduce stress. In practical terms, cages should be subdivided and a seine net used to remove batches for slaughter. Adverse conditions deplete energy reserves and affect the process of rigor mortis. Rough handling of fish is also likely to affect rigor as well as impacting on appearance and allowing entry of bacteria through damaged skin.

A number of different methods are employed to slaughter fish; common ones are a sharp blow to the cranium or anesthesia in carbon dioxide, both followed by bleeding of the fish through gill slitting. Bleeding is generally recognised as having a positive effect on post-harvest quality (see Chapter 5).

'Rigor mortis' or 'rigor' is the term applied to the overall stiffening of body muscle after death as a result of a complex cycle of biochemical processes associated with ATP depletion. Immediately after death, fish muscle is soft and limp and remains in this condition until rigor begins, anytime up to 20 hours after death. Rigor typically begins at the tail and spreads up the body towards the head. The fish may remain in rigor for several days, after which it reverts to the former limp state.

The onset, duration and intensity of rigor are dependent on many factors, but the most important are size of fish, health and nutritional status, degree of stress/exhaustion before death, and the temperature after death. For example, small, poorly-nourished fish, stressed before harvest and subjected to high temperatures after death, will enter and pass through rigor much more rapidly and with less intensity than large, well-fed fish, harvested without stress and rapidly chilled. Under ideal conditions, rigor in salmon may not commence until about 18 hours *post mortem*; however, if they are anaesthetised in CO_2-saturated water and bled, rigor may commence as early as four or five hours *post mortem*. It is therefore essential that every effort is made to handle the fish carefully and quickly, to chill them properly and to be able to pack them before the onset of rigor.

Prolonged, intense rigor is direct evidence that a fish has been handled and treated correctly and offers a certain guarantee of keeping quality. However, fish in rigor must be handled with extreme care in order to avoid quality problems. Rough handling when in rigor, and in particular the forcible straightening of bent fish when packing into boxes, results in the internal disruption of muscle. Such mistreatment leads to 'gaping' where the connective tissue between the muscle blocks has been damaged and results in their unsightly separation.

The single most important factor inhibiting bacterial growth in harvested fish is temperature. Therefore, when harvesting it is necessary to reduce the core temperature of fish below 5°C by the time they arrive at the packing station. In such cases, fish must be packed for transport in chilled seawater. Rapid cooling is also essential in order to delay the onset of rigor. Ideally, the temperature of fish should be cooled to just above the point at which they begin to freeze (0°C) as rapidly as possible after slaughter.

The core temperature of fish being held overnight should be reduced to between 0°C and 2°C and the fish should be held in a chilling facility maintained at this temperature. Salmon which are handled and cooled properly may have a shelf life of up to three weeks, whilst those which are subjected to higher temperatures in the hours after slaughter may be fit for human consumption for only a few days.

3.7 A FINAL COMMENT ON QUALITY ASSURANCE THROUGHOUT THE REARING CYCLE

In an era when all customers and consumers are keenly conscious of the produce they purchase and consume and, equally, of the environment in which they reside, it is paramount that they are aware of and can verify the quality of the salmon that is offered for sale. Adherence to a verifiable and transparent quality system is required by all participants in the rearing cycle and most salmon-producing countries, organisations and even individual farmers now have their own quality assurance schemes and all are keenly aware of the importance of quality. The key elements in any such scheme include:

- an agreed and documented system with clear responsibilities;
- written standards and detailed procedures;
- training and education for the entire workforce;
- involvement of personnel at all levels;
- measurement of performance;
- identification of non-conformance and correction through agreed actions;
- complete traceability of product through adequate documentation.

4

Fish farming and the feed companies

4.1 INTRODUCTION

The success of salmon farming has largely evolved from two key factors, both of which are essential before any fish species can be considered for cultivation:

- a complete knowledge of the life cycle of the Atlantic salmon (*Salmo salar* L.);
- developments in our understanding of fish nutrition.

With regard to the life cycle of Atlantic salmon: salmon eat to maintain their body functions but also to grow, mature and reproduce. The life cycle of a species can provide us with clues as to the way that its dietary requirements have evolved. The salmon starts life in freshwater, where it may spend up to six years if food availability is poor (Sedgwick, 1982). In fact, some Atlantic salmon stocks may spend their entire life in freshwater as landlocked strains but, more commonly, they migrate to the sea, before returning home to spawn. It is believed that Atlantic salmon have evolved this life strategy because generally food is more abundant in the ocean, compared to freshwater. By using the oceanic feeding grounds the immature salmon can soon build up stores of energy before returning to freshwater to spawn. The returning fish may then spend up to a year in freshwater, without feeding, before spawning takes place. This long fasting period is possible because the salmon is able to survive on the considerable energy reserves it has accumulated in its tissues.

It is the second key factor, which will be addressed in more detail in this chapter.

Advances in our understanding of fish nutrition have made possible the huge expansion in the cultivation of food species, such as rainbow trout (*Oncorhynchus mykiss*), sea bass (*Dicentrarchus labrax*), sea bream (*Sparus aurata*) and the Atlantic salmon. Fish nutrition is more than just an appreciation of the qualitative requirements of fishes, it also concerns their quantitative requirements. Fish nutrition is about feed and feeding.

The composition of feed for cultivated fish was initially based on the natural diet of the species. The first diets to be developed for farmed salmon followed this principle and consisted of crude pellets prepared from blocks of frozen or fresh fish. However, these 'wet fish' diets were bulky and often inconsistent in composition and freshness. They also carried the potential risk of introducing disease from wild fish stocks into farmed populations. The practice of feeding 'wet diets' to cultivated species, such as yellowtail (*Seriola quinqueradiata*) continues in some countries, such as Japan. Feed formulators responded to these concerns by developing special 'dry' diets for cultivated fish. Fish feed manufacturers were not slow to see the opportunities arising from the rapid growth of aquaculture and invested in dedicated production plants to ensure that feed supplies would keep pace with demand, so that by the late 1980s nearly all farmed salmon, for example, were fed on manufactured feed. These manufactured diets offered several important advantages over traditional sources of feed, being free from disease agents, less bulky, more physically stable in water and more consistent in formulation. They could also be manufactured as pellets across a broad range of sizes, making them suitable for all life stages of the farmed fish.

Although the rearing of juvenile salmon in freshwater for the restocking of rivers has been carried out for more than a hundred years, the farming of the Atlantic salmon, *Salmo salar*, did not begin in earnest until the mid 1970s. The global salmon feed manufacturing industry, which has naturally increased output in response to demand, is now producing more than one million tonnes of feed each year (Tacon, 1999). The growth potential for farmed salmon production is still enormous in Norway, Chile and Canada.

The complex life cycle of the Atlantic salmon has an influence on its qualitative and quantitative nutritional requirements. The salmon has evolved as an opportunistic feeder that can take advantage of feasts and endure famine. In times of plenty it 'captures' energy to provide for its metabolic requirements and stores any excess for future energy requirements and for its reproductive needs. Salmon have a number of fat depots in which to store this energy, the greatest of which is the mass of white muscle. Other major depots are found around the midgut of the body cavity and in the liver. The storage of special nutrients and energy enables the fish to function normally even when the food supply is interrupted.

The subject of fish nutrition is large and complex. This chapter deals with those facets of the subject that have the most relevance for salmon farmers. Knowledge of the fundamentals of the qualitative and quantitative nutritional requirements of the Atlantic salmon will assist the salmon farmer in the choice of diet. The influence of diet and feeding practices on fish quality and the environment will also be addressed.

There are several books dedicated to fish nutrition and a great many more reviews on the subject. Interested readers should consult Cowey *et al.*, 1985; Halver, 1989; Steffens, 1989; Wilson, 1991; Hara, 1992; and Jobling, 1994. Much of the following section addresses basic fish nutrition and is included because of its importance to understanding the principles of fish feed formulation.

4.2 DIETARY REQUIREMENTS OF ATLANTIC SALMON

Like all animals, fish must consume certain essential nutrient and energy sources for growth, reproduction and health. Nutritional deficiencies can lead to poor growth, disease and, eventually, death. Qualitative nutritional requirements and metabolic pathways are similar throughout the animal kingdom, but each species has its own characteristic quantitative requirements for amino acids, fatty acids, vitamins and minerals. These requirements vary with the life stage of the animal.

Nutrients are chemicals that are absorbed by the digestive tract, by the digestive glands and by the body wall. The body cells use nutrients for the synthesis of body constituents and for energy metabolism. The typical pattern of energy metabolism is the oxidative degradation of certain amino acids, lipids, carbohydrates and their derivatives. In common with other animals Atlantic salmon require a diet containing protein, lipid, vitamins and minerals. There is, however, no real requirement for carbohydrates as salmonids and most fish have a significant gluconeogenic capacity to synthesise this group of nutrients.

4.2.1 Protein

Food provides the fish with energy for the maintenance of bodily functions and activity. Once the energy requirements of the fish have been met then any excess can be utilised for growth. Fish can use proteins, carbohydrates and lipids as energy in order for growth to occur, and there is a definite requirement for dietary protein. This can be described as the minimum amount of protein needed to meet the amino acid requirements and to achieve maximum growth. In an early study, the minimum protein requirement for Atlantic salmon, as a proportion of the diet, was estimated to be 45% (Lall and Bishop, 1977). More recent work has shown that other factors, including the composition of the diet and its energy content, will influence the protein requirement at each life stage, so that the actual protein requirement may range from 35–55%. In general, the protein requirement of fish decreases with age. Cowey *et al.* (1985), Halver (1989), Wilson (1991) and NRC (1993) have reviewed this topic.

Proteins are found in every part and are involved in every function of an animal's body. The muscles, connective tissues, organs, glands, enzymes and hormones of salmon and other vertebrates are all made up of proteins. Proteins are composed of amino acids, which contain a fairly constant level of nitrogen (usually between 15–18%) and many also contain sulphur. These amino acids interlock with each other to form specific proteins used to construct the various body structures. Two amino acids linked together are known as dipeptides and three linked together are known as tripeptides. Polypeptides are a complex construction of many interlocking amino acids. Hormones such as glucagon and insulin, which control the fate of glucose and simple sugars, are polypeptides.

4.2.1.1 Amino acids

In order to comprehend modern feed formulation strategies it is important to understand that animals do not have a requirement for particular raw materials, but a requirement for specific nutrients. It does not matter to humans as omnivores, or to salmon as carnivores, in what package the essential nutrients are consumed as long as they are bioavailable and present in sufficient quantities.

Vertebrates thus have a requirement for amino acids, rather than protein. There are more than 20 amino acids and, although salmon can synthesise many of these, there are ten amino acids that it cannot synthesise and these have to be consumed in its diet. These are the essential amino acids (EAA): leucine, isoleucine, valine, threonine, phenylalanine, methionine, tryptophan, arginine, histidine and lysine. A continuous supply of amino acids must be made available in the diet to replace proteins that have been deaminated and eliminated by the fish and for the construction of new proteins required for the formation of new tissues, hormones, enzymes, etc. The requirement for amino acids in fish varies from species to species and is dependent on the age, life stage, growth rate, dietary composition and the environmental conditions in which the fish lives. During recent years the survival rate and general health of farmed salmon have improved, mainly as a result of the use of vaccines and improvements in fish husbandry standards. Healthy salmon have a higher growth potential and this, combined with the feeding of higher energy diets, has led to improved growth rates and feed conversion efficiencies on many salmon farms. Under such conditions the requirement for certain amino acids may increase and the feed manufacturer must build in a safety factor when formulating diets to take this into account. More research is needed to ascertain the requirements of salmon for specific amino acids, at different life stages, at different growth rates and under different environmental conditions. The same is true for other groups of nutrients such as vitamins and minerals.

The quantitative amino acid requirements of the various fish species have been reviewed (Wilson, 1989) and summarised in a National Research Council bulletin (NRC, 1993). However, despite the importance of Atlantic salmon as a food species, there is a relative paucity of data on its nutritional requirements when compared to the rainbow trout. This situation is being addressed and many papers on the subject are being generated from academic institutions in Scotland, Norway and Canada, in particular.

4.2.2 Energy

The energy required by fish is provided by the metabolic oxidation of carbohydrates, fats and amino acids. The energy consumed is used in a multitude of metabolic processes, and once this requirement has been met then the remaining energy may be used for growth or stored as fat. However, a proportion of the energy consumed is wasted in excretory products, via the intestine, kidney and gills, and as heat. The gross energy content of a diet depends on its chemical composition but it is only useful to the fish if it is digestible. The digestible energy of the diet is therefore dependent on the bioavailability of the energy in the diet. Proteins and lipids are highly available energy sources for fish but the value of carbohydrate is less to carnivorous species than to omnivorous species (Cho and Slinger, 1979).

4.2.3 Lipids

The term 'lipids' is used to describe a group of chemicals that are insoluble in water but soluble in organic solvents. Lipids provide animals with energy and essential fatty acids (EFA) and act as carriers of certain non-fat nutrients, such as the fat-soluble vitamins A, D, E and K. They also act as precursors for a number of biologically-active compounds, including various hormones, pigments and growth factors. There are simple lipids, which include the neutral fats (e.g., the triglycerides), compound lipids (e.g., the phospholipids) and derived lipids, which are the hydrolytic end-products of the other two groups. Like proteins and carbohydrates, lipids contain carbon, hydrogen and oxygen, but may also include molecules of nitrogen and phosphorus. The latter group includes the phospholipids, an important group of lipids in fish physiology. Phospholipids help to maintain the fluidity and integrity of cellular membranes, which is of particular relevance for cold-water species like the Atlantic salmon.

4.2.3.1 Essential fatty acids

Salmon, like all vertebrates, have a dietary requirement for certain essential polyunsaturated fatty acids (PUFAs). Marine fish require three long-chain polyunsaturated fatty acids for their normal growth and development: docosahexaenoic acid (DHA, 22:6*n*-3), eicosapentaenoic acid (EPA, 20:5*n*-3) and arachidonic acid (AA, 20:4*n*-6) (Sargent *et al.*, 1993, 1995, 1999). These help to maintain the structural and functional integrity of cell membranes and also act as precursors of eicosanoids, a group of highly biologically-active paracrine hormones. Eicosanoids are derived from AA and are produced in response to stressful situations. They influence the reproductive, circulatory, osmoregulatory and respiratory systems. The requirement for each of these EFAs is dependent, to some extent, on the dietary levels of the other two and should be considered in relative, as well as absolute, amounts (Sargent *et al.*, 1999).

In fish DHA and EPA are the predominant PUFAs of cell membranes and fish have a high requirement for *n*-3 HUFA. Highly unsaturated fatty acids (HUFA) constitute a group of PUFA, which is characterised by 20 or more carbon atoms and three or more double bonds. Fatty acids are usually numbered from the methyl terminal: three numbers are given in sequence, the first indicates the number of carbon atoms, the second follows a colon and gives the number of double bonds, the third is often designated as either (*n*-) or (*w*-) and refers to the number of carbon atoms between the methyl terminal and the first double bond. The natural diet of salmon parr includes freshwater crustaceans and insects, which generally have higher levels of 18:3*n*-3 and 18:2*n*-6 and decreased levels of 22:6*n*-3 (Bell *et al.*, 1998). There is some evidence that elevating levels of dietary AA, relative to DHA and EPA,

Table 4.1. Essential fatty acid (EFA) requirements of some marine fish.

Species	EFA	% of Diet	References
Marine turbot (*Scophtalmus maximus*)	*n*-3 HUFA	0.8	1
Red sea bream (*Chrysophrys major*)	20:5*n*-3 or *n*-3HUFA	0.5	2
	20:5*n*-3 22:6*n*-3	1.0	3
Gilthead sea bream (*Sparus aurata*)	*n*-3HUFA	0.9	4
Striped Jack (*Pseudocaranx dentex*)	22:6*n*-3	1.7	5

References: 1 Gatesoupe *et al.* (1977); 2 Yone (1978); 3 Takeuchi *et al.* (1990); 4 Kalegeropulos *et al.* (1992); 5 Takeuchi *et al.* (1992).
Adapted from Sargent *et al.* (1995).

could be advantageous to salmon during parr-smolt transformation and for osmoregulatory control in seawater (Sargent *et al.*, 1999).

Different species of fish have different EFA requirements and the same species may have different requirements at different life stages and under different environmental conditions. Table 4.1 shows the EFA requirements of several marine fish but the absolute requirements for Atlantic salmon have yet to be determined. There are few EFA deficiency symptoms reported for Atlantic salmon, but in a review of lipid nutritional pathology in farmed fish, it was reported that EFA deficiency produced symptoms which included reduced growth, evacuolated pyloric caeca tissue and an increased incidence of pancreas disease (Tacon, 1996).

4.2.3.2 Marine fish oils and human health

The HUFAs found in salmon, particularly DHA and EPA, are now widely acknowledged to play a significant role in the field of human health. Diets incorporating oily marine fish, such as those traditionally eaten by Inuits living in the Arctic circle, can reduce the tendency of blood to clot, thus reducing the risk of thrombosis and heart attacks (Committee on Medical Aspects of Food, 1994). Steffens (1997) reports on other beneficial effects that long chain *n*-3 polyunsaturated fatty acids may have in combating diseases, including nephritis, arthritis, cancer, asthma and skin diseases. The medical profession typically recommends that, as part of a healthy diet, people consume oily fish, such as mackerel, sardines and tuna, but farmed salmon offer a cheap and plentiful alternative to these species. There are indications that health benefits may extend to fish and it has been shown that Atlantic salmon fed diets with a low ratio of *n*-3 to *n*-6 PUFA may be less resistant to infection when compared to fish fed a high ratio of *n*-3 to *n*-6 diets (Thompson and Tatner, 1996).

It is well known that the fatty acid composition of the diet has a significant influence on the fatty acid composition of the fish (Watanabe, 1982; Henderson and

Table 4.2. Fatty acid compositions (wt %) of polar lipid from mullet (*Mugil cephalus*) fed diets containing different oils for 12 weeks.

Fatty acid	Fat free	Corn oil	Linseed oil	Fish oil
Saturates	32.6	28.2	30.2	29.5
18:1	17.6	13.7	16.4	19.0
18:2(*n*-9)	8.5	0.8	1.2	1.4
18:3(*n*-9)	4.6	0.5	0.2	1.3
18:2(*n*-6)	4.4	29.8	13.8	7.8
18:3(*n*-6)	0.3	2.7	0.5	0.4
18:3(*n*-3)	0.3	1.0	14.8	1.1
20:2(*n*-6)	0.0	1.9	1.1	0.5
20:3(*n*-6)	1.4	4.8	1.1	1.6
20:4(*n*-6)	1.6	1.0	2.7	1.5
20:5(*n*-3)	3.0	1.0	1.3	5.8
22:6(*n*-3)	8.5	4.8	5.0	10.6

Assembled from the data of Argyropoulou *et al.* (1992).
Adapted from Sargent *et al.* (1995).

Tocher, 1987; Sargent *et al.*, 1989; Waagbø *et al.*, 1991; Lie *et al.*, 1993). This has important implications on the use of plant oils in diets for farmed fish.

This influence of dietary fatty acid composition on the composition of salmon muscle is clearly demonstrated in an experiment where Atlantic salmon were fed diets supplemented with soybean oil, capelin oil and sardine oil respectively, in order to vary the dietary levels of *n*-3 polyunsaturated fatty acids (Waagbø *et al.* 1993). The fish were fed three dietary levels of *n*-3 PUFA at 1.0, 2.5 and 5.0% of the diets, each with two levels of vitamin E supplementation (0 and 300 mg alpha-tocopherol acetate kg^{-1} of diet). The results for the mean fatty acid composition of fresh fillets from these fish are shown in Table 4.2. The low *n*-3 fed groups were characterised by high contents of 18:2 *n*-6 and 18:3 *n*-3 and low *n*-3 PUFA in comparison to the medium and high *n*-3 groups. In the high *n*-3 group, the level of *n*-3 PUFA was significantly higher at 34.3% compared to only 12.9% in the low *n*-3 fed group. This experiment also demonstrated that the fillet content of alpha-tocopherol increased with increasing dietary alpha-tocopherol content and that the level of dietary alpha-tocopherol did not influence either the fatty acid composition or the lipid levels of the fillets.

Although the fatty acid composition of the salmon muscle does reflect the fatty acid composition of the diet, it has been shown that Atlantic salmon preferentially absorb PUFAs from highly unsaturated diets. They do this more efficiently than from the monounsaturated and saturated fatty acids, with the degree of absorption decreasing with increasing chain length (Johnsen *et al.*, 2000).

4.2.4 Carbohydrate

For energy, fish will first utilise protein, then lipid and then carbohydrate. Warm water species of fish can utilise much greater quantities of dietary carbohydrate than cold water and marine fish. Although no dietary requirement for carbohydrate has been demonstrated for fish, its inclusion in farmed fish diets to some extent spares protein and lipids as energy sources and as synthesisers of a number of biologically-important compounds usually derived from carbohydrates. The binding properties of carbohydrates are of great importance in feed formulations and, in addition, it is also the least expensive source of dietary energy. As salmon diets have become more energy dense, the proportion of carbohydrate used has generally decreased.

There are four groups of carbohydrates: the monosaccharides, disaccharides, trisaccharides and polysaccharides. The digestive enzymes produced by the pancreas and intestinal mucosa of fish break these down into monosaccharides that are then absorbed across the wall of the intestine. Carbohydrate can be used as an immediate source of energy or as an intermediate source when it is produced from glycogen stored in the liver and muscle. Carbohydrate can also be converted to fat and can therefore also provide a long-term energy source for the fish. The improvement in feed utilisation seen with increasing feed energy density may have been due in part to the displacement of starch in the diet as the dietary energy level increased. Increasing dietary starch levels beyond $100\,g\,kg^{-1}$ has been found to have a negative effect on feed utilisation in Atlantic salmon (Asknes, 1995; Hemre *et al.*, 1995a).

During the harvesting of salmon, poor husbandry practices, such as the prolonged crowding of fish or the inefficient use of anaesthetics, can cause acute stress to the fish. They may thrash about, burning up glycogen stored in the muscle, which is then converted to lactic acid. The effect of this can be to shorten the period before rigor sets in. Flesh quality problems, such as an increased incidence of gaping and shortening of fillet length, can occur if fish are handled during rigor (Love, 1980). However, the amount of glycogen deposited in the muscle has been found to be little influenced by the dietary starch level (Hemre *et al.*, 1995b).

4.2.5 Fibre

The fibre present in fish diets is derived from cereals and plant protein. Fish lack the enzymes for degradation of fibre, and in its untreated form fibre is regarded as an almost indigestible raw material for salmon diets. To optimise nutrient uptake and to limit the amount of waste product entering the environment, it is important to formulate diets with highly-digestible feed ingredients and to restrict the fibre content. In the future it may be possible to improve the digestibility of fibre in feed by use of enzymes.

4.2.6 Minerals

Less is known about the dietary requirement of fish for minerals compared to some other nutrients. Studies have been carried out on the effects of various mineral deficiencies and on the toxic effects of certain minerals, but our knowledge of this subject remains incomplete. Fish not only absorb minerals from their diet but also directly from the water in which they swim (Lall, 1989). The design of experiments to quantify the mineral requirements of fish must take this into account.

Minerals are incorporated into the skeleton of fish and are found in organic compounds such as proteins and lipids. They also act as cofactors in enzyme pathways and have a variety of functions as soluble salts in the circulating fluids of fish. In addition, they play an important role in maintaining the osmoregulatory status of fish. Minerals can be absorbed across the gills and intestinal mucosa. In seawater, where the osmotic concentration of the salmon is lower than the surrounding water, soluble minerals will tend to diffuse into the fish. Osmoregulatory processes of the fish counteract this process, so that any excess minerals are excreted by way of the kidney and gills. In freshwater the quantity and range of minerals are less available and the salmon actively absorbs minerals from the surrounding water using its gills, and then conserves these by actively reabsorbing them from the kidney tubules to prevent their excretion. A comprehensive review of the importance of trace minerals as essential ingredients in fish diets can be found in Watanabe *et al.* (1997).

The raw materials used in fish feed manufacture typically contain an excess of essential minerals. The bioavailability of minerals may be reduced as a result of their binding with other nutrients; this can lead to reduced growth, poor feed conversion and other symptoms of mineral deficiency. The use of high ash fishmeal in salmon diets, for example, may affect zinc absorption and utilisation, which can result in lens cataracts (Ketola, 1979). Minerals form an inexpensive component of salmon diets and it is usual for fish feed manufacturers to supplement diets with essential minerals to the required level. The phytate present in plant proteins can interact directly and indirectly with minerals, to reduce their availability in animals. For example, the addition of sodium phytate to the feed of juvenile Chinook salmon reduced the bioavailability of zinc, to the extent that the fish developed cataracts (Richardson *et al.*, 1985).

4.2.6.1 Mineral deficiencies

Most essential minerals are absorbed from ambient water or found in the raw materials used in fish feed. However, there remains an ever-present risk that factors such as an unforeseen interaction between feed ingredients, improved growth rates or a change in environmental conditions may alter the bioavailability or lead to an increased requirement for a particular mineral. Certain minerals, including copper, zinc, selenium and iron, are essential in small amounts but are toxic at higher levels. The minerals may also interact and, for example, excess copper may compromise zinc uptake.

There are several excellent reviews on the role of minerals in fish nutrition (NRC, 1993; Watanabe *et al.*, 1997; Hardy, 1998).

4.2.7 Vitamins

Vitamins comprise a complex group of organic compounds vital for growth, maintenance, health and reproduction of the fish. Dietary requirements for vitamins are dependent on various factors, including the species and life stage of the fish. The feed formulator must also take into account the composition of the diet and the growth rate of the fish, which will also influence the vitamin requirement. Salmon may have increased requirements for vitamins at times of stress, during disease and treatment and under adverse environmental conditions.

Fish require 11 water-soluble vitamins, of which eight—the vitamin B complex—have mainly coenzyme functions and are required in relatively small amounts. The other three—choline, inisitol and ascorbic acid (vitamin C)—are required in greater quantities. Feeding water-soluble vitamins in excess of the dietary requirement is not normally problematic, but feeding the essential fat-soluble vitamins A, D, E and K to excess can result in toxic effects. During fish feed manufacture vitamins can be vulnerable to the combined effects of pressure, heat and moisture encountered during the extrusion process, as well as by interactions with trace minerals. Feeding diets deficient in one or more vitamins can result in characteristic symptoms or produce a range of non-specific symptoms. One of the earliest and best-known examples of vitamin deficiency in fish was the finding that lordosis and scoliosis, both symptomatic spinal deformities, could be induced in juvenile coho salmon by feeding them a diet deficient in vitamin C (Halver *et al.*, 1969). This particular vitamin is highly labile, and for many years much of the vitamin C added to fish feed was lost during manufacture. In recent years, however, feed manufacturers have used an ascorbyl phosphate source of vitamin C that is relatively stable during feed manufacture and, in addition, is also bioavailable to fish. Further, significant losses of some vitamins will occur during prolonged storage of the finished feed. Some vitamins are also sensitive to light and whenever possible, fish feed should be stored under dry, dark and cool conditions.

There is very little information on the vitamin content of fish feed ingredients (NRC, 1993). The vitamins present in feed raw materials may vary in vitamin content and bioavailability, and for this reason feed formulators may ignore vitamins present in the dietary raw materials and supplement to the required level. Some of these vitamins are relatively expensive, but feed is formulated with a margin of safety with regard to vital nutrients. In addition, the requirements quoted by vitamin suppliers are often higher than those published in nutritional reviews. There are minimum requirements for survival and higher requirements for optimum growth. Salmon feeds are formulated to supply fish with their vitamin requirements at different life stages. Extra vitamin C and E is sometimes added to diets to counter stress, to improve disease resistance and to improve carcass quality. Under temperate environmental conditions the shelf life of feed is normally declared as between three and six months.

Some of the few known minimum vitamin requirements of Atlantic salmon are shown in Table 4.3. A number of reviews describe the various deficiency symptoms associated with particular vitamins (NRC, 1993). Vitamin–vitamin interactions are thought to occur, an example being the interaction between the folic acid and cyanocobalamin, which may partially substitute for each other in some metabolic functions. There are also reports of vitamin-mineral interactions in which the

Table 4.3. Vitamin requirements for Atlantic salmon.

Vitamin	Requirement (units/kg diet)	Reference
Vitamin E	35 mg	Lall *et al.* (1988)
Vitamin B_6	5 mg	Lall *et al.* (1990)
Vitamin C	50 mg	Lall *et al.* (1990)

deficiency of a particular vitamin may lead to disturbances in mineral metabolism (Jobling, 1994).

It is important to emphasise that the Atlantic salmon's requirements for all essential nutrients are not known. Those nutrient requirements that have been researched should be subjected to regular review, since changes in dietary composition and further improvements in feed conversion efficiencies and growth rates may well lead to an increased requirement for specific essential nutrients.

4.3 RAW MATERIALS AND FEED FORMULATION

Having discussed the dietary requirements of the Atlantic salmon it is important to address which raw materials are suitable and available as ingredients for salmon feed. The selection of raw materials depends on the dietary requirements of the salmon, the life stage, raw material cost and availability, public acceptability and government legislation. Raw materials can be characterised by their palatability, digestibility and bioavailability. The two main nutrients used in salmon diets are protein and lipid.

4.3.1 Protein sources

Protein represents the largest component of salmon feed, but there is great heterogeneity in the nutritional and biological values of different sources of protein. The biological value of a protein varies with its AA composition and digestibility (Anderson *et al.*, 1995). Fish, soya and maize meals presently provide the major sources of protein used in salmon diets.

4.3.1.1 Fishmeal

The fishmeals used in salmon feed are predominantly produced in South America and Northern Europe. The highest-quality fishmeal is produced from whole fresh fish and represents the finest source of protein for farmed salmon. Fishmeal provides a valuable source of energy, EFAs and minerals. The composition of fishmeal from a particular source is not fixed. During the fishing season the main species caught for processing into fishmeal may alter and the carcass composition of each species may also change throughout the season. The proximate composition (moisture, oil,

Table 4.4. Proximate analysis of various fishmeals.

	Norse-LT94®	Herring meal 1	Herring meal 2	Herring meal 3	Menhaden meal	Anchovy meal
Dry matter (%)	91.6[b]	97.3[a]	96.4[a]	95.4[a]	96.2[a]	89.6[b]
Protein (%)	80.6[b]	83.7[a]	79.5[b]	77.8[b]	67.7[c]	70.4[c]
Lipid (%)	11.1[a]	8.6[b]	10.2[a]	12.8[c]	10.7[a]	11.4[a]
Ash (%)	13.1[a]	11.0[a]	11.6[a]	13.1[a]	21.5[b]	17.5[c]
Gross energy (MJ/kg)	21.9[a]	22.9[a]	22.4[a]	22.5[a]	20.2[a]	21.3[a]

The protein quality evaluation of these fishmeals is presented in Anderson *et al.*, 1995. [a] Expressed as a percentage of the fish meal (as-received). [b] Expressed as percentage of the dry matter *a-d*. Means ($n = 2$) within a row, sharing the same postscript, are not significantly different ($P > 0.05$).
From Anderson *et al.* (1995).

protein and ash (MOPA)) of several fishmeals is shown in Table 4.4. Fishmeal has an AA profile that satisfies most of the salmon's requirements for essential amino acids. In broad terms, most fish have a similar AA profile, but there are subtle and important differences between species and these are reflected in the AA composition of individual types of fishmeal. Since fishmeals vary in AA content, both the fishmeal purchaser and the feed formulator must consider carefully whether their choice of fishmeal or blend of fishmeal meets the specific requirements for EAAs at each particular life stage. Table 4.5, shows the AA profiles of several different types of fishmeal. It is also important that the feed formulator is familiar with the AA digestibility values for feed ingredients. For a range of fishmeal used in salmon diets in Atlantic Canada, it was found that crude protein digestibility values ranged from 78.2–87.0% (Anderson *et al.*, 1995). There remains a scarcity of information on the AA requirements of Atlantic salmon (Higgs *et al.*, 1983), although the requirements for lysine and arginine have now been investigated (Berge *et al.*, 1997, 1998). The *in vitro* absorption of methionine from different parts of the intestine of Atlantic salmon has also been investigated (Olsen, 1998.).

In order to achieve the optimum performance from salmon diets, it is necessary to know the salmon's requirement for each EAA at each life stage and under a range of environmental conditions. If the AA composition of all available raw material protein sources is known, then the formulator can fine-tune the blend of proteins to produce the optimum dietary protein in terms of growth potential and cost.

4.3.1.1.1 Fishmeal production

As mentioned above, the highest-quality fishmeal is derived from whole fish. Fish remnants from fish processing plants are also used as raw materials for fishmeal production, but these generally have a lower proportion of good-quality protein and are higher in ash than meal from whole fish. If the fish used in fishmeal is not fresh, spoilage bacteria can produce harmful toxins, such as histamine, in the meal.

Table 4.5. Amino acid composition of fishmeals.

	Norse-LT94®	Herring meal 1	Herring meal 2	Herring meal 3	Menhaden meal	Anchovy meal
Amino acid						
Ala	5.00	5.26	5.32	4.74	4.11	4.88
Arg	5.55	6.23	6.16	5.03	4.99	4.56
Asp	9.10	8.98	10.23	8.01	8.50	8.40
Cys	0.50[a]	0.21[b]	0.51[a]	0.47[a]	0.63[c]	0.12[d]
Glu	9.39	9.97	10.32	8.63	7.52	8.29
Gly	5.57	5.10	5.43	5.06	5.49	4.91
His	1.74	1.86	1.92	1.55	1.46	1.86
He	4.04	4.13	4.41	3.51	3.62	3.95
Leu	6.68	7.30	7.33	6.04	5.61	6.28
Lys	6.94[b]	6.42[ab]	7.66[b]	5.81[a]	6.12[a]	6.15[a]
Met	2.43	2.65	2.57	2.14	2.35	2.13
Phe	3.42	3.61	3.72	3.03	2.93	3.35
Pro	4.02	4.00	4.66	4.41	4.45	3.67
Ser	3.14	3.49	3.33	3.16	3.19	2.67
Thr	2.65	3.00	3.28	2.87	3.20	2.78
Trp	0.75[a]	0.79[a]	0.80[a]	1.18[b]	0.43[c]	0.26[d]
Tyr	2.52	2.94	3.11	2.38	2.44	2.46
Val	4.38	4.80	4.85	3.99	4.25	4.11

The protein quality evaluation of these fishmeals is presented in Anderson *et al.* (1995). [a]Expressed as a percentage of the dry matter *a–d*. Means ($n = 2$) within a row, without or sharing the same postscript, are not significantly different ($P > 0.05$). From Anderson *et al.*, 1995.

The traditional manufacture of fishmeal involves processing the fish at temperatures of 70–90°C, after which the meal is pressed, the oil separated and the resulting meal dried. An improved method is used to produce low temperature (LT) fishmeal for aquaculture products, in which the fish are processed at a temperature some 20–30°C lower. This results in an improved separation of the oil and water fractions, enhancing the quality of the meal. The temperature at which the fishmeal is dried must be carefully controlled, as excess heat will damage a number of important nutrients. Antioxidants protect against oxidative damage and are added to both fishmeal and fish oil following processing. Fish feed manufacturers will normally carry out regular quality assurance audits at factories supplying fishmeal and fish oils.

4.3.1.2 Meat and poultry meals

The animal processing industry produces a number of by-products, such as meat and bonemeal and poultry meals, which can be used in salmon diets. These products generally contain 45–55% crude proteins, but may also be high in ash. Another useful byproduct, bloodmeal, is a valuable source of certain AAs and also assists in the binding process. The interested reader may wish to consult Bureau *et al.* (1999) who investigated the apparent digestibility of 20 rendered animal protein ingredients from various origins in rainbow trout.

Although meat and poultry meals can undoubtedly provide effective ingredients for farmed fish feeds their use has been called into question in a number of countries. In the United Kingdom, for example, the outbreak of Bovine Spongiform Encephalitis (BSE) in British cattle led to restrictions on the use of animal byproducts in animal feeds. BSE in cattle was officially declared a disease in November 1986, and in July 1988 the feeding of ruminant-derived meat and bonemeal to ruminants was banned in the UK. This followed public concern over the risk to human health from eating food derived from BSE infected carcasses. The major food retailers in the UK also demanded that land-animal products were withdrawn from salmon and trout diets. This included bovine, ovine and poultry products. Up to the time of writing there is no evidence that fish can pass on the causative agent of BSE, but public health concerns dictate the agenda on such issues. The spread of BSE to countries such as France, Spain and Germany led to the EU imposing a six-month temporary ban, from 1 January 2001, on the use of any animal protein, except fishmeal, in livestock diets. Chandler (1998) reported on the results of trials designed to mimic a range of processing conditions used in the rendering industry. This research demonstrated that pressure cooking at 133°C for 20 minutes at three-bar pressure successfully deactivated the BSE agent in infected fat and protein meals.

There is a strong principle that one species should not be fed to the same species and therefore material derived from salmon should not be fed to farmed salmon. It is important to note, however, that salmon are carnivores and in no way does the feeding of other fish species to salmon equate with the feeding of animal protein to herbivores.

4.3.2 Alternative protein sources

Fish feed manufacturers now typically use a variety of protein sources, which helps to buffer the costs of raw material in the feed. These sources include fishmeal and fish protein concentrate, soya meal, poultry meal, meat and bonemeal and bloodmeal. Protein from fishmeal is a costly component of salmon diets and the potential for substitution of animal proteins with plant proteins is of great interest to fish farmers and feed manufacturers alike. A number of researchers have shown that at least 25–30% of the fish or animal protein can be replaced with plant protein in rainbow trout feeds, without significant negative effects on the growth, feed conversion efficiency, carcass quality and health of the fish (Smith *et al.*, 1988; Dabrowski *et al.*, 1989; Rumsey *et al.*, 1993; Refstie *et al.*, 1997).

There are fewer studies on Atlantic salmon, but the replacement of fishmeal protein with vegetable proteins in feed for Atlantic salmon has been investigated by a number of researchers (Hardy, 1982, 1995, 1996; Arnesen *et al.*, 1989; Carter *et al.*, 1994; Olli *et al.*, 1994a, b, 1995; Koppe, 1996; Refstie *et al.*, 1998). The main candidates investigated for fishmeal replacement have been derived from the soybean. (Olli *et al.*, 1995).

When investigating the inclusion of four different soybean products at five different inclusion levels (0–56% of protein) in Atlantic salmon diets (600 g fish) it was found that a soybean concentrate gave the best results and could make up to 56% of the dietary protein without effect on weight gain (Olli *et al.*, 1994b). The level to which fishmeal may be replaced without affecting weight gain appears to be highly influenced by the soybean product used. In the same study, dehulled and solvent-extracted, solvent-extracted only and full fat soybean meals did not have a negative effect on fish weight gain when incorporated at up to 14% protein replacement, but only full fat soya and soya concentrate maintained weight gain at 28% protein replacement.

More recently, Carter and Hauler (2000) investigated the replacement of fishmeal protein with soybean meal and with protein concentrates made from narrow-leafed lupin or field peas in extruded feeds for Atlantic salmon parr. The study indicated that extruded salmon feed containing up to 27% pea protein concentrate (49% crude protein) or 22% lupin protein concentrate (46% crude protein) had no significant effect on the growth performance of Atlantic salmon parr, when compared to fishmeal and solvent-extracted soybean meal.

The AA profile of the carcass of the Atlantic salmon is typical of the species and fixed. Providing the diet contains the right mix and quantity of bioavailable AAs, the inclusion of plant protein will not affect the protein composition of the carcass. AAs, at a concentration above the level required for the maintenance and growth of tissues, will be used to provide the energy required for movement, respiration and osmoregulation and any further excess will be converted to storage fats. AAs eventually break down into carbon dioxide, water and ammonia. Ammonia is the predominant excretory product of protein catabolism and is actively excreted across the gill epithelium into the surrounding water. Smith (1971) found that about 80% of non-faecal waste nitrogen was excreted as ammonia through the gills.

The use of non-fishmeal sources of protein, particularly when making up a high proportion of the protein in salmon diets, may necessitate the use of AA supplements to match the AA requirements of the fish. In a study on rainbow trout, where solvent-extracted soybean meal replaced 66% of the protein source, the replacement diet was found to be inferior to a fishmeal-based reference diet. Supplementation of the soybean diet with crystalline AAs, methionine and methionine plus lysine (at two levels), did not result in these diets achieving the same level of performance as the fishmeal-only diet, in terms of growth, feed efficiency and protein utilisation. A further diet containing a supplement made up of methionine, lysine, tryptophan, threonine, arginine, and histidine outperformed the methionine-only and dual-supplemented diets, but did not achieve the performance of the fishmeal-only diet (Davies and Morris, 1997).

Having ascertained that vegetable proteins can successfully substitute a proportion of the fishmeal it is relevant to consider other aspects of their use as raw materials for fish feeds.

4.3.2.1 Vegetable protein

Fishmeal and fish oils are finite resources. Fish feed manufacturers and environmentalists are, quite naturally, concerned about the long-term sustainability of the fishmeal producing fisheries. The rich fishing grounds of Peru and Chile, in South America, provide much of the fishmeal used by salmon-farming countries. In 1995 Peru exported almost 1.9 million tonnes of fishmeal and Chile 1.3 million tonnes of fishmeal, almost 86% of World exports (source IFOMA). During the cyclical phenomenon of El Niño, which may occur every five to seven years, warm surface waters prevent cold water currents that contain an abundant food supply reaching the surface. The warm surface water contains few nutrients and local fish stocks must starve or migrate to areas where food is more abundant. The Peruvian and Chilean authorities are careful to ban fishing during these periods until more typical conditions are restored. This results in a significant reduction in fishmeal production from these areas during these periods. Fish feed manufacturers and fish farmers alike feel the repercussions of this in terms of higher prices for fishmeal and fish feeds. Although fishmeal is also available from areas such as the North Atlantic fisheries of Iceland, Denmark, Norway and the Canary Isles, its price moves quickly upward when supplies become limited. If the farming of 'carnivorous' fish such as salmon is to have a long-term future then alternative sources of protein must be found. Plants are the most plentiful source of protein on the planet and are the logical replacement for fishmeal, provided the AA requirements of farmed fish can be met. Following intensive research on the use of plant proteins, as outlined above, it is now a common formulating strategy to replace some of the fishmeal in salmon diets with plant proteins.

Salmon diets now routinely contain 10–25% of their protein from plants. However, although vegetable protein sources are less costly than fishmeal, they generally contain only 40% of protein, compared to 70% in fishmeal. Concentrates and isolates of plant proteins can be used to reduce the larger volume otherwise taken up by plant proteins. In order to provide all EAAs for salmon it may be necessary to supplement diets containing plant protein with synthetic AAs such as methionine and lysine (see above). Synthetic forms of the AAs tryptophan and threonine are also available as feed ingredients, but are presently considered too costly and are not yet routinely used in salmon diets. However, synthetic AAs may not be a straightforward replacement for 'natural' protein-bound AAs. The total intake of AAs is important but the timing of delivery of specific AAs to the tissue may also be a critical factor. Synthetic AAs may be transported at different rates compared to AAs from intact proteins (Schuhmacher *et al.*, 1997).

The predominant plant protein sources for salmon feeds are soya meals and maize gluten, with rape and sunflower meals being used to a lesser extent. Plant protein may contain substances toxic to fish, which are collectively known as anti-nutritional factors (ANFs). These ANFs may include phenolic compounds, phytic acid, glucosinolates and a number of indigestible carbohydrates. The reader may come across the term 'canola', which is the registered name given to genetically-selected varieties of the *Brassica napus* and *Brassica campestris* species that are low in both glucosinolates or antithyroid factors and erucic acid. It is therefore important to heat-treat and process these meals to ensure these ANFs are removed or minimised.

However, not all toxins are destroyed by heat, and moulds growing on plant raw materials can produce heat-resistant mycotoxins, such as the dangerous aflatoxins. Aflatoxins are the toxic metabolites of the common blue-green mould, *Aspergillis flavus* and were once responsible for a worldwide epizootic of rainbow trout hepatoma (Halver, 1965).

The potential for the enzyme phytase to improve the nutritive value of canola protein concentrate has been investigated in rainbow trout (Forster *et al.*, 1999). The authors replaced anchovy meal in the control diet, where it made up 89% of the dietary protein, with canola protein concentrate (CPC) to make up 59% of the dietary protein. They found that the trial diets gave results in terms of growth rates, protein utilisation and feed efficiency comparable to the control diet in which anchovy meal made up 89% of the protein. They also found that there was a clear positive dose-response of phytase on dietary phytate digestibility and that at the higher level of phytase addition the availability of dietary phosphorus was significantly improved.

4.3.2.2 Protein concentrates

Rapeseed/canola protein concentrates typically contain more than 60% protein. The digestibility of this protein has been shown to be higher at around 96% than is found in most fishmeals (Higgs *et al.*, 1996). These concentrates are low in ANFs, with the exception of phytic acid which may be present in levels of 5.3–7.5% (Higgs *et al.*, 1995). High dietary levels of phytic acid may complex with proteins and divalent ions, particularly zinc, in the acid conditions found in the fish intestine decreasing their bioavailability.This can lead to depression of growth, feed and protein utilisation, thyroid function and in anomalies in the structure of the pyloric caecal region of the gut (Richardson *et al.*, 1985).

4.3.2.3 Soya proteins

The use of soya-derived meals in salmon diets has become commonplace. Soya bean meal has one of the most suitable plant AA profiles for fishmeal substitution. The growing importance of soya meals as a protein source for salmon merits giving this raw material further mention. The cultivation of soya beans began more than 4000 years ago in China, but it was not until early in the 1900s that they were introduced to the United States. Early interest centred on the bean's oil, but soya protein was soon found to be an excellent AA source for livestock, once it had been toasted to reduce ANFs and to improve digestibility. Food-grade soya protein isolates were developed in the 1950s and then, approximately ten years later, improvements in extrusion technology led to the development of textured soya flours. The first soya protein concentrates were introduced in the 1970s and further developed in the 1980s. The raw, dehulled beans are approximately 38% protein and 18% oil.

4.3.2.3.1 Soya bean processing

Soya beans are processed to varying degrees; meals may be derived from crushed whole beans, crushed dehulled beans, pressed meals or solvent extracted meals. Provided they have been heat-treated, all of these meals can be considered as raw materials for salmon diets. Pressed and solvent-extracted meals have most of the soya oil removed. For production into meals for further processing, soya beans are first cleaned, then cracked and dehulled. The oil is extracted from the meal using a solvent, which is removed before the meal is dried. These soya meals can then be processed into a range of soya products, used in both human foods and animal feeds. Toasting of soya beans markedly reduces, but does not eliminate ANFs such as trypsin inhibitor and urease, and does not significantly reduce its antigenic properties. Soya-bean concentrates, containing approximately 65–70% protein, have now been developed by removal of complex carbohydrates. This process significantly reduces ANFs and the antigenic properties of the product, making the concentrates more suitable for use in aquaculture feeds for juvenile fish.

4.3.2.4 Maize gluten

Maize gluten, produced as a byproduct when starch is extracted from maize, is a highly-digestible source of protein (>60%) which is used, in moderate amounts, to replace fishmeal in salmon diets.

4.3.2.5 Other plant meals

A number of other plant meals, such as cottonseed, groundnut and rapeseed, have been considered for use in salmon and trout diets. Of these, rapeseed-derived meals have been tested with some success (Higgs *et al.*, 1983). Global supplies of rapeseed protein exceed those of fishmeal (Higgs *et al.*, 1996) and can provide a very cost-effective alternative to the use of fishmeal on a per kilogram protein basis. CPC contains more than 60% protein: the digestibility to salmonids is higher, at around 96%, than for most fishmeals (Higgs *et al.*, 1996). The levels of phytic acid within CPC can be higher than in the meal and can be problematic as it has the potential to reduce the bioavailability of protein to fish. The enzyme, phytase, has been used in several animal species to dephosphorylate phytic acid (dephytinization) to enhance the nutritive value of CPC (Nelson *et al.*, 1971; Prendergast *et al.*, 1994; Rodehutscord and Pfeffer, 1995; Forster *et al.*, 1999).

4.3.2.6 Genetically-modified crops

The use of fishmeal from 'sustainable' fisheries and the increasing use of plant protein in salmon diets may help to improve the public's perception of salmon farming. The world's major fisheries are currently protected from short-term exploitation, and this must continue so that future generations can also benefit from their continued existence. However, the replacement of animal proteins with plant proteins in aquaculture diets has been complicated by the sudden introduction of genetically-modified (GM) crops into sensitive markets. In the late 1990s, it became both difficult and expensive to obtain supplies of guaranteed genetically-unmodified soya, because the North American producers and suppliers of soya bean meal did not segregate GM soya meal from unmodified soya meal. The use of GM soya in processed human food, particularly in vegetarian diets, contributed to a backlash of public opinion in the UK and other European countries, which resulted in several of the major retailers blacklisting all food products containing GM soya. Other GM crops, such as maize and wheat, are now also produced on a global scale. Although the production of GM plant proteins offers some advantages to the farmer, in terms of decreased production costs, some of the larger North American producers have switched a proportion of their crops back to traditional production methods in order to satisfy European demand.

4.3.3 Fish oils

Fish oils are global commodities. They are produced when 'non food' fish and fish waste are processed into fishmeal. The lipid content of commercially-fished species is dependent on factors such as season, food abundance and sexual status. Capelin, *Mallotus villosus*, may contain more than 14% lipid in summer and less than 9% in winter. Fish oils contain high levels of PUFAs and must be protected against oxidation. Methods of detecting and quantifying the extent of oxidation in fish oil involve measuring oxidative breakdown products, such as aldehydes and peroxides. Peroxides are usually measured using the peroxide value method (POV) and aldehydes by anisidine or thiobarbaturic acid reactive compound (TBARs) values. When buying fish oils it is usual to specify a range of values for free fatty acid content (2–5%), peroxide values (3–20 $Meq\,kg^{-1}$), anisidine number (4–60), moisture and impurities (0.5–1.0%), iron (0.5–7.0 $mg\,kg^{-1}$) and iodine content. Figures for typical values found in fish oils, in parentheses, are taken from Bimbo, 1990.

Human activities are now believed to affect the climate on a global scale and may be responsible for the apparent trend in rising temperatures. There are also more insidious effects and it is now apparent that some of the toxic byproducts of industry, such as heavy metals, PCBs and dioxins, are present in the food chain. As a result, some of these toxins can accumulate, albeit in minute proportions, in the lipids of fish used to provide fishmeal for aquaculture and therefore have the potential to pass into farmed fish. Fortunately, the fish feed manufacturer is able to control the levels of such undesirable substances by sourcing fishmeal from areas that remain less affected by industry and by the judicial substitution of a proportion of fishmeal and fish oil with raw materials from vegetable origins. It is also possible to filter a variety of environmental contaminants from fish oil.

4.3.4 Plant oils

The supply of fish oil is finite and is unlikely to rise much above the average levels of 1.3 million tonnes per annum produced over the past decade (source: *Oil World*). In addition the aquaculture feed industry must compete with other users of this precious commodity, such as biscuit and margarine manufacturers. However, the world production of plant oils dwarfs fish oil production with over 100 million tonnes of plant oils produced in 1997 alone (source: *Oil World*). Plants from which oil is extracted include soya, cotton, groundnut, sunflower, rape and palm. Fish have no requirement for a particular type of oil, but they do have a requirement for dietary energy and for specific EFAs. The influence of dietary fatty acids on carcass composition has already been discussed (Section 4.2.3).

4.3.4.1 Substitution of fish oil with plant oils

In 1998, global fish oil prices increased, to the extent that some salmon feed producers included a proportion of vegetable oils in salmon diets. The substitution of marine fish oils with vegetable oils and tallow in farmed salmon diets had previously been investigated (Hardy *et al.*, 1987). In order to further clarify the potential for alternative sources of dietary oils for farmed salmon, Nutreco Aquaculture Research Centre (ARC) and Akvaforsk in Norway have researched the potential of certain vegetable oils as partial replacements for fish oils (Rosenlund *et al.*, 2001). In the trial, Atlantic salmon were fed diets supplemented with three sources of fish oil, three vegetable oils, or combinations of the plant and fish oils. The trial examined the effect of feeding the different oils at 7°C for a period of 90 days and at 13°C for 42 days. The results showed that there was a clear correlation between the lipid composition of the diet and the triglyceride fraction of the fish muscle. As the proportion of vegetable oil in diet increased, the amount of fish oil-related monoenes in the fish muscle decreased. In contrast the amount of EPA and DHA in the muscle was only slightly reduced, indicating that the physiology of the salmon includes mechanisms that can control the levels of these important fatty acids. The results of this screening study showed that at least half of the fish oil added to high-energy salmon diets could be replaced by alternative plant lipid sources without sacrificing growth, feed conversion and survival. The researchers also found that a 100 g portion of farmed salmon would be enough to provide the recommended daily intake of EPA and DHA, even with partial substitution of fish oil with plant oils in salmon diets.

In a subsequent trial carried out by Trouw Aquaculture, up to 50% of the marine fish oil was substituted with a vegetable oil and fed to salmon over a four-month period. The fish grew from 3 to 4.5 kg over the trial period and growth and FCRs were comparable to control fish fed fish oil only diets. Independent testing, using a panel of trained evaluators, found no significant effects on various critical carcass quality parameters such as taste, texture or succulence. Neither were any negative effects reported from a number of fish processors who cold-smoked samples of the trial fish (unpublished data).

A study by a UK animal feed producer found that the replacement of half the fish oil in rainbow trout diets with two types of vegetable oil had no significant effect on growth, feed conversion and survival. The study also found that, while members of a sensory evaluation panel could discriminate between two of the plant oils used, none of the fish grown on the different oils were unacceptable. In an American study

(Skonberg *et al.*, 1993) herring oil was replaced by sunflower oil (12.4% of the diet by weight) in diets for coho salmon (*Oncorhynchus kisutch*) and rainbow trout. In the sensory assessment a significant number of panellists were able to differentiate between the fillets from the herring oil-fed fish and the sunflower oil-fed fish by the fishier aroma emanating from the former. The panellists, however, tended to prefer the fillets from the plant oil-fed fish.

In summary, research on the substitution of fish oils with vegetable oils indicates that it is possible to use vegetable oils to replace up to half the fish oil currently used in salmon diets, and thus extend the time period before marine fish oil becomes a restricted commodity. This is, however, likely to be a staged process and, for the near future at least, fish oil is likely to remain the dominant source of lipid in farmed salmon diets. As has been shown, the type of vegetable oil used not only influences the carcass composition of the fish, but also affects some of its sensory characteristics. The results of emerging research show that there can be other advantages from using plant oils in combination with fish oils. As the American study, cited above shows, some consumers may actually prefer 'blander', less fishy-tasting fish products. The shelf life of fish products is a critical consideration to fish retailers and there is good evidence that the incorporation of vegetable oils into farmed fish diets can extend the shelf life of fish products.

In the future, it will probably become common practice to feed salmon on a diet containing plant oils and fish oil. For some markets it may be necessary to feed salmon a diet containing lipid originating only from fish oil for a period before harvest. This feeding strategy would transform the fatty acid composition of the edible muscle and make it more similar to that of a wild salmon, while helping to conserve limited fish oil stocks. The continuing success of aquaculture will be largely dependent on the image of fish as a healthy food, which provides people with a very good source of protein and EFAs. The ratio of *n*-6 to *n*-3 fatty acids in the 'western diet' is gradually increasing and there is a real concern that the substitution of fish oils with vegetable oils may further reduce the proportion of the long chain *n*-3 fatty acids in the human diet.

4.3.5 Animal fats

Although research continues into the use of hard fats, such as tallow, for use in salmon diets, lipid sources with high melting points tend to be poorly digested at low temperatures and are generally regarded as unsuitable for cold water species.

4.3.6 Carbohydrate

Earlier the role of carbohydrate in nutrition was discussed but carbohydrate has other properties that make it a useful raw material for fish feed manufacturers. Dietary carbohydrate is used in extruded feed, where it acts as a binder and as a source of starch. The heat, steam and pressure in the extrusion process cause the starch to gelatinise and the wheat to expand. The extrusion process helps increase the digestibility of carbohydrates and the physical stability of feed in water. The extent to which the feed will expand is related to the starch content of the wheat.

4.3.7 Antioxidants

Modern high-energy salmon diets contain high levels of unsaturated lipids, which are highly vulnerable to oxidation. The antioxidant level added to fishmeal and fish oil at the processing factory is calculated to protect these products until they are transported to the fish feed factory and during subsequent storage. To prevent rancidity of the oils developing in finished feed more antioxidant is added during manufacture. As modern salmon diets have become more concentrated in lipid, so the requirement for dietary antioxidant, used to prevent rancidity, has increased. The most common antioxidant presently used in fish feed is ethoxyquin and there are alternatives, such as butylated hydroxanisole (BHA) and butylated hydroxytoluene (BHT). The antioxidant vitamin E, in the form of alpha-tocopherol acetate, is also added to feed in increasing amounts as the levels of unsaturated fatty acids in the dietary lipid increase. However, alpha-tocopherol acetate acts as an antioxidant source for the fish, once the acetate has been removed releasing vitamin E, and not as an antioxidant in feed. Some of this dietary vitamin E passes into the organs, liver and muscle tissues of the fish where it is stored and where it continues to function as an antioxidant even after death. Failure to provide enough antioxidant in the feed can result in the development of premature rancidity in the fish and reduce its shelf life. Ascorbic acid (vitamin C) also has antioxidant properties and appears to act synergistically with vitamin E, while selenium has an important function in the enzyme pathways that prevent lipid peroxidation occurring.

4.4 THE MANUFACTURE AND DEVELOPMENT OF SALMON DIETS

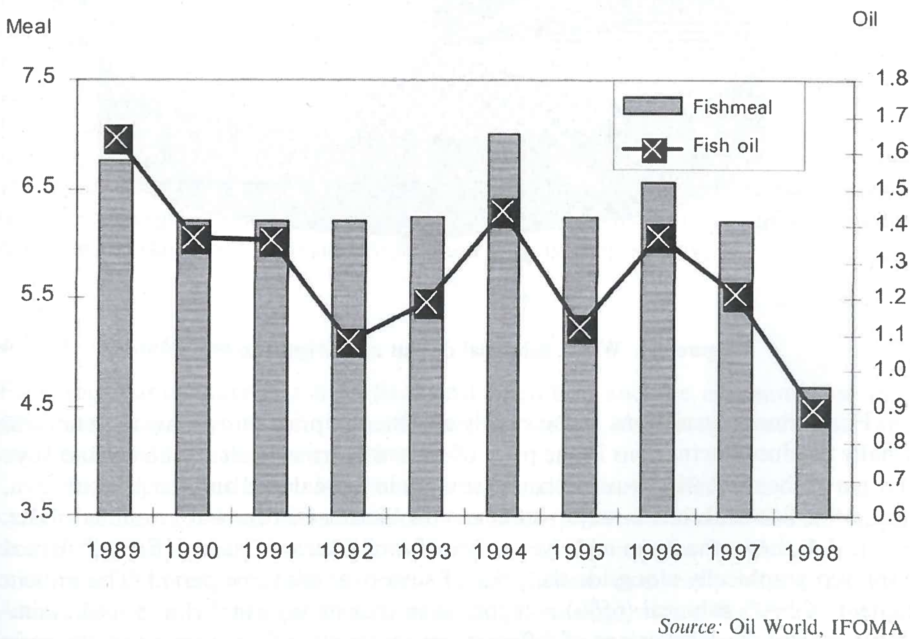
Fish feed manufacturers operate in a competitive business environment. Each manufacturer aims to make a profit by supplying its customers with feed, but a healthy feed supply business needs profitable customers. The cost of feed represents between 40–60% of the cost of producing farmed salmon, the variation being explained by many factors including scale of operation, financial set-up, farming practices, location and fish health status. The feed manufacturer must therefore formulate feeds that have the potential to enable the salmon farmer to produce fish at a cost that will allow both themselves and their fish farming customers to achieve profitability. The feed producer formulates diets to supply the nutritional requirements of each farmed species at every stage of the salmon's life. An understanding of the life cycle of the Atlantic salmon is fundamental to developing diets and feeding strategies that will produce salmon at a minimum cost to the farmer and of the desired quality to the consumer.

4.4.1 Raw material supply and purchasing

The raw materials used in the manufacture of farmed salmon diets are primarily: fishmeal, fish oil, soya, maize or rape protein meals, wheat, carotenoids, vitamins and minerals. Although domestic supplies of the main feed ingredients are available, the growth of the aquaculture industry has made it necessary to purchase raw materials from other geographical locations. The majority of fishmeal and fish oil is purchased from the principle producing areas of Scandinavia and South America. The USA is the major source of the maize and soya protein used.

4.4.1.1 Protein sources

Figure 4.1 shows world fishmeal and fish oil production for ten years from 1989–1998. Over most of this period the world production of fishmeal has been relatively stable. However, El Niño can clearly be seen to have had a major effect on global fishmeal production during 1998. This is further demonstrated in Figures 4.2 and 4.3, which show world fishmeal output for 1994 and 1998 respectively. The reduction in fishmeal production of 2.3 million tonnes can be attributed mainly to the 27% drop in production in South America, a direct result of El Niño. Simple supply/demand economics resulted in the price of fishmeal escalating dramatically in 1998 to an all-time high.



Source: Oil World, IFOMA

Figure 4.1. World production of fish meal and fish oil 1989–1998.

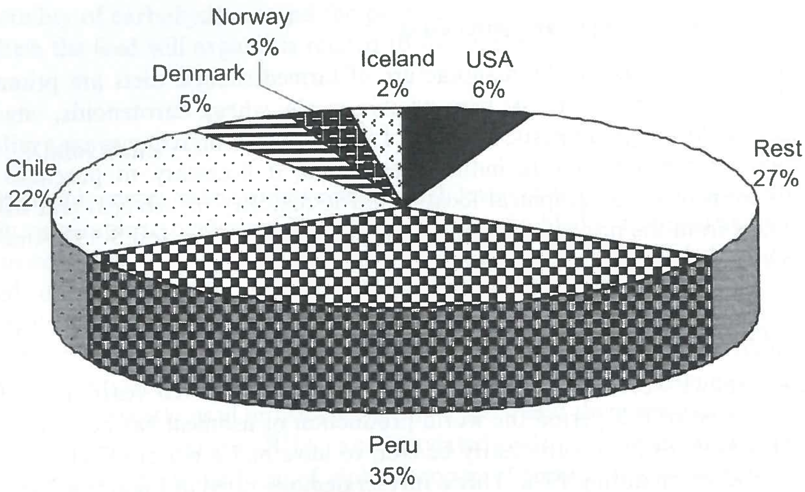


Figure 4.2. World fish meal output and origin for 1994.

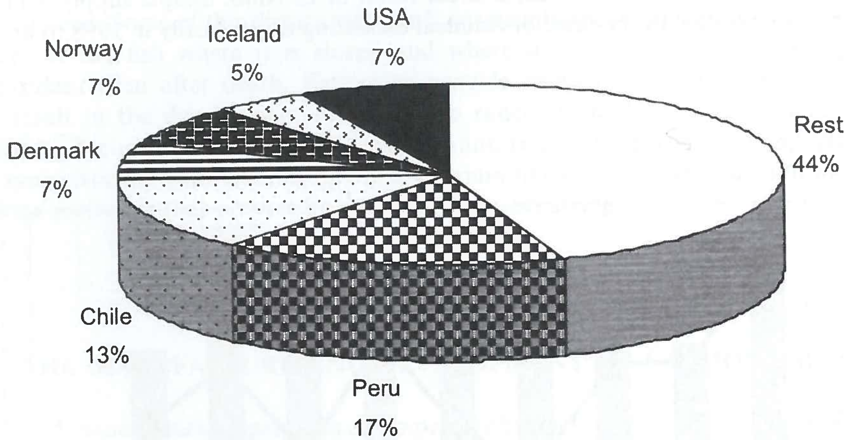


Figure 4.3. World fish meal output and origin for 1998.

Furthermore, variations in the supply and, hence, price of one raw material will usually produce fluctuations in the price of related raw materials. Fishmeal and soya are two of the most widely-used protein sources in animal feed and the price of soya, relative to fishmeal, has a major influence on the use of fishmeal in animal feeds. Figure 4.4, shows the mean eight-year price of Fair Average Quality (FAQ) fishmeal displayed graphically alongside the price of soya over the same period. The protein content of FAQ fishmeal (65%) is higher than that of soya (45%) and feed manufacturers vary the proportions of different raw materials in formulations on the basis of the unit cost of protein.

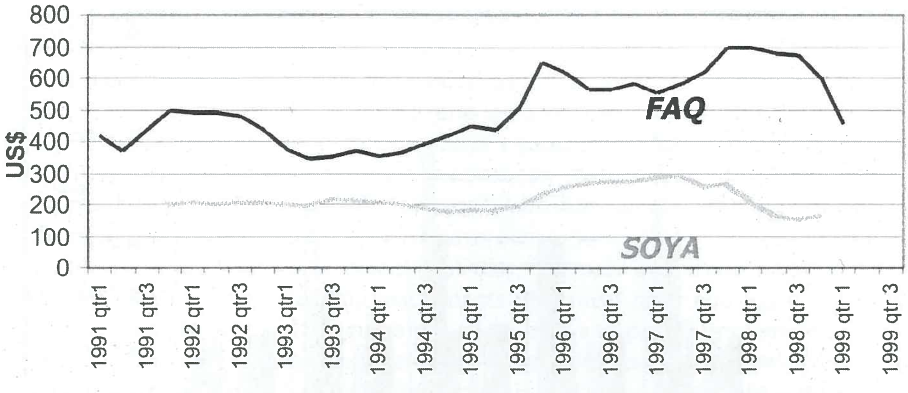


Figure 4.4. Price movements in fish meal (FAQ) and soya 1991–1999.

4.4.1.2 Fish oil

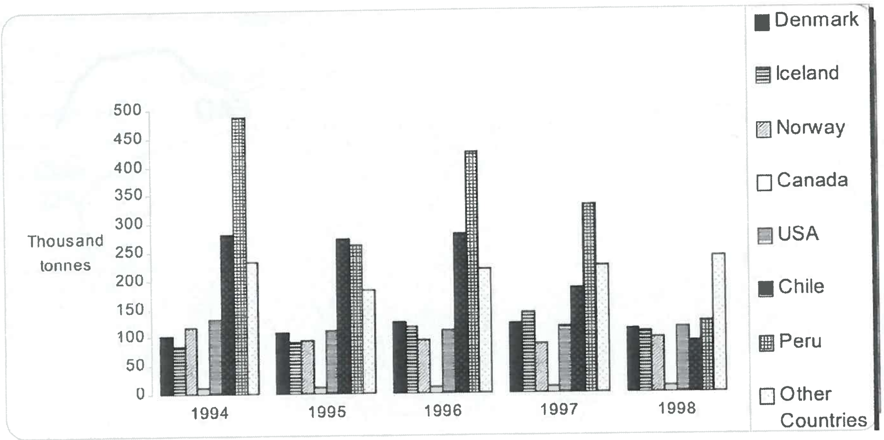
The countries in which fish oil is produced and their respective outputs are shown for the period 1994 and 1998 in Figure 4.5a. World production of fish oil in 1994 is steady at around 1.3 million tonnes per annum (Figure 4.1) but in the future demand is predicted to outstrip supply.

Figure 4.5b shows the fluctuating price of fish oil with a strong upward price trend over a ten-year period up to January 1999. There is a high probability that this continuing upward trend in the price of fish oil will lead to the partial replacement of fish oil with vegetable oils in farmed salmonid diets. In 1998 the FAO reported the global production of plant oils to be 110.6 million tonnes, a figure which far outstrips the supply of fish oil. Traditionally, and prior to the growth of the aquaculture industry, the major use for fish oil was in margarine and industrial shortenings. However, as the margarine manufacturers now predominantly produce spreads made from vegetable oil, this sector's requirement for fish oil has shrunk rapidly, delaying the day when aquaculture demand will outstrip supply.

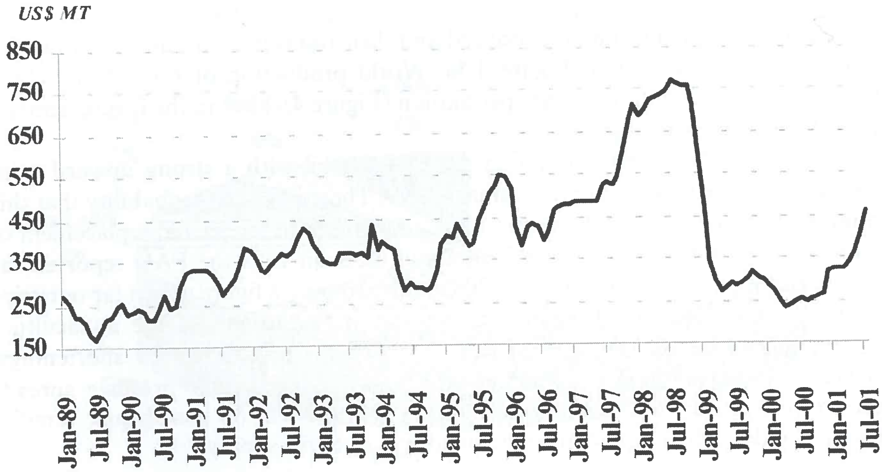
4.4.1.3 Manufacturing capacity

Fish feed manufacture is a high fixed-cost operation and the maximum use of a producer's capacity is the most effective means of absorbing fixed costs and overheads and increasing competitiveness.

Salmon feed production is typically a seasonal business, affected by the natural cycle of salmon production. In the Northern Hemisphere most smolts are still put to sea in the spring months and there spend up to 18 months, which generates a maximum demand for salmon feed in the autumn and early winter months. Although the imbalance in demand is gradually easing, with a higher proportion of smolts being put to sea in the autumn, the maximum production capacity is still only reached for 3–4 months a year. In order to fulfil such seasonal variation in



(a)



(b)

Figure 4.5. (a) World fish oil production and origin 1994–1998; (b) fish oil prices 1989–2001. *Source*: Oil World.

demand, manufacturing plants are much larger than they would be if demand were non-seasonal, adding to fixed costs and overheads.

4.4.1.4 Purchasing raw materials

With fish farming companies demanding long contracts, the feed manufacturers need certainty both as to the supply and price of raw materials.

There are two possible purchasing strategies, the first of which is simply to follow the market and purchase on a spot basis. This increases flexibility but also increases the manufacturer's exposure to fluctuations in the market, which will almost certainly have an impact on profitability. The second is to secure long-term contracts for raw materials, which ensures a fixed cost structure but reduces flexibility and may impact on the manufacturer's competitiveness in the market place.

With this latter strategy, in order to cover raw materials in the medium or long term, purchasers need to be able to forecast future demand and supply accurately. It is therefore vital for the purchaser to have access to market intelligence which is available from analysts, government statistics, journals and trade bodies, and to consider the use of price hedging instruments to protect price and margin. Despite these tools, it is still difficult to guarantee the supply and price of raw materials, and constraints such as supply uncertainty, competition and consumer/government-imposed restrictions all have an impact. It is not easy to switch suddenly the supply of raw materials such as fishmeal and fish oil, which may have to be shipped from South America, and which tend to be produced out of synchronisation with regard to the major periods of demand.

The skill of the raw material buyer is vital in determining the product cost, price and eventual profitability of the feed companies.

4.4.2 Feed formulation

When formulating salmon diets, the feed formulator will normally first consider the qualities of the available protein sources, before adjusting the energy content of the feed to provide the optimum protein to energy ratio. Computerised linear feed formulation programmes enable the formulator to use a basket of raw materials to provide the most cost-effective diets, taking into account the dietary requirements of the fish, the stability of potential ingredients and the cost and availability of raw materials. This least-cost formulation strategy requires knowledge of the nutritional requirements of Atlantic salmon, the bioavailability of the raw materials under consideration and their energy content and cost. These programmes operate within predetermined ranges for each essential and desirable nutrient.

4.4.2.1 Protein sparing

The manufacturing capability for adding oil to feed has improved to the extent that even 40% oil diets have been produced for trial purposes. In terms of cost, fish oil has typically been a less expensive form of energy than dietary protein. While this remains so, it is usual to formulate farmed fish diets to contain just enough protein to satisfy the growth and maintenance requirements of the salmon, leaving the lipid to provide most of its energy requirements. This strategy is known as 'protein sparing'.

4.4.3 Wet diets

The earliest farmed salmon diets were produced from fresh or frozen 'industrial' fish sometimes mixed with animal waste products. This was a natural development in, for example, the rural areas of Scandinavia, where marine salmon and trout farms sprang up in close proximity to traditional fishing villages. This practice increased the vulnerability of farmed stocks to disease agents present in wild fish. In addition, such feeding practices sometimes led to a local deterioration in water quality around fish farms if uneaten fish sank to the seabed. Silage techniques offered an improvement over the use of fresh and frozen fish. During this process whole fish and fish waste is ensiled in acid, under controlled conditions and later added to a dry feed mix before being fed to the fish. The silage produced is highly digestible and free from disease agents and has the advantage of using local raw materials, but the product can be variable in nature and difficult to handle. The process has fallen out of favour as a method of producing salmon feed but is widely used to dispose of dead fish on fish farms. The resulting silage is not fed back to farmed salmon.

4.4.4 The development of manufactured salmon diets

Early salmon diets were formulated using knowledge of wild salmon diets and from analysis of the carcass composition of wild salmon. From the relatively small number of post-smolts caught at sea, it is known that the diet of wild salmon includes *Themisto* spp., krill (*Euphasidae*), herring, redfish larvae and blue whiting larvae (Holst *et al.*, 1996). In a review of published dietary EAA requirements of fish, it was concluded that carcass AA profile could be used as a guideline for formulating feed (Mambrini and Kaushik, 1995). These early formulations for salmon diets were further refined, using the knowledge and experience gained from the dietary formulations previously used for rainbow trout diets. Salmon farming is now a strategically important industry in Norway, Chile and Scotland and this has stimulated investment in further necessary research on the nutritional requirements of commercially-farmed species, including the Atlantic salmon.

Fish feed manufacturers generally produce a range of specialist feeds, which may include diets formulated for broodstock, special environmental conditions, stimulating health and for carcass quality.

4.4.4.1 Conventional pelleting

The early commercial diets were manufactured using a conventional pellet press process, in which the raw materials are first blended, followed by the addition of steam, before the material passes under pressure through rollers and a ring die. As the pellets emerge through a large number of identically-sized holes in the rotating die they are cut off to the appropriate length. During this process the temperature of the material rises to between 60–70°C. This production method produces pellets with a limited ability to contain oil and the early manufactured salmon diets usually contained no more than 16% lipid.

The first manufactured diets enabled salmon farmers to make good profits but 20 years ago salmon farmers were getting almost £7.00 for each kilogram of salmon produced, compared to less than £2.00 in 1999. It was thus possible to make money then even though salmon farmers grew fish more slowly and fewer fish survived compared to today.

4.4.4.2 Pellet production by agglomeration

Agglomeration techniques have also been used to produce freshwater diets for juvenile salmon. This method involves the use of a large spinning sunken disk, on to which the raw materials are added while being sprayed with water. As the pellets form they gradually move toward the edge of the disk. The formed pellets then fall over the edge, where they are collected and dried. The size of the pellets can be adjusted by changing the speed at which material is added to the disk and by altering the angle and speed of rotation of the disk. This process produces a high-energy diet with a high product density. Agglomerated products tend to have a relatively fast sinking speed and may be more suitable for feeding where the water column is deep, such as in silo systems.

Pellets produced by this method can have a tendency to break down rather quickly in water and this can lead to water-quality problems in hatcheries.

4.4.4.3 Extruded pellet production

As the price of salmon began to fall farmers demanded improved diets, and fish feed manufacturers developed and introduced extruded feeds for fish farming. A typical salmon grower diet produced by this process would contain 45% protein and 26% oil. During extrusion, the feed ingredients are pressurised and treated with water and super heated steam at temperatures up to 120°C. Starch, from cereal in the raw materials used, is gelatinised by a combination of work, moisture and heat in the extruder barrel. As the material passes through the die about 6% of the moisture content 'flashes' off, causing the material to puff up. This improves the digestibility of the carbohydrate content and gives the extruded pellet an improved, more stable matrix to which higher levels of oil can be added. Once the pellets have passed through the die another 14–15% of moisture must be removed by a drying process. The extruded matrix also has the advantage of allowing the feed producer to control the speed at which the pellets sink (normal range 0.28–0.38 m/s). The increased heat used during manufacture has the further advantage of killing any pathogens present within the raw materials used. This is a more expensive process than conventional pelleting but improves the energy density of the product and the digestibility of several feed ingredients.

4.4.4.4 Fat coating technology

Recent developments of the fat coating process on the manufacturing lines of some salmon feed producers have enabled dietary lipid levels to be increased further. The raw materials used in the production of salmon diets will normally contribute approximately 6% of the lipid in the mix before further oil is added. In order to achieve the high levels of lipid now used in salmon diets, extra lipid is coated on to the extruded pellet. The effectiveness of the fat coating process can be improved by several methods: bathing the product in warmed oil can increase the exposure time of the product to the oil or, alternatively, a vacuum infusion coating process can be used to 'pull' the oil into the pellet. These improvements have led to a new generation of high-energy salmon grower diets containing 30–36% oil. Since manufactured salmon diets were first produced there has been a continuing trend for the energy content of diets to rise, while during the same period levels of dietary protein and, more particularly, dietary carbohydrate have fallen.

4.4.4.5 Digestible protein: energy ratios

It is now common practice to use the terms digestible energy (DE) and digestible protein (DP), rather than total energy and total protein in the feed. The optimum DP : DE ratio will vary with fish size, so that a fast-growing small salmon, with a high requirement for dietary protein, will have a higher optimum DP : DE value than a large salmon where the demand for dietary protein is lower. In a trial on Atlantic salmon, ranging in weight from 1–5 kg and fed on a range of high-energy diets, it was found that the dietary protein/energy ratio should be reduced as the fish increase in weight. The following DP/DE ratios were suggested for Atlantic salmon in seawater: $19\,g\,MJ^{-1}$ for fish of 1–2.5 kg and $16–17\,g\,MJ^{-1}$ for fish of 2.5–5.0 kg (Einen and Roem, 1997).

Optimising the DP:DE ratio minimises the use of protein as an energy source and maximises the use of dietary lipid for energy (protein-sparing). There are distinct advantages to be gained from use of more energy-dense diets: feed conversion efficiencies are improved and less waste material is produced by the fish (Hillestad *et al.*, 1998).

4.5 SALMON DIETS

4.5.1 Freshwater diets

Freshwater smolt diets typically contain between 50–54% protein and 16–24% oil, with protein levels decreasing and oil levels increasing as the fish grows. For juvenile salmon the size of the feed particles is of prime importance. To achieve a range of suitably-sized feed particles, a larger 'grower'-sized pellet can be crumbled under controlled conditions. The resulting mixture of dust, particles and chips can then be sieved using specifically selected sieve meshes to give the chosen range of feed sizes. Using an 'extruded' pellet for crushing gives a marked advantage in terms of reducing the sinking speed of the particles and in improving the water stability of the feed. This latter point is particularly important in the salmon hatchery, where the presence of uneaten food, breaking down before it leaves the rearing enclosures, can lead to poor water quality and potential fish health problems.

Some research has been carried out on the importance of pellet shape, and it has been reported that pellets of long and intermediate length elicited a more rapid response but were more likely to be rejected by juvenile salmon (Stradmeyer *et al.*, 1988; Smith *et al.*, 1995). Juvenile salmon apparently preferred a softer pellet, but it was acknowledged that there may also be an interaction between the effects of pellet size and hardness (Mearns, 1990). Wild salmon have presumably evolved to cope with food of variable dimensions, and in most conditions hungry farmed fish are able to ingest a wide range of pellet sizes (C. Talbot, personal communication). At critical times or at times of low feeding motivation, such as following transfer to seawater, pellet size may be more important (Stradmeyer, 1994).

4.5.1.1 Phosphorus

Another of the factors that fish feed formulators must take into account concerns the addition of dietary phosphorus. Phosphorus is usually the first limiting nutrient for algal blooms in fresh and brackish waters, while in seawater nitrogen is usually assumed to be limiting (Auer *et al.*, 1986; Sakshuaug and Olsen, 1986). Fish require a relatively high input of phosphorus, which is used in the formation of bone and in their metabolic processes. Phosphorus contained in fishmeal is poorly absorbed and supplemental phosphorus is required in the diet (Nordrum *et al.*, 1997). Fish excrete some of the dietary phosphorus as well as ammonia, which can combine to contribute to the build up of nutrients in freshwater leading to the eutrophication of freshwater lakes and lochs. The amount of phosphorus entering Scottish freshwater systems is monitored and closely controlled by the Scottish Environmental Protection Agency (SEPA). The formulator of freshwater fish feeds must therefore satisfy the dietary requirements of the fish but minimise any excess dietary phosphorus. Salmon diets usually contain between 0.90–1.80% total phosphorus. The use of fishmeal containing little or no bone and the replacement of some of the animal protein with vegetable protein has helped to reduce dietary phosphorus levels without the occurrence of deficiency symptoms. Bergheim and Sveier (1995) found that the replacement of 60% of the herring meal with vegetable protein in a commercial salmon diet almost halved phosphorus excretion without affecting growth rate or feed utilisation. Phosphorus deficiency may result in poor growth, poor feed utilisation and reduced bone mineralisation (Lall, 1991). However, soya, wheat and corn-based protein concentrates may be lower in total phosphorus but are also lower in available phosphorus. This is because phytate binds phosphorus so tightly that fish cannot digest it. The dietary requirement for phosphorus for Atlantic salmon has been found to be $11\,g\,kg^{-1}$ (Asgard and Shearer, 1997) and the total phosphorus content of dry feed for salmonids is usually 10–$15\,g\,kg^{-1}$ feed (Bergheim and Sveier, 1995). The use of the enzyme phytase can improve the bioavailability of phosphorus from plant proteins and offers the potential to reduce phosphorus output from freshwater smolt production. The use of enzymes as ingredients of salmon diets must first be sanctioned. The use of phytase was discussed earlier (see Section 4.3.2.5).

4.5.2 Transfer diets

As the parr age they migrate downstream and undergo a series of physiological changes that will adapt them for life in the sea. Some feed manufacturers formulate 'transfer diets' that have added salt, and such diets have been shown to increase the number of chloride cells in the gills. These chloride cells naturally increase in number following seawater transfer and act by excreting excess sodium salts from the blood of the fish. Virtanen *et al.* (1989) studied the use of betaine/amino acid as a feed additive for improving the osmotic adaptation of Atlantic salmon smolts. Some feed manufacturers now offer smolt diets supplemented with FinnStim (betaine plus 3% protein hydrolysate) which has been shown to act as an osmoprotectant in coho salmon smolts. In this study it was concluded that the betaine acted by decreasing muscle potassium load, resulting in improved seawater performance of smolts relative to fish fed a non-supplemented diet (Castro *et al.*, 1998). Transfer diets containing extra salt could increase the osmoregulatory loading on the fish and should therefore never be fed to newly-transferred post-smolts in the sea.

In a more recent development smolt diets supplemented with nucleotides have been fed to smolts for a period of several weeks prior to seawater transfer and for several weeks post-transfer. This practice is said to improve the growth performance and survival of vaccinated fish during their first year at sea, but the research behind this has yet to be published. A more detailed description on the use of nucleotides is given in Section 4.5.5.

4.5.3 Marine salmon diets

Once the smolts have adapted to seawater they are fed a diet with high DP:DE ratio, which is typically reduced with increasing fish weight. The protein level in the diet may approach 48–50% following transfer but can be gradually reduced to 36–42% approaching harvest at 3–4 kg. Conversely, dietary lipid levels move in the opposite direction, starting at 24–26% and reaching 30–40% prior to harvest. Figure 4.6,

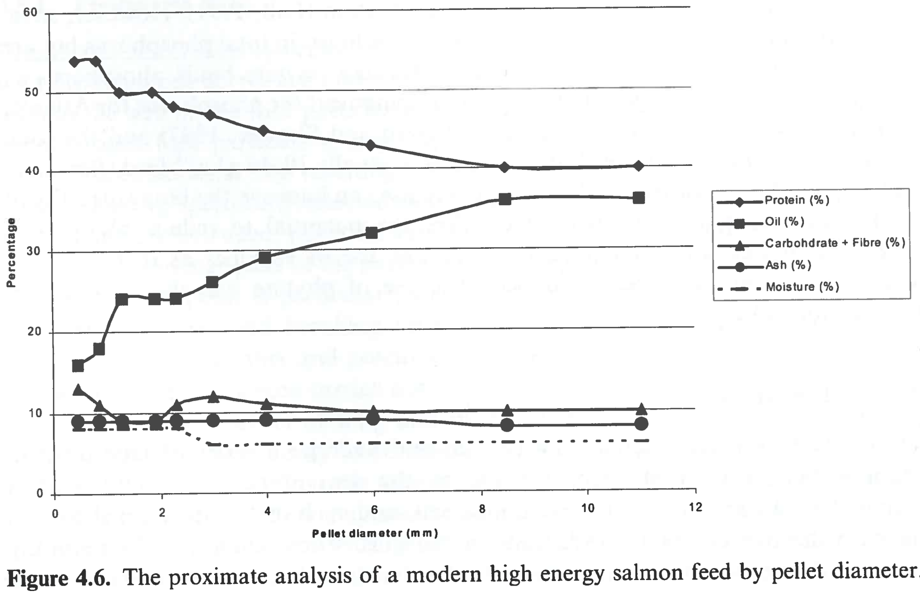


Figure 4.6. The proximate analysis of a modern high energy salmon feed by pellet diameter.

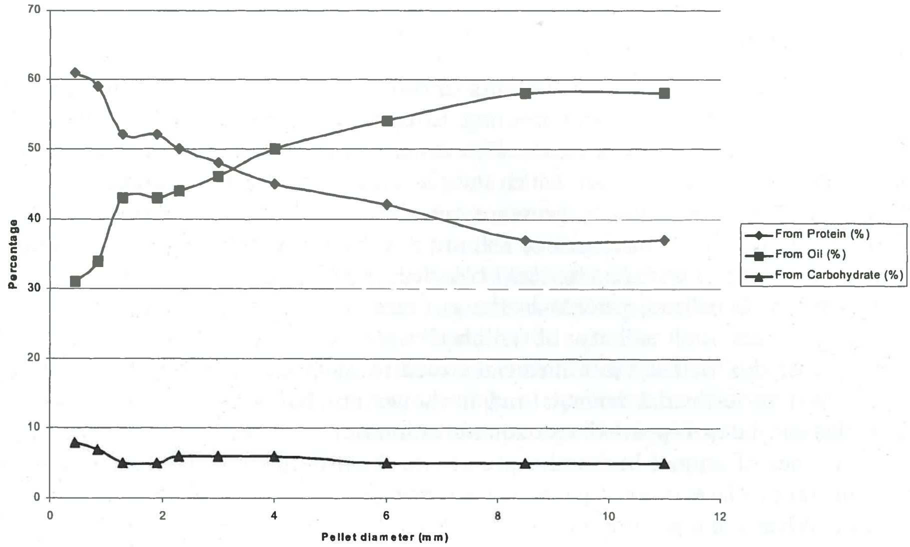


Figure 4.7. The energy distribution in high energy salmon feed by pellet diameter.

shows the proximate analysis of a range of modern high-energy salmon diets formulated for fry through to harvest-sized salmon. The energy distribution for the same range of diets is shown in Figure 4.7.

4.5.4 Broodstock diets

The survival of broodstock and the production of healthy eggs and sperm underpin the success of salmon farming. Research has shown that there is a link between nutrition and the survival of broodstock, fecundity, hatching percentage and the survival of fertilised eggs in both freshwater and marine fish (Watanabe, 1985; Washburn *et al.*, 1990; Watanabe and Kiron, 1995). It has further been shown that the effect of changes in feed accessibility and feed composition on egg and fry quality decreases with the time left until spawning (Ridelman *et al.*, 1987). The number and quality of the eggs are determined at an early stage and it is therefore important to ensure the fish has good nutrient and energy reserves before the maturation process begins. In practice this means that broodstock diets, specially formulated with extra vitamins and minerals, should be fed 8–12 months prior to spawning. As soon as salmon have been graded and broodstock selection is complete, the selected fish should be fed the broodstock diet. Salmon usually spawn in the late autumn but will stop feeding several months before this. The fecundity or the number of eggs produced by each fish is primarily related to the size of the fish, which in turn will be determined by the quantity and quality of feed the fish consumes. For a more comprehensive review on this subject see Bromage (1995).

4.5.5 Health supplements

When considering the potential benefits of orally-administered fish medicines and health supplements it is worth pausing to consider some important differences between fish and terrestrial animals. Fish drink the water they swim in, and this is particularly true of marine fish, which have to drink considerable amounts of water to counter the higher osmotic pressure outside compared to within the fish. The internal surfaces of the intestines of fish are therefore constantly exposed to water-borne pathogens. Fish are also cold-blooded (poikilotherms) and any bacteria, pathogenic or beneficial, present in the gut must be able to adapt to changes in the temperature and salinity of imbibed water if they are to prosper. The relevance of this is that most medicines used in animal husbandry systems have been tested in terrestrial animals and it should not be assumed that the results from this can be extrapolated into aquatic animals.

All types of animal husbandry are at risk from outbreaks of disease. Salmon farming takes place in an aquatic environment, over which the farmer has little control. When a disease breaks out the salmon farmer has only a narrow range of licensed treatments available and is therefore heavily reliant on the prevention of disease through improved husbandry strategies, better fish nutrition and especially the use of vaccines. The use of antibiotics in the food chain is attracting more scrutiny as the medical microbiologists point to the danger of human pathogens becoming more resistant to antibiotics, when the same antibiotics are used both in humans and in livestock. The use of antibiotics in salmon farming has shown a marked decrease in recent years; thanks mainly to improvements in husbandry techniques and the introduction of effective vaccines for the major bacterial salmon diseases, such as furunculosis (*Aeromonas salmonicida*).

Interest is now increasingly focused on feeds supplemented with a range of natural immunostimulants and on nutritional enhancement of the immune system (Raa, 1996). Much of the pioneering work centred on the intraperitoneal administration of various immunostimulants to test their effects on the fish's immune system. More recent work has focused on the oral administration of immunostimulants. Glucans and oligosaccharides are now used extensively in aquaculture to stimulate the non-specific immune system and to beneficially alter the microbial flora, respectively. Several types of glucan have been studied in fish, such as the yeast glucan and glucan (VST), but the peptide-glucan beta-1, 3 has probably been in most common use as an immunostimulant. Glucans are often recommended to be administered in a phased way, which may involve feeding the substance for six weeks followed by two weeks of normal feeding. This alternating cycle is designed to avoid habituation of the fish's non-specific immune system. The current status of the above immunostimulants, and several other substances including chitin, lactoferrin and levasimole are described in a review by Sakai (1999). Another class of immunostimulants attracting interest from salmon farmers is derived from algae.

The term 'probiotic' is sometimes used to describe these nutritional immunostimulants, however, the various definitions for the term might exclude several of those mentioned above. One definition defines probiotics as microbial cell preparations, or components of microbial cells that have a beneficial effect on the health and well being of the host (Salminen *et al.*, 1999). Landolt (1989) has reviewed the relationship between diet and the immune system of fish.

In Section 4.5.2 the use of transfer diets supplemented with nucleotides was mentioned. Nucleotides are the basic constituents of DNA and RNA and studies in mice (Kulkarni *et al.*, 1986) rats (Ogoshi *et al.*, 1988; Uauy *et al.*, 1990) and humans (Sanchez-Pozo *et al.*, 1985) have shown various potentially beneficial health effects for these species. At the time of writing there are a number of commercial companies claiming that nucleotide supplemented diets can increase growth performance in post sea water transfer salmon and fish survival rates, but studies backing these claims are yet to be published in the scientific literature.

The importance of vitamins in relation to fish health has been discussed above. Fish feed manufacturers may supply a range of specialist health-promoting diets containing boosted levels of vitamins, often in conjunction with immunostimulants such as glucans.

4.5.6 Medicated feed

Although the use of antibiotics in aquaculture has fallen dramatically there are still occasions when salmon farms are hit by bacterial infections. Failure to act quickly can result in severe losses of stock, and at such times fish feed manufacturers are often asked to provide medicated feed at very short notice. The legislation covering the use of fish medicines varies from country to country. Taking the UK as an example, all antibiotic medicines for salmon are prescription-only drugs and the farm veterinarian has the responsibility for prescribing the most effective treatment regime. Upon receipt of a 'prescription for a medicated feedingstuff' the feed manufacturer may coat antibiotics, or any other medicines licensed for in-feed use, on to feed pellets for in-feed administration. The manufacture of medicated feed can be a labour-intensive process, which typically takes place on a dedicated feed line. It is essential that cross contamination between different medicines and between non-medicated and medicated feed cannot occur. Between each batch of a different medication every part of the line must be cleaned. Each batch of feed must be sampled to ensure that the medication is present as prescribed and distributed effectively in the feed. In order to help farmers avoid the accidental feeding of medicated feed to the wrong fish some feed manufacturers use distinct coloured labelling and packaging, which clearly identifies the medicated product. It is important to ensure that all fish to be treated receive the medicine and it is normal to add the medicine to between 50–75% of the daily ration.

It is illegal to sell fish containing residues of a medicine that exceed a certain legal maximum level. In order to assist this process, each licensed medicine is issued with a withdrawal period. The withdrawal period is typically described in degree-days (e.g., 50 degree days are 5 days at 10°C or 10 days at 5°C). It is calculated to ensure that any medicinal residue in the edible tissues will be below the legal limit designated for that medicine at the time the fish is harvested for consumption. A new generation of in-feed lice treatments are now licensed for use in Atlantic salmon and these offer the fish farmer great advantages in terms of ease of application, accurate dosing, and uninterrupted feeding and growth during treatments. Traditional bath-type treatments involve withdrawal of feeding both before and immediately after treatment.

4.5.7 Organic diets

In the more wealthy countries there is a growing demand for organically-produced food. The standards for organic salmon feed are still evolving but there are already a number of schemes for organic farmed salmon production operating in different parts of the world. The organic movement typically focuses on the following areas:

- stocking densities;
- sustainability of raw materials;
- GM ingredients;
- synthetic ingredients;
- antioxidants;
- use of medicines;
- animal welfare.

Restrictions are commonly set, for example for maximum stocking densities, for the use of medicines and for feed ingredients. Organic fish feeds must not contain GM feed ingredients and the incorporation of synthetic pigments into organic fish feeds is generally prohibited, although some schemes allow the use of pigments derived from yeast and algae.

4.6 QUALITY ASSURANCE

The fish feed manufacturers must satisfy their customers—the salmon farmers—that their diets are safe, effective and economic. In addition, fish retailers may insist on full traceability so that the full history of any fish purchased at their store can be traced back to the broodstock from which the fish originated. Through the recording of ticket numbers from feed bag labels it should be possible for the feed manufacturer to trace back the manufacturing details and the raw materials used.

4.6.1 Raw materials

Use of the highest-quality raw materials is the key factor in producing high-performance salmon diets. Each feed manufacturer draws up its own purchasing specifications and often these are jealously guarded. The digestibility of the main raw materials, such as fishmeal, soya and fish oil, is an obvious key specification. The major raw materials should be analysed routinely for proximate composition, typically MOPA, and for selected essential nutrients such as the limiting AAs, lysine and sulphur AAs and essential fatty acids. Protein digestibility of raw materials can be tested *in vitro* using enzyme assays.

Most of the raw materials are tested for quality before they reach the feed mill. It is usual to buy fishmeal and fish oil in bulk and samples of these raw materials are typically sent to the feed manufacturer for testing prior to delivery. Once the raw materials reach the feed mill there is normally a visual check against referenced samples. This is followed by a series of tests specific to each raw material developed to confirm their conformity to the buying specification.

4.6.2 Process quality control

Modern analytical techniques allow the on-line measurement of various quality factors in raw materials and feed during the manufacturing process. At critical points throughout the manufacturing process the use of modern near infra-red reflectance techniques (NIR) allows greater control over the process, so ensuring a higher degree of product conformity and process optimisation. An example of this is the ability to generate real-time information on product protein, oil, moisture content and ash. This technology also allows the on-line analysis of costly ingredients, such as pigment.

4.6.3 Finished product

The more efficient fish feed manufacturers adopted the 'just in time' principle long ago. Providing that raw materials can quickly be replenished, raw material turnover can be fast, and at the busiest times of year feed can be out of the factory gate the same day as it is manufactured. During manufacture salmon feed is typically subjected to a number of laboratory tests to ensure compliance with statutory regulations (e.g., Feeding Stuffs Regulations). Feed samples are tested for a number of undesirable substances such as aflatoxins, mycotoxins, heavy metals, pesticides, dioxins and levels of potentially toxic fat-soluble vitamins. Statutory regulations also require the testing of all feeds produced to confirm the absence of *Salmonella spp.*

Feed pellets may be checked for sinking speed, hardness and for any visual sign of oil leakage. The large-scale automatic feeding systems now in widespread use on many salmon farms require pellets that are hard enough to resist damage during the feeding process. Some feeding systems have the potential to damage feed pellets, which can result in the formation of chips and dust which in turn can lead to blocked feed delivery pipes and result in interrupted feeding and loss of growth. In addition, the high oil levels found in modern salmon diets must not leach from the pellets as this can also cause blockages in feed delivery pipes. High oil diets (35–40% oil) can be sensitive to rough handling and environmental conditions. Warm storage conditions and compression, for example, can result in oil leakage from feed pellets.

The feed should not float and ideally should sink slowly through the water column although the introduction of floating pellets from deep within fish pens has also been tried. The idea here is that feed would float to the surface once the fish had reached satiation.

4.6.4 Packaging

Feed is typically supplied in 20–25 kg bags but there is a strong trend for the use of 0.5–1.0 tonne bulk bags. The machinery available on a modern salmon farm can handle these safely and easily and their use can produce economies in terms of labour and handling costs. The standard of packaging must be high as mould can develop in the feed if it comes into contact with moisture during transport and storage, particularly under warm and humid conditions. The packaging must therefore be waterproof but allow the product to breathe. The packaging for smaller bags may be paper with a polyethylene liner or a heavier duty polyethylene bag. Bulk bags may be made of polypropylene or polypropylene with a polyethylene liner. There are regular calls for the recycling and reprocessing of fish feed bags but the packaging is often contaminated with fish oil, which can make it an unpopular raw material for the recycling industry.

4.7 FEED PERFORMANCE AND FISH GROWTH

In theory, fish farming is essentially a simple process: the farmer aims for the highest growth rate possible, using the least amount of feed to produce the best quality fish. To achieve this goal, the farmer must use a good-quality feed, and a feeding strategy that maximises production. There is no universally-correct feeding method that guarantees optimal results, but there are a number of basic principles that can help the farmer to derive the maximum nutritional, and therefore economic, value from their feed.

In order to measure the value of a particular feed it is helpful to understand some of the terms used in fish farming to describe the growth performance of farmed fish. Although the cost of feed as a proportion of the production costs of smolts is relatively small, for on-growers fish feed represents their single biggest cost and it is important to understand how to measure its effectiveness. Worked examples of the calculations outlined in this section can be found in Appendix 4.1.

Two terms are commonly used to describe the performance of feed: feed conversion ratio (FCR) and feed efficiency (FE).

$$\text{FCR} = \frac{\text{Weight of food consumed over a given time (kg)}}{\text{Increase in fish weight over the same time (kg)}} \tag{1}$$

$$\text{FE} = \frac{\text{Increase in fish weight over a given period (kg)}}{\text{Weight of food consumed over the same period (kg)}} \tag{2}$$

4.7.1 Feed conversion ratio

It is more usual to use FCR to express the performance of fish and feed rather than FE. FCR can be affected by a number of physical, biological, nutritional and

Table 4.6. Factors affecting fish growth and feed conversion efficiency.

Environmental	Nutritional	Biological	Feeding	Personnel
Temperature	Energy level	Growth rate	%Ration	Motivation
Day length	Protein:energy ratio	Maturation	Feed type	Knowledge
Light	Amino acid profile	Health	Feed rate	Manning levels
Salinity	Fish meal quality	Egg quality	Intensity	Farm ownership
Stocking density	Feed storage	Fish weight	Timing	
Season		Stage in life cycle	Feeding equipment	
Location		Sex	Spread	
		Age	monitoring	

personnel factors which can make finding the correct feed strategy seem like an impossible task (see Table 4.6).

A decreasing FCR means an improving FCR. The best-performing salmon farms are now operating with FCRs of less than 1.2:1 for fish harvested at an average weight of 4 kg. Controlled trials have shown that it is possible to grow salmon to harvest with a FCR of less than 1:1. It sometimes puzzles people that fish can convert food to flesh at less than 1:1, but this is because a modern commercial salmon diet has a moisture level of 5–10%, compared to a well-conditioned salmon with a moisture content of 65–70%. The true FCR is therefore much higher on a wet weight basis. Later in the chapter methods of improving FCRs on salmon farms are discussed.

4.7.2 Specific growth rate

To a fish farmer, growing stocks at the lowest FCR possible is crucial for minimising production costs, but of equal importance is the rate at which these stocks grow. The growth rate is dependent on many factors, of which water temperature and food intake are the most important. Other factors include genetic strain, fish size, quantity and qualities of diet, composition of diet, fish health, sexual maturity status and water quality.

In fish farming we tend to describe growth as a change in total wet weight of the fish over a period of time. It is worth bearing in mind, however, that the Atlantic salmon uses its large mass of white muscle as an energy store and that the amount of fat in the muscle of well-fed salmon increases with fish size, particularly in the winter before maturation. The level of fat in the muscle is inversely proportional to the muscle moisture level; therefore the muscle of smaller fish is higher in moisture content than large salmon but lower in fat. Small salmon have a much greater potential for growth compared to large salmon, and growth is highly dependent on water temperature. The expression of growth most commonly used is the specific growth rate (SGR) which is a measure of the percentage body weight increase per day.

$$\text{SGR} = \frac{\ln \text{final weight (g)} - \ln \text{initial wt (g)}}{\text{Time interval (days)}} \quad (3)$$

Where ln = natural logarithm

4.7.3 Feed rate

It is also important to measure how much feed is administered over a given period. This is usually called the 'feed rate' (FR) and is typically expressed as the amount of feed fed per day as a percentage of body weight. As salmon get larger the potential maximum FR declines, so that first-feeding salmon may consume more than 4.0% body weight per day at 14°C and a 3 kg salmon only 0.4% body weight per day at 4°C. The FR is not an actual measurement of feed consumption, although it is sometimes used as such.

Using the SGR and the FCR, the FR can be calculated:

$$\text{FR} = \text{SGR} * \text{FCR} \quad (4)$$

As long as two of these parameters are known, the third can be calculated thus:

$$\text{SGR} = \frac{\text{FR}}{\text{FCR}} \quad (5)$$

$$\text{FCR} = \frac{\text{FR}}{\text{SGR}} \quad (6)$$

Specific growth rates for Atlantic salmon vary with size and with temperature but may range from around 3.0% in small salmon to less than 0.4% body weight per day in large salmon.

4.7.4 Thermal growth coefficient (GF3)

Temperature can exert a dramatic influence on growth rates in fish and can make cross-site comparison of growth performance difficult. Over recent years another measure of growth, the 'thermal growth coefficient' (GF3), has become widely used. This can be used to compare fish performance on individual farms, where the water temperature profiles differ. The GF3 equation relates growth directly to the sum of the daily water temperatures over a particular period (expressed as day degrees).

$$\text{GF3} = \frac{(\text{Final weight}^{1/3} - \text{Start Weight}^{1/3}) \times 1000}{\text{Total sum temperature}} \quad (7)$$

GF3 can also be used to predict growth providing the temperature profile over a particular period can be anticipated.

$$\text{Final weight} = \{(\text{Start weight}^{1/3} + \text{GF3} \times \text{Total sum temperature})/1000\}^3 \quad (8)$$

4.7.5 Feeding tables

In the early days of salmon farming, great emphasis was placed on the use of feeding tables to calculate daily feed rations on the farm. As more became known about the appetite of salmon, feed tables became highly evolved (Austreng *et al.*, 1987). Feed manufacturers typically produce brochures containing the latest feeding recommendations and feed tables for their range of products. Such tables are certainly useful as an approximate guide, but do not take account of daily fluctuations in appetite caused by water quality, disease or physiological changes in the fish. The usefulness of feed tables is also dependent on the farmer having accurate figures for fish numbers and biomass on the farm. Salmon farmers may have a reasonably accurate figure for fish weights based on regular batch sampling, but many would admit to being less certain about the accuracy of their estimation of the numbers of fish in each pen. Many of the larger farm sites transfer several hundred thousand smolts to sea over a very short period of time, and even with modern automatic fish counting systems errors in fish allocation records can easily occur. Even if the counting is accurate, losses occur during the growth cycle from predation and escapees. Nevertheless, it is important to understand how to use feeding guidelines and feed tables.

Table 4.7 shows Trouw's recommended feeding guidelines for their AminoBalance(TM) range of diets, expressed as percent body weight per day, for fish weighing from 0.3 g to 80 g. Table 4.8 is a similar table for fish weighing from 30 g to 200 g and Table 4.9 is a table for fish weighing from 180 g to 3000+ g. Different feed tables apply to different feed types, but mainly reflect differences in the digestible energy levels of each feed product. Other feed manufacturers have different recommendations based on their own feeding trials and experience.

Example:
To find the feed rate for an 1800 g salmon at a seawater temperature of 10°C go to Table 4.9, and move down the left-hand column until you reach the size range

Table 4.7. Recommended feeding rates for juvenile Atlantic salmon (% body weight day^{-1}).

Fish size (g)	Water temperature °C: Less than 4	4	6	8	10	12	14	16	18	Over 18
0.3–0.8		1.9	2.3	2.9	3.5	3.9	4.1	4.3	4.3	
0.8–5.0		1.7	2.1	2.6	3.1	3.4	3.6	3.7	3.7	
5.0–9.0	Appetite	1.5	1.9	2.3	2.7	2.9	3.0	3.1	3.1	Feed
9.0–25	will be	1.3	1.7	1.9	2.3	2.5	2.7	2.8	2.9	To
25–40	severely	0.9	1.4	1.8	2.0	2.2	2.4	2.5	2.6	oxygen
40-60	reduced	0.7	1.1	1.4	1.8	2.1	2.3	2.4	2.5	levels
60–80		0.6	0.8	1.2	1.6	1.8	2.1	2.3	2.4	

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Table 4.8. Recommended feeding rates for salmon (30–200 g) as percentage body weight day^{-1}.

Fish size (g)	Water temperature °C						
	Less than 4	6	8	10	12	14	16	Over 16
30–50	Appetite	2.4	2.6	2.8	3.0	3.2	3.5	Feed to
50–80	will be severely	2.2	2.4	2.6	2.8	3.0	3.2	oxygen
80–200	reduced	2.1	2.3	2.5	2.7	2.9	3.0	levels

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Table 4.9. Recommended feeding rates for salmon (180–3000+ g) as percentage body weight day^{-1}.

Fish size (g)	Water temperature °C						
	4	6	8	10	12	14	16
180–275	1.55	1.70	1.90	2.10	2.25	2.45	2.60
275–475	1.20	1.35	1.55	1.70	1.90	2.10	2.25
475–675	0.90	1.00	1.20	1.35	1.55	1.70	1.90
675–825	0.80	0.90	1.00	1.20	1.35	1.55	1.70
825–1000	0.80	0.80	1.00	1.10	1.20	1.35	1.55
1000–1250	0.65	0.70	0.90	1.10	1.15	1.25	1.35
1250–1500	0.55	0.65	0.85	1.00	1.05	1.15	1.25
1500–1750	0.50	0.50	0.75	0.90	0.95	1.05	1.15
1750–2000	0.45	0.45	0.60	0.80	0.85	0.95	1.05
2000–2250	0.45	0.45	0.60	0.75	0.80	0.90	1.00
2250–2500	0.45	0.45	0.60	0.70	0.70	0.80	0.95
2500–3000	0.45	0.45	0.60	0.60	0.60	0.80	0.90
3000+	0.40	0.45	0.50	0.60	0.60	0.70	0.80

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'1750–2000 g', then move across to the right until you reach the water temperature column headed '10'. The recommended feeding rate for this diet is 0.8% body weight per day.

4.7.6 Growth prediction

It is also useful for the farmer to be able to calculate how long it will take for a fish of a certain weight to grow to another weight. If an assumption can be made for the average water temperature over the period in question and a prediction made for the FCR then taking the FR from the feeding guidelines the time taken (T) in days is:

$$T = \frac{\text{FCR (ln end weight} - \text{ln start weight)}}{\text{FR (\% body weight per day)}} * 100 \qquad (9)$$

4.7.7 Growth on the salmon farm

In Scotland, smolts put to sea at the end of April can reach an average weight of 3 kg within 12 months at sea. Figures 4.8, 4.9 and 4.10 have been produced from a computer model simulating growth, weight, FCR, SGR and GF3 for a Scottish salmon farm using a high-energy feed. Although this series of graphs is modelled it does mimic the growth expected on a well-run Scottish farm, where factors such as husbandry, feeding practices, fish health and water quality are good. The data used for this projection are shown in Table 4.10. Figure 4.8 shows the annual sea temperature of a typical Scottish salmon farm and the growth of salmon over a 15-month period. The model assumes that grilse rates are negligible and no fish are harvested before the end of July in the second sea year. In the model these salmon have reached 4 kg by this time. Figure 4.9 projects the FCR and growth. The FCR is high following transfer, when fish are commonly offered an excess of food, but falls dramatically to around 1:1 before gradually increasing to 1.2:1 as the fish get larger. Figure 4.10 charts the development of SGR and GF3.

4.7.8 Pellet sizing

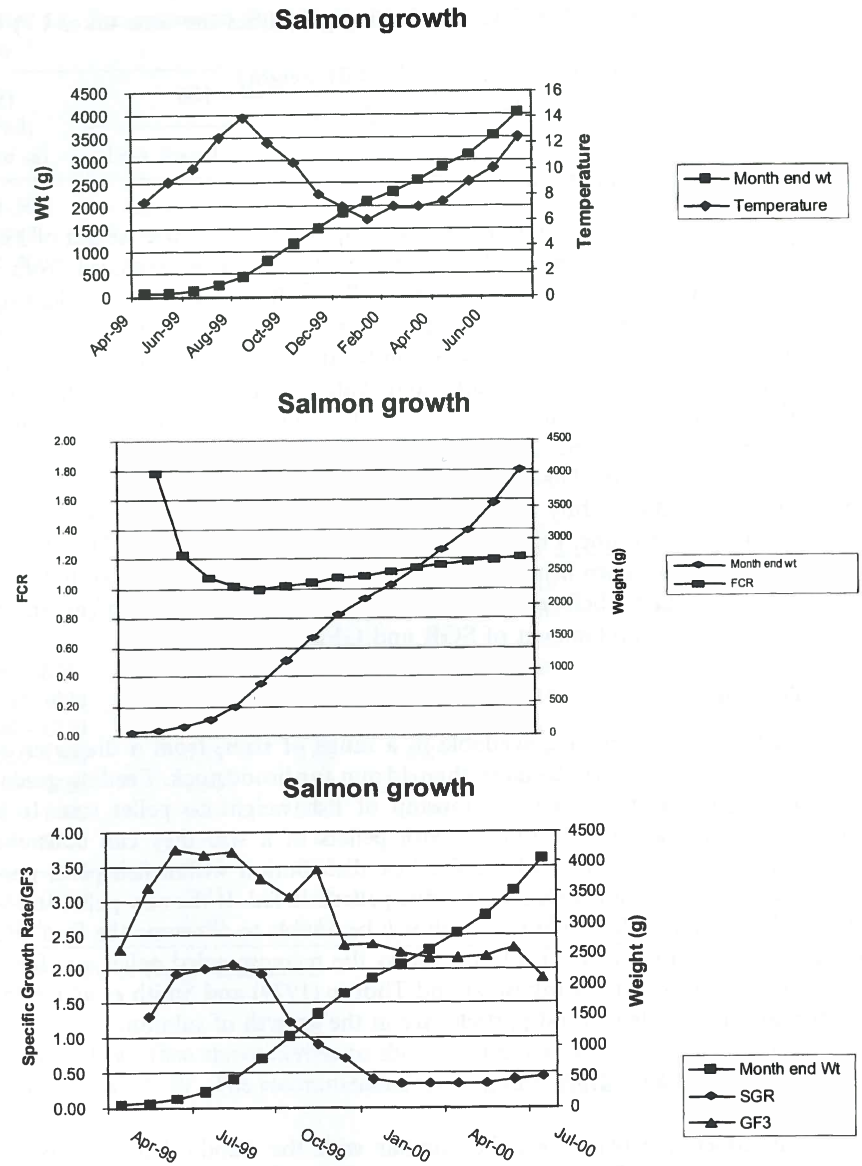
Commercial fish feed pellets are available in a range of sizes, from a diameter of 0.3 mm or less, for salmon fry, to more than 14 mm for broodstock. Feeding guidelines include information on the relationship of fish weight to pellet size. It is obviously important to provide salmon with pellets of a size they can consume and the farmer should be aware of the fish size distribution within fish pens, particularly when contemplating an increase in the pellet size fed. If the new pellet size is too large for the smallest fish then these fish will be unable to consume the feed and will either become runts or die. Table 11, shows the recommended pellet size for a particular fish weight range. Wankowski and Thorpe (1979) and Smith *et al.* (1995) have reported on the role of food particle size in the growth of salmon.

4.8 FEEDING STRATEGIES

By now it is hoped the reader will be familiar with the standard terms used to describe fish growth and feed performance. In order to feed salmon economically it is necessary to understand the way in which feeding practice influences FCR and SGR.

4.8.1 Feeding for optimum growth

There is obviously a relationship between the amount of food fed and the growth obtained. The rate at which a salmon can grow is dependent on many factors



Figures 4.8, 4.9, 4.10. Simulated growth on a well performing Scottish salmon farm.

including genetic history, environmental conditions, health, quantity and quality of food consumed and life stage. The relationship between SGR, FCR and the ration administered is shown in Figure 4.1.1. On this graph the x-axis represents the ration fed in % body weight per day and the y-axis both the FCR and the SGR. The graph is explained in more detail below.

Table 4.10. Simulated farm growth data for a pen stocked from seawater transfer with 21,000 smolts of an average weight of 50 g on a well-performing Scottish salmon farm.

Projected growth: month end weights

Date	Temp °C	Estimated month end weight (g)	Efficiency Factor	Feed %	FCR	No fish	Biomass	Estimated monthly feed (kg)	Rolling FCR	SGR	GF3
Apr-99	7.5	50		2.4	0.9	21000	1050				
May-99	9	74	0.60	2.6	0.9	19950	1476	756	1.77	1.31	2.28
Jun-99	10	132	0.90	2.6	0.9	19800	2608	1152	1.22	1.92	3.18
Jul-99	12.5	240	0.95	2.7	0.9	19652	4720	2034	1.07	2.00	3.75
Aug-99	14	446	0.95	2.45	0.9	19504	8690	3823	1.02	2.06	3.66
Sep-99	12	791	0.95	1.55	1	19358	15315	6387	0.99	1.91	3.70
Oct-99	10.5	1141	0.95	1.1	1	19213	21915	7122	1.02	1.22	3.32
Nov-99	8	1498	0.95	0.9	1.1	19069	28570	7232	1.04	0.91	3.04
Dec-99	7	1848	0.95	0.5	1.1	18926	34968	7714	1.07	0.70	3.44
Jan-00	6	2087	0.95	0.45	1.2	18784	39201	5245	1.09	0.41	2.34
Feb-00	7	2310	0.95	0.45	1.2	18643	43066	5292	1.11	0.34	2.36
Mar-00	7	2557	0.95	0.45	1.2	18503	47311	5814	1.14	0.34	2.23
Apr-00	7.5	2830	0.95	0.45	1.2	18364	51974	6387	1.16	0.34	2.16
May-00	9	3133	0.95	0.55	1.2	18227	57098	7017	1.18	0.34	2.16
Jun-00	10	3542	0.95	0.6	1.2	18090	64072	9421	1.20	0.41	2.18
Jul-00	12.5	4047	0.95	0.6	1.2	17954	72653	11533	1.21	0.44	2.30
Aug-00	12.5	4623	0.95	0.6	1.2	17820	82384	13078	1.23	0.44	1.86

Table 4.11. Feeding guidelines for farmed Atlantic salmon: recommended pellet sizes for a range of fish weights.

Pellet size range (mm)	For fish weight (g)
0.3–0.6	0.3
0.6–1.1	0.3–1.1
1.1–0.5	1.0–5.0
1.5–2.3	4–25
2.3–3.4	30–80
3.0	80–200
6.0	500–1300
8.5	1300–2200
11.0	2200+

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4.8.1.1 Feed rate

From Figure 4.11, it can be seen that as the feed ration increases from zero it crosses the x-axis at a ration size, termed 'R maintenance', which is the ration required to satisfy the metabolic requirements of the fish and to maintain its body weight at a constant level. Feeding at a ration level below 'R maintenance' will result in a reduction in body mass and an increased FCR. As the ration increases, the fish will eat until its appetite is satisfied (point of satiation); this is the maximum amount of food the fish can consume under a particular set of circumstances and is referred to as 'R max'. Increasing the ration beyond this point will result in feed

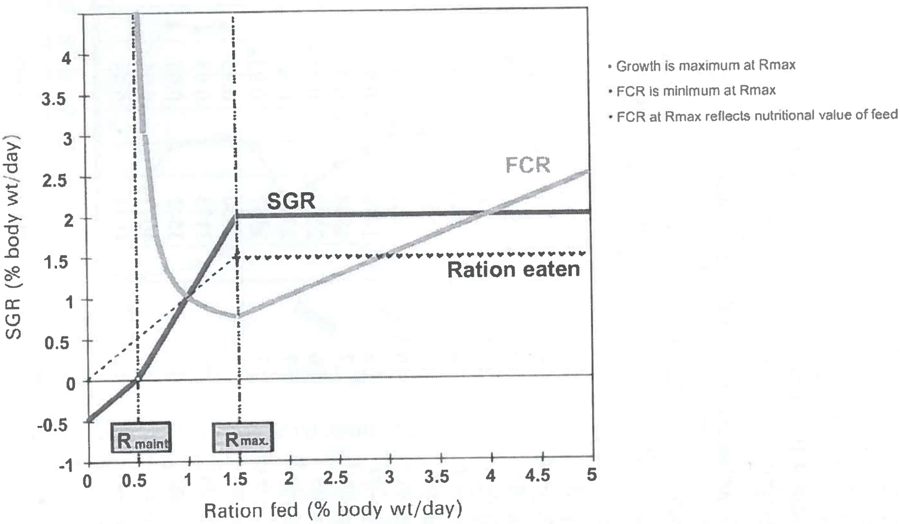


Figure 4.11. General growth-ration and FCR relationships in fish.

being wasted, resulting in financial loss and environmental pollution. It is important to remember that both 'R maintenance' and 'R max' will alter with fluctuating water temperatures, as this will influence the metabolic physiology of the fish. At higher temperatures fish will have a higher maintenance requirement, but also a higher appetite, moving both 'R maintenance' and 'R max' further to the right-hand side of the graph.

4.8.1.2 Feed conversion ratio

At ration levels below 'R maintenance' there is no growth and FCR is infinite. As the ration increases beyond 'R maintenance' the FCR decreases until it reaches a minimum point. The ration consumed by the fish at the point of lowest FCR is termed 'R optimum', which is the optimum ration to obtain the lowest FCR for a given set of conditions. At 'R optimum' the ration required for maintenance is at its lowest percentage of the ration consumed and therefore 'R optimum' and 'R max' should coincide. Increasing the ration beyond 'R optimum' does not result in further growth, so that the FCR continues to increase, as increasing amounts of feed remains uneaten. However, the above hypothesis, regarding the position of the optimum ration with regard to FCR, is not universally accepted. It has been shown that feeding fish to satiation may cause an increase in the gut evacuation rate and reduce digestion efficiency (Usher *et al.*, 1990). In this case the optimum ration for obtaining the lowest FCR would be less than the maximum ration that the fish could consume. There is general agreement, however, that the optimum ration, with regard to FCR will be close to the potential maximum voluntary intake of the fish.

High FCRs can therefore result from both overfeeding and underfeeding. It was once commonplace for farmers experiencing high FCRs on the farm to assume that the situation was linked to overfeeding. This assumption led to a downward spiral, in which the farmer fed increasingly smaller rations in an effort to correct the situation. The result of this was chronic underfeeding and an even worse FCR.

The term 'overfeeding' has been used in criticism of modern feeding practices on salmon farms with the insinuation that salmon are being force fed. Commercially-grown salmon cannot be force fed and only eat to the level of their appetite. The feed intake of salmon is limited by stomach capacity ('R max'), therefore 'overfeeding' in practice will result in feed going to waste.

4.8.2 Practical feeding strategies

An effective feeding strategy which maximises growth and minimises FCR will therefore require the farmer to feed at a point as close as possible to 'R optimum'. At this point, SGR is highest, FCR is lowest and the farmer derives the full nutritional and financial value from his feed. The primary skill of the salmon farmer is to apply this theory practically, in order to improve cost efficiencies on the farm. However, there are many other considerations, such as how to measure when fish are approaching satiation, meal frequency and how fast to feed these meals. Some of the factors affecting the growth of salmon and the performance of feed are listed in Table 4.6. Talbot (1993a) has written a comprehensive review on the interaction between feeding biology and feeding regimes, with particular reference to salmonids.

4.8.2.1 Meal size

Many automatic feeding systems administer feed over the whole period of daylight, rather than as discrete meals. Is it wrong to feed salmon this way or is it better to feed discrete meals. This question has no easy answer. The salmon has a well-defined stomach and in its wild state may be considered an opportunistic carnivore. This might suggest that discrete meals would be preferable to continuous feeding. In practice farmed salmon will make use of the available food to satisfy their need for energy. Provided the food supply is administered to the fish in such a way that each fish in a pen has free access to the feed and in adequate amounts, then each fish should eat until satiated. If, however, the daily ration fed is less than that required by the fish then competition for feed and the development of hierarchies and bimodal size distributions will occur (McCarthy *et al.*, 1992; Kristiansen, 1999). In this event a proportion of salmon may dominate their siblings, causing an increase in stress levels, which in turn can lead to a suppression of appetite. This situation commonly arises when dominant maturing fish share pens with their immature siblings. It is therefore important to feed fish in such a way that each fish will get an equal chance to access the available feed. There are a number of ways in which the farmer can adjust the feeding strategy to minimise competition and the development of hierarchies.

4.8.2.2 Feed distribution

It is important to consider the number of pellets in the daily ration. If there are 10,000 salmon in a pen and only 2000 pellets are fed during a meal then it is obvious that many fish will go hungry. It has been shown that salmon require relatively few pellets to make up their daily ration, typically between 10 and 30, for a ration of 1% body weight per day, for fish weighing between approximately 100 and 5000 g (Talbot, 1993b). Using feed tables and the relationship between pellet diameter and pellet weight to provide a guide to the daily ration required, Talbot (1993b) drew up a feed distribution guide (shown in Table 4.12). This shows the relationship between fish weight, pellet weight and the number of pellets required to be eaten for a ration size equivalent to 1% body weight per day. Therefore, using the recommended feeding rate for a given fish size at a certain water temperature, it is possible to estimate the number of pellets required per pen per day.

4.8.2.3 Meal frequency

If food is not to be administered throughout the day, then into how many meals should the ration be divided and should these meals be of equal size? To answer this question it is useful to consider the behaviour and physiology of the fish. The feeding behaviour of salmon in sea pens has been studied under commercial conditions

Table 4.12. The average number of pellets for different pellet sizes.

Fish weight (g)	Pellet diameter (mm)	Pellet weight (g)	Pellets/kg	Pellets per 1% body wt/day
125	3.5	0.093	10750	13
500	5.0	0.160	6250	31
1000	7.5	0.320	3125	31
2000	10.0	0.920	1090	22
3000	12.0	1.860	540	16
4000	12.0	1.860	540	22
5000	12.0	1.860	540	27

After Talbot (1993).

(Kadri *et al.*, 1991; Smith *et al.*, 1995; Blyth *et al.*, 1999; Talbot *et al.*, 1999). During the summer months it has been observed that salmon will feed throughout the day, but there is a peak in the feeding response first thing in the morning, followed by another peak twelve hours later (Kadri *et al.*, 1991). The appetite of fish is highly dependent on water temperature, but also appears to be linked to stomach fullness and gut evacuation rate. In continuously-fed salmon smolts at about 12°C, both stomach and hindgut fullness showed a diurnal rhythm, with peaks at 17.00 h and 01.00 h respectively (Rawlings *et al.*, 1991). This study also found that the stomach did not empty completely before appetite peaked. Gut evacuation time does not seem to be influenced by fish size, but is influenced by meal size, dietary composition and by interactions between consecutive meals (Grove *et al.*, 1978; Talbot *et al.*, 1984; Elliot, 1991). Using the available information on gut evacuation rates and building in a 'safety-margin' Talbot has drawn up a practical recommendation for the numbers of feeds per day based on the assumption that fish are fed to 80% of satiation at each meal (Table 4.13). For smaller fish in freshwater and post-smolts, feed should be administered regularly throughout the day.

A number of farms, feeding salmon at sea temperatures between 8–14°C, obtain good growth and FCRs when feeding a large meal in the morning followed by another meal late in the afternoon. Although meal feeding has its advantages, the feeding of every sea pen to satiation at the same time could actually produce a sudden high oxygen demand, first from feeding activity and later from feed digestion. It is advisable to be aware of this potential problem, particularly in summer months when the combination of warm sea temperatures, high salinity and the presence of algae blooms can make salmon farms vulnerable to oxygen crashes. An oxygen data logger is a useful piece of equipment that can be used to profile site specific seawater oxygen levels over 24-hour periods during the summer and autumn months. If an oxygen problem is suspected or anticipated, feeding should cease until conditions improve. Feed should then be reintroduced gradually and water quality monitored carefully to ensure that the oxygen levels remain adequate.

Table 4.13. The recommended number of feeds per day for different seawater temperatures.

Temperature°C	Stomach evacuation time (h)	Feeds/day
2	36	1
5	24	2
10	12	3
15	6	5
20	3	7

After Talbot (1993b).

4.8.2.4 Feed rate

It has been shown by a number of researchers that feed can be administered rapidly to healthy fish in optimal environmental conditions (Brett, 1971; Grove *et al.*, 1978; Talbot, 1993b). Talbot concluded that an ingestion rate of around two pellets per fish per minute for salmonids in intensive culture would seem to represent a realistic estimate for fish fed to satiation, at intervals corresponding to the development of maximum appetite. However, to feed at this rate some form of waste pellet detection method should be used to accurately gauge the point of satiation in the pen (see below). When pellets are found to be passing through the main body of the fish biomass, the majority of fish in the pen have eaten their ration, and further feeding at this rate will lead to wastage.

Researchers at Nutreco ARC fed salmon one meal per day per 5°C over a range of sea temperatures and fish sizes (Talbot, 1998). Using pellet detection methods, the average duration of a meal was found to be between 8–18 minutes and to be linearly related to the ration consumed. It was recommended that fish weighing less than 2500 g can initially be fed at a rate of 0.5 kg per tonne of fish per minute, at water temperatures above 10°C, and 0.4 kg per tonne of fish per minute at temperatures below 10°C. For fish weighing more than 2500 g the initial feeding rates should not exceed 0.3 kg per tonne of fish per minute at temperatures above 10°C, and 0.2 kg per tonne of fish per minute at temperatures below 10°C. It was further noted that the feed ingestion rate decreased during the administration of the meal. The researchers found by using pellet detection technology to assess appetite that it is effective to feed meals in two stages. In the first stage feed is administered up to the initial rates suggested above until uneaten feed is passing through the fish and going to waste. At this point there is a high probability that some individuals in the pen may not have been able to access feed given at such a high rate and this initial 'stop' signal can be used as an indicator to reduce input rate. The feed input rate should then be halved until a second 'stop' signal is sensed at which time feeding should cease. This results in a 'stepped' meal shape, which allows a rapid feed input, while reducing waste feed to a minimum. The quick introduction of feed helps to eliminate aggression between fish by increasing the number of feeding opportunities per individual fish. Indeed, the fact that a pen of fish can be fed to satiation in less than 20 minutes often surprises farmers. The large oxygen demand that results from feeding at such a high rate means that the farmer must ensure that oxygen levels are adequate (minimum 6–mg l^{-1}) and the use of oxygen monitoring equipment is advisable.

4.9 FEEDING METHODS

The delivery of feed to fish can be carried out by manual, semi-automatic (cannon) or automatic means, but is there a best way? Again there is no simple answer as factors such as the cost of labour and equipment, the available labour, the dimensions of the site, the numbers of fish, type of pens, capital available, etc., will influence the choice. It is important to remember that salmon cannot grow unless they are fed, and any feeding method used should be able to provide the salmon with sufficient feed to grow at the rate required. Farms which hand-feed only and rely on a small pool of labour almost inevitably find it difficult to keep salmon well fed when other urgent operations such as harvesting, net changing and sea-lice treatments interfere with daily routine.

4.9.1 Hand feeding

The experienced feed operative will spend time monitoring the fish and will know when to feed and when not to. A good feeding operative will also ensure that feed is distributed to maximum effect and will peer as deep as possible into the fish pen to watch the fish feeding in order to gauge the point at which they become satiated. In murky water conditions and in large pens it is difficult to do this accurately.

The expansion of the salmon farming industry and resultant economies of scale have resulted in larger fish farms using significantly greater volumes of feed, while the numbers of workers per tonne of salmon produced has fallen. On larger sites hand feeding is often impractical, due to the large volumes involved, and most of the larger fish farming companies now use mechanised or semi-automated feeding systems. The two feeding methods are not mutually exclusive and a blend of automatic feeding with top-up feeding by hand works well for many farms.

4.9.2 Automatic feeders

There are numerous makes of automatic feeders, the principles of which are outlined below. Essentially a feeder must be able to deliver the volume of feed required at the right time and distribute it across the feeding area.

4.9.2.1 Single point feeders

Feed hoppers that administer food to fish from one location are commonly known as single point feeders. These are used in hatcheries, freshwater loch sites and marine farms and are connected to timers for automatic feeding. The hoppers are normally topped up by hand and the better types are equipped with some form of spreader for better distribution of feed. They can also be linked to certain waste pellet detectors. These types of feeder are relatively inexpensive and will deliver food throughout the day, allowing farm staff to carry out other tasks. The administration of feed from a single point can, however, encourage the development of hierarchies in fish populations. Aggression between individuals can result and, in extreme cases, a few dominant individuals can discourage the main body of fish from feeding (Jobling and Reinsnes, 1986; Jobling *et al.*, 1995). Using spreaders and increasing the number of feeders in each pen can help to resolve such situations.

4.9.2.2 Large-scale automatic feeders

The larger salmon farming companies may have several hundred thousand fish on each site. Rather than employ an army of staff to move feed around and feed fish they have invested considerable sums of money in feeding machinery. A modern large salmon farm will receive feed in one tonne bulk bags, which are then tipped into feed silos located on a centralised feed barge moored close to the fish pens. A computer within the feeding system automatically calculates the amount of feed to be delivered to each pen. An automatic feeder then doses and distributes the feed through plastic pipes to each pen. These feed pipes can be several hundred yards long and water, or more commonly air, is used to propel the feed through the pipe and out into the fish pen. At the pen end of the pipe adjustable spreaders ensure good feed distribution. Oily or dusty feed can cause these pipes to block, necessitating a difficult cleaning job. Some feeding systems also have temperature, oxygen and tidal flow sensors that provide information to the feeder's computer, which then automatically regulates the amount of feed distributed to the farm. Earlier automatic feeding systems typically delivered relatively small amounts of feed into each pen before moving to the next pen. With an increasing trend towards feeding discrete meals, modern systems are adapted to feed large volumes of feed at a high feed rate.

4.9.2.3 Feeding cannons

Feed can be administered directly from a boat using high-pressure feeding cannons, which utilise air or water to spread feed pellets over the pen surface. This method is well suited to feeding salmon at high input rates over a large pen area, and is particularly common in Norway where cannons are used to feed salmon in large circular plastic pens and feeding behaviour and appetite are monitored using underwater video cameras.

4.10 FEED MONITORING SYSTEMS

To some extent the debate regarding the size of ration and number and duration of meals has been superseded by new technology. The appetite of salmon will vary with a number of factors including age of fish, dietary composition, water temperature, life stage and water quality (see Table 4.6) and will rarely be the same on successive days. This is particularly true at cold temperatures when gut evacuation rates are very slow and salmon may eat well one day and very poorly the next. For the same water temperature salmon will typically eat more in the spring when daylight is increasing than in autumn when it is decreasing.

In an increasingly competitive market, farming companies are under pressure to reduce their production costs. The greatest outlay for any fish farming operation is feed, which generally amounts to 50–60% of total production cost. The way in which food input is monitored and controlled therefore represents the area of greatest potential performance improvement for any farm. Assessing the appetite of salmon visually is possible in shallow pens in clear water conditions, but it is difficult to judge the appetite accurately in modern deep pens and when the water is unclear. Over recent years, a number of feed monitoring systems have been developed to accurately feed and gauge the appetite of farmed fish and eliminate the problems of under- and over-feeding. All systems work on the theory that any feed above appetite will pass through the main body of fish in a pen and trigger a detection device, giving a so-called 'stop' signal. The advantages this gives to the farmer are huge; waste feed is minimised, fish can be fed to satiation and there is no longer the concern over whether the ration has been worked out correctly.

There are numerous systems now available, with varying levels of complexity, automation, cost and ease of use. All of the systems give the farmer the ability to monitor exactly what is happening below the surface in the sea pen. Some of these are described below.

4.10.1 Waste feed recovery systems

The method of detecting when fish have reached satiation by collecting waste feed and returning it to the surface is commonly referred to as a 'lift-up system'. It works by gathering uneaten feed into a collection cone from where it passes into a narrow tube and is airlifted up to a sieve-like de-watering device at the edge of the pen. As soon as waste feed appears in the de-watering device the feeder can adjust the feed rate and volume as previously described. This is a simple and very effective system but relies on an operator being present as the feed is administered. It also works best when the feed rate is high as this gives the feeder a stronger signal that the fish are becoming satiated. It is recommended that after the first waste feed appears, the feeder will then halve the feed rate until the second 'stop' signal, when feeding should cease. Lift-ups are not suitable for all locations and problems have been experienced on sites where currents run fast. Lift-ups are relatively inexpensive and the cost of these systems is soon recovered from reduced feed wastage and better growth and FCR.

4.10.2 Computerised pellet sensors and feedback systems

There are systems that use electronic sensors to detect when pellets are passing through the satiated biomass, and which communicate this information to the feed operative or an automatic feeding system. One device uses a pellet sensor, located in a collection cone suspended under the feeding fish, to send an audible stop signal to the feed operative as a predetermined number of pellets pass the sensor. The number of pellets required to set off the stop signal can be adjusted as a threshold rate of waste pellets/minute. Another version uses a radio signal to inform the feeder—who can be alongside in a boat—that feeding should stop. Both types require a feed operative to be present. A more advanced system integrates the same sensor with software that controls an automatic feeder. At regular intervals during the day 'test' amounts of pellets are dispensed into the pen. The sensor signal is used to increase, decrease or maintain the feeding rate to match the ingestion rate of the fish. This type of equipment is also a very useful tool for research on feeding rhythms in fish, but is generally more expensive than lift-up devices; however, the capital costs are soon recovered. As with lift-ups, advice should be sought before planning to install this type of equipment on sites with unusually fast currents, although these can be fitted with a simple current flow sensor that send a signal to the automatic feeder if the current speeds are too fast. Both these methods of detecting when fish have reached satiation have the potential for increasing growth rates and reducing FCRs but there are several other methods for judging the appetite of fish that should be taken into consideration.

Although such systems can seem expensive it is worth considering the pay-back time.

4.10.3 Polaroid sunglasses

The cheapest and simplest method of assessing the feeding response is visual and one that every fish farm should consider. Polaroid sunglasses work surprisingly well by eliminating glare and allowing fish to be seen feeding deeper in the pen. The feeder will still be working to surface activity, however, and a truly effective monitoring system will provide an 'eye' in the bottom of the pen.

4.10.4 Underwater cameras

Underwater video cameras have been used very successfully to monitor fish behaviour and health and are also well suited for waste feed detection. The method works well if the camera is suspended above the centre of the pen and lowered to about one metre above the pen bottom or just below the feeding biomass. The camera is then turned to face directly upward so that the feeding fish are above it. When the fish are satiated, excess pellets fall past the camera and the operator can interpret this as a stop signal. With practice this method produces excellent results, and some Norwegian farms are equipped with cameras permanently located in every pen. Underwater cameras are becoming less expensive and are essential pieces of equipment on farms where they can also be used to check for the presence of stock mortalities and the integrity of nets and moorings.

4.10.5 Doppler systems

A novel method of appetite estimation has recently come into commercial production that uses a combination of cameras and the Doppler effect to monitor the appetite of salmon in sea pens. The Doppler sensor is located deep in the pen and incorporates a camera, which is positioned facing upward. This camera gives a good view of feeding salmon and feed pellets. There is a further camera integrated in the transmission device normally positioned on the top-ring of the pen, monitoring the surface of the pen. The sensor itself uses the Doppler effect to differentiate pellets from fish. The Doppler effect can be likened to one hearing a train approaching from a distance. As the train nears and then passes, the frequency of sound changes. The sensor produces an acoustic signal and receives the echo. The sensor is tuned to recognise pellets and is capable of transmitting the information by radio link to the feed controller over distances up to half a mile away. The user watches the monitor and determines when feeding should be stopped. Alternatively, a threshold level of waste pellets can be set by the operator and the feeder will automatically switch off when this is exceeded. This system should prove to be particularly suitable for use in the very large circular pens serviced by centralised feeding systems.

4.10.6 Sonar systems

Sonar-type systems, as used by modern fishing fleets to locate shoals of fish, have been tested in Norway. These devices trace the feeding behaviour of fish and a skilled operator can use the information to tell when fish are close to satiation. This method can involve a great deal of subjective interpretation.

None of these systems are 'plug and play' and require training, experience and the commitment of management and staff to work effectively. Choosing suitable feed monitoring equipment for a particular operation is also a critical success factor (i.e., the use of waste feed cones in heavy tidal flow environments is not recommended). Regular data analysis, modification of routines and dedicated staff can, however, produce substantial improvements in farm performance.

4.11 PRACTICAL CONSIDERATIONS ON THE FISH FARM

All farm sites differ in terms of location, staff, pen types, water quality, discharge consents, salmon stocks, etc. It is the skill of the site manager, therefore, to apply the theoretical knowledge of nutrition and best feeding practices to the local situation.

4.11.1 Freshwater feeding

Following hatching of the eggs, the swim-up fry is supplied with nutrients from its yolk sac, but once this supply is exhausted the resulting salmon parr require frequent feeding. At this stage it is usual to use single point automatic feeders, or 'belt type' clockwork feeders, to administer feed. Salmon parr are normally fed throughout daylight hours or during the entire light phase of a photoperiod regime. Maintaining good water quality in the hatchery is crucial and waste feed should be removed along with any dead fish at regular intervals during the day. For small fish the cost of feed is inexpensive relative to the value of smolts and it is usual to provide a slight excess of feed. It is, however, important to ensure that this does not lead to the breaching of discharge consent criteria. The importance of minimising phosphorus excretion in freshwater fish was discussed earlier (Section 4.5.1.1). Freshwater diets specially formulated to contain low levels of phosphorus should be used in these situations.

4.11.2 Post transfer period

Following transfer from freshwater into seawater, it is both usual and advisable to continue to feed the same freshwater diet the fish were eating prior to transfer. There is an important exception to this general rule; if, before transfer to seawater, the fish were fed a special diet containing salt this should not be fed to smolts in seawater. The salt is sometimes added to 'transfer' diets to 'pre-adapt' the fish to seawater. Every effort should be made to reduce stress by minimising the changes the fish experience during and after the transfer period.

To maximise the value of fish feed it is important to appreciate the changes that smolts undergo during the transfer period. Newly-transferred smolts may have moved from highly-stocked tanks or net pens into large marine enclosures, where the stocking density is low. The light conditions are different, the salinity is higher and a whole number of environmental stimuli combine to create a potentially stressful environment for the fish. It should be no surprise that smolts can be reluctant to start feeding and great care should be taken to encourage fish to feed at this stage. In freshwater, pre-smolts are typically fed small amounts of feed at regular intervals and this practice should continue until the majority of fish are judged to be feeding. It has been found that it can take up to a month from seawater transfer for all viable smolts to begin feeding (Stradmeyer, 1994). It has also been shown that the growth performance in freshwater was not a significant determinant of subsequent growth in seawater as, irrespective of size at transfer, those individuals that start to feed early can have a definite growth advantage over the rest of the population (Stead *et al.*, 1996). Although every salmon farmer will wish to avoid wasting feed, an excess of feed should be offered at this time to increase the feeding opportunities for individual fish. Over the growth cycle this 'extra' feed will represent a tiny proportion of the total feed input. In view of the small biomass relative to the volume of water, in sea pens it may be difficult for the newly-introduced fish to locate the feed. To improve the chances of fish locating the feed some farmers pull up the nets to reduce the feeding volume, but this can increase the susceptibility of fish to cataracts from exposure to ultra-violet light and increase the interest of avian predators.

One week after transfer, seawater smolt diets should be introduced. When changing feed type or when increasing pellet size, it is advisable to mix the new diet with the original diet. The most recent guidelines suggest that the original diet should initially make up 75% of the total mix, with the proportion of the 'new' diet gradually increasing to a 100% over a period of 10–14 days. If mixing feed sizes is a practical problem then the old diet may be fed at the beginning of each feed, followed by a gradually increasing top-up with the new feed. A proportion of smolts may never feed or may cease feeding after a short period in the sea, and these are sometimes referred to as 'failed' smolts. Some farmers report that the incidence of failed smolts can be reduced by feeding a diet to which no extra fat has been spray coated on to the pellet, at the end of each normal meal. The uncoated pellet absorbs water and becomes softer than conventional pellets, which may improve its palatability to fish. Underwater cameras can check for mortalities and also to assess when all fish are feeding normally. During the first few months following transfer it is recommended to provide 4–6 feeds a day. At this stage, when feed volumes are low, it may be advisable to feed by hand, ensuring that the entire feeding volume of the pen receives food. The feeding volume may reduce and change shape with currents and tide and an experienced feeder will take account of this.

Once the smolts are all feeding, it is typically recommended that the number of feeds per day be reduced in line with temperature, following the recommendations given in Table 4.13. In one study it was found that growth rates became positive and comparable to fresh water rates from 58–86 days post transfer (Stead *et al.*, 1996). Once acclimated, Atlantic salmon smolts can grow at similar rates in a variety of salinities (Duston, 1994).

4.11.3 Batch weighing

For the fish farmer it is vital to know the biomass present at any time on the farm. It is relatively straightforward to check the mean weight of the stock by a programme of sample weighing. Fish numbers are, however, more difficult to assess and the number of salmon recovered at harvest can often be less than expected. This situation can occur despite smolt numbers being checked first by the smolt supplier and then again by the recipient on delivery at the sea site. These 'unaccountable' losses may be due to fish escaping, cannibalism, theft and predation as well as from miscounting the fish on arrival at the farm. Without good knowledge of fish numbers and stock weights, estimates of ration fed and feed conversion efficiencies will be inaccurate.

In order to keep track of production costs and growth targets, fish should be sampled for weight at regular intervals. In the hatchery this could involve weekly weighing, with the interval extending to monthly weighing on marine farms. Although batch weighing of fish to give an average weight is better than nothing, it is also important to look at the frequency of distribution of individual fish weights within the sample. It is advisable to weigh between 150 and 200 fish per tank or pen sampled and to get a representative sample from each pen using, for example, a sweep net rather than using feed pellets, which attract only those fish feeding at or close to the surface. In order to reduce stress on the sampled fish it is recommended that they are anaesthetised immediately after capture. It is also a good idea to draw up a sampling schedule so that the same pens are not disturbed and weighed every time sampling takes place. An alternative method, which is less stressful to the fish, is to use an electronic biomass estimator, which analyses length-to-depth relationships and calculates biomass using a constant value. The biomass estimator systems typically consist of computerised frames hung at various depths in the pen that calculate the weight of fish swimming through them. There are also various camera- and sonar-based estimators, which use image analysis and sound waves respectively to estimate fish weight.

Once the data are collected the SGR of fish from the last sample point can be calculated and this can be compared to the amount of feed administered over the same period. From this information the FCR and FR can be determined. Poor fish growth, coupled with a low feed rate, could indicate underfeeding, a palatability problem, or the onset of a health problem such as pancreas disease. The frequency of distribution of fish weight can also be examined for clues to the reason for poor performance. For example, if the number of large individuals has increased but the overall growth is disappointing then the feed rate may be too low or the feed distribution may be poor so that only a few dominant individuals gain access to the feed. In order to gain the maximum benefit from feed it is important to have regular information about fish performance.

4.11.4 Sexual maturation

There is evidence that growth rate and rates of sexual maturity are linked. Fast-growing salmonids may mature at a younger age than slower-growing siblings under the same conditions (Alm, 1959; Thorpe *et al.*, 1983; Wooton, 1990; Silverstein and Hershberger, 1992). It is hypothesised that some threshold for size, rate of growth or energy storage must be surpassed during critical periods for the maturation process to begin (Bailey *et al.*, 1980; Saunders *et al.*, 1982; Rowe and Thorpe, 1990a,b; Rowe *et al.*, 1991; Berglund, 1992; Silverstein and Shimma, 1994; Silverstein *et al.*, 1997; Silverstein *et al.*, 1998). For salmon farmers this can mean that more salmon will mature as grilse after only one sea winter.

Stead *et al.* (1999) identified two phases of sexual maturation in Atlantic salmon. During the early phase (October–April) a slow rise in serum steroid hormone levels was accompanied by a relatively high rate of food consumption and growth. The late phase (May–October) was characterised by a more rapid rise in serum steroid hormone levels, but a decreased growth rate in association with inappetance.

Maturation has serious implications for salmon farmers; as well as the inappetance mentioned above, the fish soon lose condition. Sexually mature salmon are unfit for sale, being dark skinned, pale fleshed and having a poor flesh texture and would normally be graded out and sold before reaching maturity. The proportion of fish in a pen maturing as grilse is not entirely predictable and will vary from year to year. Grilse will grow faster than immature salmon and may average more than 3 kg at harvest. However, a lower price may be obtained for grilse, as the market is aware that farmers must sell them before they reach maturity. Some of the larger salmon farming companies are deliberately growing high grilsing strains of salmon as a part of a strategy for the production of market-sized fish throughout the year. Maturation rates can be reduced using a restricted feeding regime during certain months of the year (Rowe and Thorpe, 1990a, b; Berglund, 1992) and by the use of controlled photoperiod (Porter *et al.*, 1999).

4.11.5 Marine pen lighting

Under natural light conditions salmon exhibit variations in appetite and growth rate. The use of overhead or underwater lighting during the early part of the year can cause a marked reduction in the number of maturing fish. Lights are also sometimes used to achieve better survival of S0 autumn smolts following transfer to sea and for improvements in subsequent growth. In this case lights may be used from October through to the following April. The use of continuous lighting may cause the fish to lose appetite for the first 5–12 weeks' exposure, but this can be followed by up to a threefold increase in growth compared to natural conditions (Oppedal, 1998). Feeding practices should reflect changes in appetite related to the use of lights.

4.11.6 Sea lice

During the marine phase of growth, farmed salmon may miss a number of feeding days because of problems accessing exposed farm sites during bad weather. The largest numbers of feeding days are lost, however, because of the need to starve fish prior to sea lice treatments. This practice can cause some Scottish salmon farms to lose up to 30 days feeding during the marine phase of their growth cycle (personal communication). Fish can recover at least some of this lost growth potential as long as the food supply is adequate (Jobling, 1994). This type of growth response is often referred to as 'catch-up', recovery or compensatory growth. For the farmer to take advantage of this compensatory growth potential they will have to be aware of any increase in the appetite of his stocks and match this by increasing the feed rate concomitantly.

4.12 FATE OF FISH FEED: ENVIRONMENTAL IMPACT

In the process of digestion of feed a certain amount of waste is produced, which mainly derives from metabolic activity. Further waste, typically to a lesser degree, can derive from uneaten feed pellets. The waste matter from excreted products and uneaten feed pellets consists of a number of both organic and inorganic compounds. With regard to assessing their effect on an aquatic environment the most important parameters are:

- suspended solids;
- organic matter;
- total nitrogen;
- nitrate;
- ammonia (ammonium and un-ionised ammonia);
- total phosphorus;
- phosphate;
- nature of the receiving water.

Excess emission of waste matter from fish-farming activities can have an effect on the receiving water, be it a river, loch or coastal area.

In freshwater, phosphorus is normally the growth-limiting nutrient and, if present in excess, will stimulate algae and weed growth. In running waters, excess organic matter can have an effect on oxygen levels as oxygen is used for its decomposition. Discharged solids can alter the nature of riverbed substratum and influence the macro fauna. In a loch, excess phosphorus can cause an increase in primary production, i.e., increased phytoplankton growth, and change its trophic state.

In the marine environment, nitrogen is normally the growth-limiting nutrient and, if present in excess, an increase in primary production may occur. Deposits of fish excreta and uneaten feed pellets can have an effect on the seabed below the pens (likewise in freshwater lochs). The decomposition of this waste on the seabed creates an oxygen demand, which can give rise to physical, chemical and biological changes in the sediment. These occurrences are, however, normally only visible under the pen rearing system or in the immediate area around it and not in a larger area in general.

Most coastal salmon farming activities have little or no significant effect on the environment, with regards to enrichment caused by feeding. At present, it is only under particular circumstances, such as the combination of poor hydrographic conditions and excessive fish production, that noticeable impacts may occur.

To control existing and plan future salmon farm developments, one must know the amount of waste matter emitted per given size of production. This can be calculated from knowledge of the content of various compounds in the feed and by knowledge of the content of these same compounds in the fish. When one knows how much feed is used for a given production, i.e. the feed conversion rate (FCR), then:

$$\text{Nutrient in feed used minus that retained in fish} = \text{waste matter} \qquad (10)$$

A typical protein content in salmon feed is 45% and the protein content in whole salmon is around 18.75%. The nitrogen content in protein is 16%, i.e., one tonne of salmon feed contains $450\,\text{kg} \times 0.16 = 72\,\text{kg}$ of nitrogen and one tonne of salmon growth has retained $187.5 \times 0.16 = 30\,\text{kg}$ of nitrogen. With an FCR of 1.2 : 1, the amount of nitrogen emitted per tonne of growth is calculated as follows:

Feed usage	1.2 tonne @ 72 kg N tonne feed^{-1}	= 86.4 kg
Retained in fish	1 tonne salmon @ 30 kg N tonne fish^{-1}	= 30.0 kg
Waste		= 56.4 kg

This gives the following equation for nitrogen discharge in kg per tonne of salmon produced:

$$(\text{Protein (\%) in feed} * 0.16 * \text{FCR} * 10) - 30$$
$$= \text{kg N emitted per tonne salmon produced}$$

Modern high-energy salmon on-grower feeds may contain less than 40% protein and therefore the nitrogen discharge will be less than 50 kg N per tonne of salmon produced, provided the FCR is 1.2 : 1 or less.

4.12.1 Phosphorus

The phosphorus level in fish feed can be derived from the declared content or by analysis. In today's high-energy and highly-digestible feeds, typical phosphorus contents lie around 1.0 to 1.1%. The phosphorus content in salmonids is around 0.5%. This gives the following equation for phosphorus discharge in kg per tonne of salmon produced:

$$(\text{Phosphorus content in feed in } (\%) * \text{FCR} * 10) - 5$$
$$= \text{kg P emitted per tonne salmon produced}$$

Table 4.14 illustrates clearly that the lower the FCR then the lower the amount of waste matter created. Feed and a good feeding regime are very important aspects in minimising the environmental impact of salmon farming. Today, typical FCRs for smolt hatcheries lie around 1 : 1, whereas some 5–10 years ago, FCRs in excess of 1.5 were common. In pen farming of salmon, FCRs are typically around 1.2–1.4 : 1 whereas 5–10 years ago they were between 1.5–2 : 1. These improvements within recent years are due to a combination of the improved quality of salmon feed and through improved feeding strategies, which include monitoring of fish feeding habits and monitoring of feed loss.

Feed formulators sometimes use vegetable protein to replace a certain amount of fishmeal in freshwater diets and thereby reduce the dietary phosphorus content. The use of enzymes may give the feed formulator a further potential to reduce phosphorus discharge by making the phosphorus present in the dietary raw materials more bioavailable to the fish. It has been demonstrated that the enzyme phytase can be used to improve the nutritive value of canola protein concentrate and decrease phosphorus out put (Forster *et al.*, 1999). The authors demonstrated that dietary phytase has the potential to improve the availability of phytate phosphorus in canola protein concentrate.

Table 4.14. Discharge of total nitrogen and phosphorus in kg tonne^{-1} of salmon produced, at different feed conversion rates.

FCR	Discharge in kg tonne^{-1} of salmon produced	
	Total N (45% protein)	Total P (1%)
0.8	27.6	3.0
1.0	42.0	5.0
1.2	56.4	7.0
1.4	70.8	9.0
1.6	85.2	11.0
1.8	99.6	13.0

The improvements over the last 5–10 years have meant a significant reduction in nutrient emission from salmon farming per tonne of salmon produced.

4.12.2 Control and monitoring

A water body has a capacity to assimilate a certain amount of organic matter and nutrients without causing noticeable ecological change. To ensure that concentrations of various water-quality parameters do not exceed certain predetermined levels in the receiving water, a land-based fish farm, such as a smolt production unit, is issued with a 'discharge consent' setting maximum concentrations of various waste materials in their discharge. To check that land-based fish farms comply with their discharge consent, water authorities typically carry out monthly sampling of key water-quality parameters. In the UK, for example, this is typically followed by regular biological assessments of the fauna in the area downstream from the discharge water.

Emission from a pen farm is a diffuse discharge and it is not possible to actually measure discharge concentrations. For this reason a salmon farm will typically be granted a certain maximum annual production. The size of the maximum production (maximum nutrient release) will be dictated from the hydrographic conditions, for instance water volume of the immediate area, tidal water exchange, etc. Water authorities may carry out regular control and monitoring of coastal fish farming activities and focus on nutrient levels, primary production, and look for effects on fauna normally residing in or on the seabed below the pen system and in the surrounding area.

Talbot and Hole (1994) commented on the role of fish feed manufacturers in reducing the environmental impact of fish farming. They considered that fish feed manufacturers could contribute by:

1 Providing information to facilitate efficient husbandry in order to reduce wastage through uneaten food.
2 Optimisating nutrient retention through improved digestibility of nutrients and dietary nutrient balance.
3 Producing palatable feeds.
4 Using appropriate feed process technology to reduce leaching, dust and pellet disintegration.
5 Minimising fish mortalities through the development of health-promoting diets.

4.13 THE INFLUENCE OF NUTRITION ON SALMON CARCASS QUALITY

Market-sized farmed salmon are now available throughout the year and represent a healthy, affordable and malleable source of food that can easily be processed into a variety of value-added products. Salmon is gradually displacing some of the more traditional fish seen on our restaurant menus and this trend is likely to continue as farmed species, such as salmon, offer continuity of supply, freshness and documented quality assurance from egg to the market place. This scenario is, however, dependent on the consumer continuing to view farmed fish as wholesome and tasty food items, and this section considers the role that dietary composition and feeding regimes have in influencing the carcass quality characteristics of farmed salmon. Earlier, the reader's attention was drawn to the possibility of potentially limiting world supplies of fishmeal and fish oil and the high probability that partial substitution of these raw materials with vegetable proteins and oils will be required. It is therefore essential for the continuing growth and success of salmon farming that the effects of altering dietary composition and feeding practices are thoroughly researched and clearly understood. Both these factors can impinge on the quality of salmon; however, it should always be remembered that the most economically-important carcass quality characteristics, such as flesh colour, muscle fat and texture, are strongly influenced by other factors, particularly genetics.

4.13.1 Carcass fat

Farmed salmon is generally considered fatter than it was ten years ago. Higher standards of fish health and husbandry and improvements in diets and feeding regimes have led to higher growth rates in farmed stocks. Ten years ago, farmed salmon were typically fed sub-optimally and flesh fat levels were consequently lower. The ability of salmon to accumulate relatively high levels of fat in muscle is a consequence of their evolution and is perfectly natural. Salmon with high fat stores may be more difficult to process, but such fish are merely taking advantage of the available feed to fulfil their genetic potential to accumulate energy stores. Provided salmon have access to enough feed the muscle lipid levels increase as the fish gains weight (Lie *et al.*, 1988a; Waagbø *et al.*, 1993; Arnesen *et al.*, 1995; Hemre *et al.*, 1995a,b; Asknes, 1995). The typical development of muscle lipid for salmon fed high-energy diets is shown in Figure 4.12, which also clearly shows the wide range in muscle lipid values for any particular weight. Because the tendency for salmon to lay down muscle fat is under a high degree of genetic control there is a good potential for selectively breeding for lean salmon. Flesh lipid levels are typically higher in grilse when compared to immature salmon of the same weight and, as a result, grilse may be less favoured by processors for curing into traditional smoked products. The flesh levels of grilse may contain more than 20% lipid per kg in a mid-dorsal section of muscle (personal observation). This compares to the muscle lipid level typically found in immature harvest-sized Scottish salmon of 3–4 kg, which will typically range from 10–14 % (personal observation). Bell *et al.* (1998) found that commercially-grown Scottish salmon fed 30% oil diets had flesh lipid levels averaging 11.8%.

Salmon may be divided up into various sections for sampling and a number of these cuts are shown in Figure 4.13. In Scotland the Scottish Quality Salmon (SQS) cut is used and would approximate to Section 3, the Fecamp cut. Salmon from farms where feeding is optimised for high growth rates may have muscle lipid levels higher

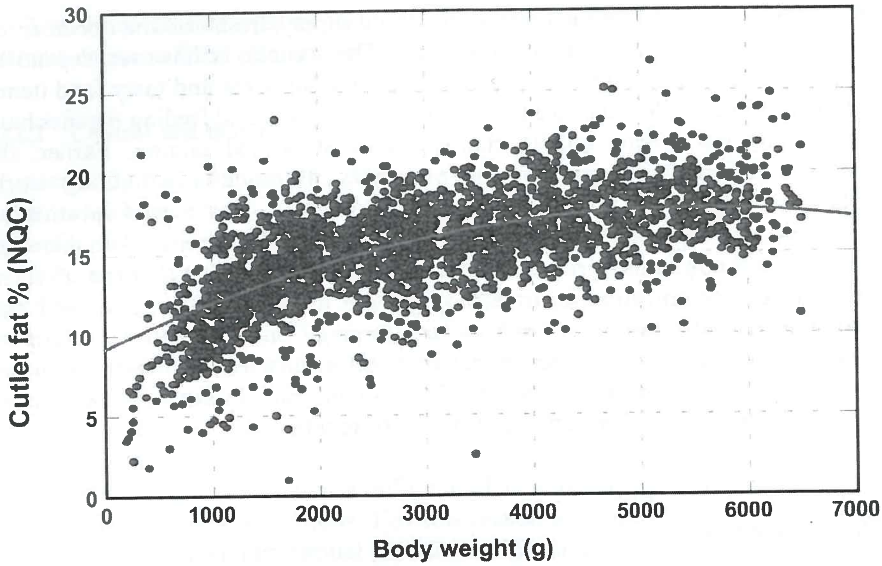
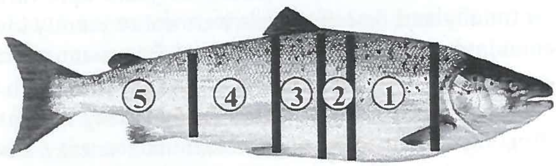


Figure 4.12. Development of muscle fat in famed Atlantic salmon.



Sample cut	Dorsal %	Ventral %
1 Front part	15.1	15.5
2 Labeyrie cut*	14.3	14.8
3 Fecamp cut*	12.9	16.1
4 Norwegian Q. cut	9.0	11.8
5 Tail part	6.0	9.1

* After Bakke and Holm, (1993)

Figure 4.13. Fillet fat distribution of a Norwegian farmed salmon (% wet weight).

than this. Figure 4.13 shows an example of the lipid levels found in the various sections of a harvest-sized Norwegian salmon.

The lipid in salmon flesh, unlike land animals, contains high levels of the HUFAs that are beneficial to human health and which fulfil recommendations for healthy lipids in the human diet (Groom, 1993; Frøyland *et al.*, 1996).

4.13.1.1 Dietary composition

The expression 'you are what you eat' has been applied to fish, but this really applies to the similarities between the fatty acid characteristics of the diet and the resulting carcass characteristics of the salmon. Provided a sufficient quantity of EAAs are supplied in the diet then the protein composition of the fish will be predetermined by genetic factors. Excess dietary protein will be deaminated but may also be broken down and stored as fat. Earlier the concept of protein sparing was discussed (Section 4.4.2.1), in which the protein is spared for growth with the energy supplied by dietary lipids. Excess dietary protein as well as lipid can result in increased carcass fat levels, and it is a prime objective for the feed formulator to balance diets to minimise the production of excess fat in market-sized salmon. The composition and amount of the dietary lipid fed has been shown to influence the fatty acid profile of the fish, which is important in terms of taste and nutritional quality (Hardy *et al.*, 1987; Thomassen and Røsjø, 1989; Waagbø *et al.*, 1993). The effects on carcass quality of partially substituting vegetable oils for fish oils were discussed earlier.

4.13.1.2 Dietary energy

The energy density of commercial salmon diets continues to increase for reasons of improved feed efficiency. This must be balanced against potential negative changes in carcass quality. There has been some concern at the processing and retailing end of the value chain that the higher energy density of diets is producing salmon that are becoming oilier and more difficult to process, particularly into traditional smoked salmon products. Comments from the marketplace must be heeded carefully by the salmon feed and farming companies, but it is necessary to consult the growing amount of available scientific literature on the subject to form an objective view of this topic. The interested reader can use the references quoted below as a source of further research on the relationship between dietary energy and carcass quality.

The amount of energy the fish consumes will affect the level of lipid in the carcass and can also influence the time of maturation (Rowe and Thorpe, 1990a, b; Rowe *et al.*, 1991; Hillestad *et al.*, 1998). Feeding studies on the relationship between dietary formulation and carcass composition must take into account the positive correlation between fish weight and muscle lipid levels. Several feeding studies found no significant correlation between diet and carcass composition in Atlantic salmon (Waagbø *et al.*, 1993; Hemre *et al.*, 1995b). However, Sheehan *et al.* (1996) found that a variation in dietary lipid from 210 to 300 $g\,kg^{-1}$ produced a variation in muscle lipids from 8–15% of muscle wet weight using fish in the same size range. In an experiment to determine the effects of feeding increasing lipid concentrations Hemre and Sandnes (1999) fed Atlantic salmon of around 1 kg weight three isonitrogenous diets with dietary lipid levels of 310, 380, and 470 $g\,kg^{-1}$ until they reached approximately 2.7 kg in weight. They found that there was a positive correlation between dietary lipid and muscle lipid, when fish of the same weight from the three groups were compared. Although the muscle fatty acid composition reflected the dietary fatty acid profiles and was similar in the different dietary groups the ratio of *n*-3/*n*-6 fatty acids was highest in the group fed the highest level of dietary lipid. Overall the results supported the findings of Einen and Roem (1997) that a diet with a lipid level of $350\,g\,kg^{-1}$ and a digestible protein/digestible energy ratio of 16–$17\,g\,MJ^{-1}$ was optimum for growth and feed conversion in large (2–4 kg) salmon. Another interesting finding, with regard to carcass quality, was that the level of vitamin E in the muscle slowly decreased as the muscle lipid increased. Vitamin E acts as an antioxidant to protect biomembranes from damage by free radical-mediated oxidation (Hemre and Hansen, 1998) and has been found to be effective in delaying the development of rancidity after slaughter and freeze storage in Atlantic salmon (Waagbø *et al.*, 1993; Hemre *et al.*, 1998). Supplementation of diets with alpha-tocopherol (AT) has been shown to increase the concentration of AT in the tissues (Waagbø *et al.*, 1993). The influence of AT acetate on the short- and long-term storage properties of fillets from Atlantic salmon fed high lipid diets has been studied (Scaife *et al.*, 2000). Flesh colour score, but not carotenoid content of fillets, was significantly higher in fresh fillets from fish fed diets in which the dietary AT:PUFA ratios were 6.3 and $9.5\,mg\,g^{-1}$, compared to $2.0\,mg\,g^{-1}$ in the control diet. Colour score, carotenoid content and AT content decreased and the content of the lipid oxidation products increased following storage of fillets at $-20°C$ for up to 12 months, although the two groups highest in AT content had significantly lower oxidation products than the control.

Although the influence of diet and feeding regimes on carcass composition in Atlantic salmon is a well-researched area, further research is likely to be generated as a result of the increasing levels of lipid used in farmed salmon diets. In Norway the use of 40% oil diets is already widespread. The phenomenon of free oil leaching from the muscle, especially during processing, is an increasing problem and has become the focus for new research.

4.13.2 Flesh texture

The rate of growth of salmon is dependent upon the feeding regime, dietary composition and environmental parameters. These factors can influence the structure and metabolic characteristics of the muscle tissue. Muscle cellularity has been shown to be a major determinant of flesh texture, and texture characteristics have been shown to be related to the fibre diameter and the firmness value (Hatae *et al.*, 1990; Fauconneau *et al.*, 1993; Hurling *et al.*, 1996). A network of collagenous sheets, the mycommata, surrounds individual fibres and blocks of fibres and holds the muscle structure together. The formation of collagen involves specific nutrients such as vitamin C, selenium and the amino acid, proline; however, the extent to which dietary composition can influence the mycommata remains unclear. Johnston (1999) has reviewed the influence of muscle development and growth on flesh quality.

Major changes in flesh texture can occur following death and it has been demonstrated that, following rigor mortis, fish stored on ice become softer with increasing storage time (Azam *et al.*, 1989; Ando *et al.*, 1992). Faergemand *et al.* (1995) found that storage time was the dominating factor affecting fillet texture in rainbow trout.

The role of nutrition in other aspects of quality, such as juiciness and smell, is less thoroughly researched. A study investigating the impact of dietary lipid source on muscle fatty acid composition also evaluated several sensory parameters (Obach *et al.*, 2001). Atlantic salmon were fed a diet coated with a mixture of 50% capelin oil (CO) and 50% soybean oil (SO) for an initial period during which their average weight increased from 873 g to 1666 g over 107 days. These salmon were then split into three groups and fed the SO diet, a diet coated with pure CO or a diet coated with pure Peruvian anchovy oil (PO) for a period of 93 days. In a sensory evaluation on smoked salmon from the three groups, a panel of trained judges found significant differences in two out of 26 sensory attributes that were tested. The differences in colour tone and firmness—where the SO group scored lowest and the PO group highest—were, however, relatively small. In cooked salmon, significant differences were found in four out of the 19 attributes tested. Salmon taste, acidic taste and juiciness were significantly higher in the CO group compared to both the PO and SO groups, while the PO group had a significantly higher intensity of bitter taste. Again, these differences, although significant, were relatively small.

4.13.3 Flesh pigmentation

The characteristic pink or red flesh colour of Atlantic salmon is an important factor in the marketing of farmed salmon. When ranking the most important quality criteria for Atlantic salmon, Koteng (1992) found flesh colour second only to freshness. The price and quality of farmed salmon are becoming increasingly significant factors as the global production of salmon flourishes. The attractive colour of both wild and farmed salmon flesh is characteristic of salmonids and originates from carotenoid pigments ingested in the diet and subsequently deposited within the white muscle mass. More than 20 different carotenoids have been found in the flesh of salmonids, but the predominant carotenoid found in salmon and trout muscle is astaxanthin (Czeczuga, 1979; Torrisen *et al.*, 1989; Putnam, 1991). Many animals utilise carotenoids but fish, like higher animals, cannot synthesise carotenoids *de novo*, neither can they convert astaxanthin into canthaxanthin or vice versa. In fact, only plants and protists are able to synthesise carotenoids. In nature wild salmon consume the carotenoid pigment, astaxanthin (3,3′-b,b-carotene-4,4′-dione) from natural food sources, such as small crustaceans like krill and shrimp. Farmed salmon do not generally have access to natural food containing carotenoids and the flesh would therefore be grey rather than pink. (The same is true of certain species of flamingos, whose beautiful pink plumage is also coloured by astaxanthin.) Farmed salmon should therefore be fed diets containing specific carotenoids, such as astaxanthin and canthaxanthin, in order to develop the flesh colour characteristic of the species.

To relegate astaxanthin to the role of a cosmetic flesh colour enhancer would do it an injustice. Carotenoids are believed by many to have a role in the natural physiology of salmon and trout. They are accumulated in the muscle of salmonids, but not in the muscle of most other fish species. In salmonids the pigment is removed from the muscle at spawning time and directed to the skin and reproductive organs where it accumulates in high amounts. The pigments enhance skin colour and probably act as a colour attractant to potential mates. In addition to this behavioural role in the reproduction process, a number of other physiological functions have been suggested for carotenoids. These include:

- antioxidant action;
- camouflage for first feeding fry;
- improving egg viability;
- improving the growth and survival rate of fry;
- involvement in the immune system;
- acting as a precursor for vitamin A.

For reviews on the possible biological functions of carotenoids see Burton (1989), Schiedt *et al.* (1985) and Putnam (1991).

4.13.3.1 Natural sources of astaxanthin

Crustacea

Crustaceans such as shrimp and krill (*Euphasia* spp.) are natural dietary sources of pigment for wild salmon. These and other crustaceans and crustacean by-products are commercially available and, when included in the feed, have been shown to pigment salmonids. However, these products contain low levels of protein and high levels of moisture, ash and chitin, which limit the amount of these products that can be formulated into salmon feeds. They may also contain low and variable amounts of astaxanthin, often in an esterified form that is generally less bioavailable than pure forms of the carotenoid (Torrissen *et al.*, 1989). Synthetic canthaxanthin, for example, has been shown to accumulate in the muscle of rainbow trout at a higher rate than astaxanthin from shrimp (*Pandalus borealis*) waste (Tidemann *et al.*, 1984). In order to produce the flesh colour currently demanded by the market (approximately 6–8 mg astaxanthin per kg of salmon flesh) the salmon diet would typically have to contain 10–25% of this material.

Salmon diets are energy dense and designed to produce rapid growth with the minimum amount of waste. The incorporation of large amounts of crustacean waste would reduce feed conversion efficiency and increase faecal mass. The astaxanthin content of crustacean waste varies both with the species but also with the processing method used to separate the waste from the primary commercial product. The astaxanthin found in crustaceans is usually found as a mixture of its free form and as monoesters and diesters. Astaxanthin esters must first be hydrolysed in the digestive tract before free astaxanthin is deposited in the flesh (Torrissen and Braekkan, 1979). Certain plants, such as the pheasant's eye narcissus, *Adonis aestivalis*, also produce astaxanthin, and in the future it may be possible to produce commercial quantities of this pigment from plants. The choice of pigment source is partially dependent on local market forces and natural sources of pigment are used in some organic salmon diets.

Yeast and algae

Alternative sources of astaxanthin are now also produced commercially from yeast and algae. The yeast *Phaffia rhodozyma* (Johnson *et al.*, 1980) and the algae *Haematoccocus pluvialis* (Sommer *et al.*, 1992) and *Chlorella vulgaris* (Gouveia *et al.*, 1996) have been studied as potential commercial pigments sources for salmonids. The bioavailability of yeast and algae products can be reduced unless the cell wall is ruptured as was demonstrated for *P. Rhodozyma* (Johnson *et al.*, 1980). However, increasing the bioavailability of the pigment may make it more vulnerable to oxidation. When priced competitively these products can offer a realistic alternative to synthetic forms of pigment (Whyte and Sherry, 2001), but for use in feed plants the synthetic forms of pigment offer several advantages in terms of volume, consistency and stability under manufacturing conditions. In most salmon-producing countries it is now legal to incorporate these naturally-derived sources of pigments into salmon feeds. Readers interested in alternative sources of pigments can refer to Spinelli (1979), Torrissen *et al.* (1989), Sanderson and Jolly (1994) and Hinostroza *et al.* (1997).

4.13.3.2 Synthetic pigments

From a global perspective, synthetically-produced astaxanthin is the most widely-used source of pigment for farmed salmonids. Before commercial quantities of astaxanthin were available, the fish farming industry used another carotenoid pigment, canthaxanthin (β,β-carotene-4,4′-dione), to colour the flesh of salmonids. Canthaxanthin has also been used to colour egg yolk and in other food and human tanning products. It is a naturally-occurring pigment found in certain algae and fungi, but in the marine environment it is found in only small amounts in a few aquatic crustaceans (Choubert, 1991). Astaxanthin, the natural pigment of salmon and trout, is now in widespread use and has become the pigment of choice for many markets. The astaxanthin used in commercial salmon diets is sometimes described as 'nature-identical' as it is very similar to the form of astaxanthin found in the natural prey of wild salmon (Choubert *et al.*, 1995). This astaxanthin differs slightly from some other natural forms of astaxanthin, which can have a different proportion of the three optical isomers of astaxanthin. The ratio of the three optical isomers (3R, 3′R, 3R, 3′S and 3S, 3′S,) found in wild salmon and trout flesh has been shown to be surprisingly similar from different geographical locations, with between 78–85% of the isomers composed of the (3S, 3′S) astaxanthin isomer (Schiedt *et al.*, 1981). This contrasts with astaxanthin from Phaffia yeast (*Phaffia rhodozyma*) which is in the 3R, 3′R form. The ratio of optical isomers in muscle generally reflects the ratio of optical isomers in the ingested feed.

Nickell and Springate (2001) have recently reviewed the subject of pigmentation in farmed salmonids.

4.13.3.3 Pigmented fish feed production

During the manufacture of fish feed, pigment can be added to the feed mix before it passes through the pelleting or extrusion process, or it can be emulsified and added to the dietary lipid which is then coated on to the pellet. However, carotenoid pigments are highly vulnerable to oxidation and oxidative losses of pigment can occur during the manufacturing process. Such losses can be influenced by the source of pigment, the type of extruder and the manufacturing conditions, in terms of heat, moisture and pressure within the extruder. To counter this, the synthetic forms of pigment are usually protected from oxidation within a beadlet, in which a complex matrix containing antioxidants surrounds the pigment granules. The beadlet maintains stability of the pigment during the manufacturing process with the minimum effect on its bioavailability to the fish.

In Norway and Chile the predominant pigment used in salmon diets is astaxanthin, but in the UK farmed salmonids are typically fed either of the two pigments (canthaxanthin or astaxanthin) or a variety of mixtures. A number of papers reporting on the use of these pigments in rainbow trout (*Oncorhynchus mykiss*) have shown that astaxanthin is the superior pigment for this species in terms of its deposition efficiency and flesh-colouring properties. Pigmentation studies on rainbow trout may be completed within 3–4 months whereas the completion of a similar protocol for salmon might take 2–3 times as long. This may explain the tendency to use results from rainbow trout as an indicator of the relative performance of the two pigments in Atlantic salmon. A study by Buttle *et al.* (2001) found that canthaxanthin outperformed astaxanthin in Atlantic salmon fed either of the pigments, or mixtures of both, over a period in which the mean fish weight increased from 220 g to 810 g. This would suggest that the absorption or utilisation of the two pigments might differ between these species.

In the major salmon producing countries the use of carotenoid pigments in farmed food fishes is controlled by domestic feedstuffs regulations. In the EU, for example, astaxanthin may be added up to a maximum of 100 mg kg^{-1} of feed and canthaxanthin up to 80 mg kg^{-1} of feed. Mixtures of pigment can be added to a maximum of 100 mg kg^{-1} of feed. The popular use of mixed pigments in markets such as the UK may have been prompted by economics and research showing an apparent beneficial synergistic effect on flesh colour when astaxanthin and canthaxanthin were simultaneously fed to rainbow trout (Torrissen, 1989a). In this experiment both pigments were fed at high levels (approx. 200 ppm) and later work utilising the lower levels used in commercial salmonid diets failed to demonstrate any synergistic effect (Torrissen and Christiansen, 1991).

4.13.3.4 The absorption and transport of pigments

The consumed pigment must be digested, transported across the gut wall and pass into the blood before being deposited in the muscle, skin and other body organs. The pigment is mainly absorbed in the midgut and hindgut (Torrissen *et al.*, 1990). In immature rainbow trout the pigment has been shown to be transported in the various lipoprotein fractions of the blood serum with the majority of the pigment found in the high density lipoprotein (HDL) fraction (Choubert *et al.*, 1991). The retention of dietary carotenoids in salmonids varies with factors such as fish size, sex and species and diet composition, but are generally in the range of 1–18% (Foss *et al.*, 1984; Torrissen, 1985).

4.13.3.5 Factors affecting pigmentation in salmonids

A number of physiological factors have been shown to influence the deposition of pigment in salmonid flesh. The various species of salmonids accumulate pigment in different amounts; the rainbow trout, for example, has been shown to reach higher flesh levels of carotenoids compared to Atlantic salmon (Storebakken *et al.*, 1986), which typically accumulates 4–10 $mg\,kg^{-1}$ of pigment in its flesh (Torrissen *et al.*, 1989). March and MacMillan (1996) found that Atlantic salmon deposit less pigment than either Chinook salmon (*Oncorhynchus tshawytscha*) or rainbow trout. The authors found that Atlantic salmon had the slowest response to dietary supplementation, the least difference in response to different dietary concentration of astaxanthin and the lowest final tissue concentration of the pigment. Differences in pigmentation also exist between strains of salmonids and between individual fish within a population and these have been shown to involve genetic factors (Gjerde and Gjedrem, 1984; Torrissen and Naevdal, 1988). The age, size and life stage of Atlantic salmon are other important factors (Torrissen, 1985). Providing there is an adequate supply of carotenoids, Atlantic salmon will accumulate pigment in the white muscle from an early age, and this pigment will continue to accumulate up to a maximum value until the maturation process reaches a critical level. At this time flesh levels of pigment fall dramatically (Torrissen and Torrissen, 1985). It has been shown that it is possible to detect differences in flesh pigmentation between immature and maturing fish more than five months before the expected spawning time (Torrissen and Torrissen, 1985). A positive effect on pigmentation of time and final weight and a negative effect of initial fish weight were found in a study on Atlantic salmon by Torrissen *et al.* (1995). The growth rate may also be important and it has been reported that pigment deposition was reduced in fast growing rainbow trout (Torrissen, 1985). However, in another study on rainbow trout (approx. 300 g) an apparent increase in the deposition efficiency of fast grown fish was reported (Nickell and Bromage, 1998). Muscle dynamics, maturation and seasonal factors may complicate the picture.

There are also a number of important feed-related factors that impinge on fish pigmentation. The influence of the dietary source of pigment is discussed in detail in the next section, but the interested reader can also consult the following papers on the subject (Johnson *et al.*, 1980; Foss *et al.*, 1987; Torrissen *et al.*, 1982; Storebakken *et al.*, 1987). The fat content of the diet has been shown to promote deposition of pigments in the flesh (Torrissen, 1985; Storebakken *et al.*, 1987; Torrissen *et al.*, 1989, 1995; Nickell and Bromage, 1998). The dietary concentration of pigment and the period over which the pigment is fed are two of the most important factors governing the pigmentation of salmonids (Torrissen, 1985). In a study on Atlantic salmon, Torrissen *et al.* (1995) found that increasing the dietary concentration of astaxanthin from 60 $mg\,kg^{-1}$ to 100 $mg\,kg^{-1}$ gave an insignificant increase in muscle pigment concentration of 3%. Other studies report similar findings and have demonstrated that increasing the dietary concentration above 40 $mg\,kg^{-1}$

significantly reduces the relative astaxanthin retention. The potential feed conversion efficiency of the diet containing the pigment can affect the total exposure of the fish to pigment over its growth period and if salmon diets continue to improve in performance, in the future it may be necessary to increase the pigment content of salmon diets.

For further reading on the subject see Torrissen (1985) and Torrissen and Naevdal (1988).

4.13.3.6 Choice of dietary pigment

There is a reasonable amount of published research comparing different pigment sources in rainbow trout, but rather less on Atlantic salmon. Although it is probable that the mechanisms of pigment uptake are similar in the two species, we know that Atlantic salmon are less efficient at laying down pigment in the flesh compared to rainbow trout (Storebakken *et al.*, 1986). One should therefore be wary of interchanging conclusions on the subject between the two species. For rainbow trout it has been shown that the relative deposition rate of astaxanthin is between 1.3–2.1 times higher than canthaxanthin (Foss *et al.*, 1984; Torrissen, 1989a; No and Storebakken, 1992). Henmi *et al.* (1987) found that astaxanthin and canthaxanthin were bound to actomysin in the muscle of sockeye salmon (*Oncorhynchus nerka*) by weak hydrophobic bonds. Another study showed that this binding is not specific for canthaxanthin and astaxanthin, and that the mechanism for binding was one β-ionine ring binding to a hydrophobic binding site on the surface of the actomysin (Henmi *et al.*, 1987). This infers that astaxanthin, with twice the number of potential binding sites, should combine more strongly to actomysin than canthaxanthin (Storebakken and No, 1992).

Canthaxanthin and astaxanthin have been used successfully to pigment farmed trout and salmon for many years. The literature does, however, contain a number of papers in which the two forms of synthetically produced pigments are compared. Some of the differences are given below.

- The digestibility (ADC) of astaxanthin has been found to be higher than canthaxanthin (Choubert *et al.*, 1995), but not by Torrissen *et al.* (1990).
- Astaxanthin is preferentially transported in the blood (Gomez *et al.*, 1993).
- Astaxanthin is more efficiently deposited in the muscle than canthaxanthin (Choubert *et al.*, 1995).
- Astaxanthin binds more strongly to the muscle than canthaxanthin (Storebakken and No, 1992).
- Astaxanthin is more efficiently utilised than canthaxanthin (Foss *et al.*, 1984).

These studies refer mainly to rainbow trout and may not be entirely relevant to Atlantic salmon.

Another major consideration when selecting the carotenoid for a pigmentation regime is its performance under a variety of fish processing conditions. There is not the space to devote to this subject but the literature suggests the following:

- the colour of astaxanthin is redder than canthaxanthin (No and Storebakken, 1992);
- colour retention during flesh processing is better with astaxanthin pigmented flesh compared to canthaxanthin (Skrede *et al.*, 1989; Choubert *et al.*, 1992; No and Storebakken, 1992);
- lower losses of astaxanthin, compared to canthaxanthin, were found in flesh following processing of rainbow trout into steam cooked and smoked product (Skrede and Storebakken, 1986);
- following freezing, less visual reduction in flesh colour is seen in astaxanthin pigmented Atlantic salmon flesh compared to canthaxanthin (Sheehan *et al.*, 1998);
- Astaxanthin fed to rainbow trout at 50 ppm produced similar flesh colour values to canthaxanthin at 100 ppm (Choubert *et al.*, 1992).

There are, however, other important points to consider:

- the price of the different pigment sources;
- different pigment sources can produce subtle but distinct flesh colour changes;
- the market may prefer fish pigmented with astaxanthin, as it is the predominant natural flesh pigment of Atlantic salmon;
- the production of 'organic' salmon may require astaxanthin derived from natural products.

4.13.4 The influence of dietary composition on flesh pigmentation

4.13.4.1 Dietary lipid

Several workers have reported a positive effect of dietary lipid level on carotenoid utilisation in salmonids, including Atlantic salmon (Torrissen *et al.*, 1990, Einen and Roem, 1997; Einen and Skrede, 1998; Nickell and Bromage, 1998). This contradicts earlier work by Choubert (1981) and more recent studies by Sheehan *et al.* (1998) and Bell *et al.* (1998). It is postulated that these discrepancies may result from the influence of dietary oil source and fatty acid composition on the utilisation of carotenoids by salmonids (Bjerkeng *et al.*, 1997). In a study comparing four different fish oils it was found that astaxanthin retention and fillet carotenoid content were significantly higher for fish fed a Peruvian high PUFA oil than salmon fed herring oil (Bjerkeng *et al.*, 1999). In a comparison of diets supplemented with menhaden fish oil, SO or tallow, Atlantic salmon fed the fish oil diet deposited more canthaxanthin in the flesh than fish fed either of the other diets (Hardy *et al.*, 1987). Thomassen and Røsjø (1989) found inferior pigmentation of Atlantic salmon fed diets enriched with high erucic rapeseed oil when compared with salmon fed diets containing capelin, low erucic or SO. A positive influence of AT acetate on astaxanthin deposition in Atlantic salmon has been demonstrated by Bjerkeng *et al.* (1999). Their investigation showed that at a dietary astaxanthin level of 30 mg kg^{-1} astaxanthin deposition may be enhanced by up to 14% by increasing the dietary concentration of AT acetate from 200 to 800 mg kg^{-1}.

4.13.4.2 Dietary protein

A number of plant materials have been considered for the partial replacement of fishmeal in salmonid diets. Plant materials may, however, affect the sensory attributes of fish flesh and impinge on its colour. These changes may have a negative effect if the resulting taste, texture and colour fail to match consumers' expectations. A yellow colour has been invoked in the flesh of rainbow trout fed a diet containing lutein (Lee *et al.*, 1978). In an American study raw fillets coming from rainbow trout fed diets containing wheat gluten and corn gluten were found to be visually less acceptable than fillets from a canthaxanthin-supplemented diet. The corn gluten diet is reported to have coloured the flesh yellow (Skonberg *et al.*, 1998). These results emphasise the importance of investigating the potential effects of alternative feed ingredients on the product quality of farmed salmonids.

4.13.5 Factors affecting pigmentation regimes

Flesh colour is one of the most attractive features of salmonid flesh and farmers pay great attention to achieving good flesh colour in their harvested fish. The supplementation of farmed Atlantic salmon diets with carotenoid pigments adds between 10–15% to the sales price of finished feed. It is therefore important to devise pigmentation regimes that provide enough visual coloration in the flesh at harvest but which are also cost effective.

The flesh colour demanded varies from market to market, but is typically achieved once the flesh pigment level reaches 6–8 mg of pigment per kg of flesh. Atlantic salmon astaxanthin fillets typically retain only 10–15% of the ingested astaxanthin (Storebakken and No, 1992), which may be related to digestibility (Torrissen *et al.*, 1990), metabolism (Torrissen and Ingebrigtsen, 1992) or transport rather than the actual binding capacity of the muscle (Torrissen *et al.*, 1995). In one study the average retention of astaxanthin in the flesh of Atlantic salmon was found to be as high as 27.9%, but shown to be inversely related to the final weight of the fish and the dietary astaxanthin level. At higher dietary concentrations the retention has been shown to decrease to less than 10% (Torrissen, 1995). Although the retention of pigment is higher at low dietary concentrations, this does not necessarily compensate for the increase in flesh pigments seen when the dietary pigment concentration is increased. In other words, in order to achieve marketable flesh colour it is advisable to feed salmon a diet pigmented at 40 mg kg^{-1} rather than 10 mg kg^{-1} despite the greater retention at the lower dose. Torrissen *et al.* (1995) found a plateau in muscle concentration of astaxanthin for salmon of 3–3.5 kg fed astaxanthin fortified diets containing 23% fat and above 60 mg kg^{-1} astaxanthin for their whole sea phase of about 8.5 mg kg^{-1}.

4.13.6 Practical pigmentation regimes for farmed salmon

A pigmentation regime must offer the fish farmer security in knowing that his investment in pigment will deliver flesh colour suitable for his chosen market but, because pigment is costly, it must also be cost effective. When considering the pigmentation regime to employ, it is first imperative to analyse the published research on the pigmentation of Atlantic salmon and to take account of the importance of acceptable and consistent flesh colour to the fish retailer and the consumer. The evidence suggests that it is advisable to include pigment in the diets of farmed salmon from an early stage (Torrissen *et al.*, 1995). In practical terms, it is usual to feed pigment as soon as the fish have been transferred to seawater or when the fish reach 50–80 g, whichever comes earlier. The dietary pigment concentration at this stage is typically between 60–80 mg kg^{-1} and feed can continue to be administered at this level until the flesh pigments reach a minimum concentration of 7–8 mg kg^{-1}. Once this has been established from the analysis of sampled fish then dietary pigment levels can be reduced. Unpublished research by Nutreco ARC has found the maintenance concentration for astaxanthin to be about 25 mg kg^{-1} feed for salmon weighing from 2–5 kg. The maintenance concentration is one that will maintain flesh carotenoid levels at their initial level. It is also sensible to include a safety margin and it is not recommended that dietary pigment levels for salmon fall below 30 mg kg^{-1}.

On many farms it has become common commercial practice to reduce the dietary pigment level in stages. The first reduction to 50 mg kg^{-1} typically follows removal of grilse and/or when the salmon are 2.5–3 kg in weight. For immature salmon of 3.5–4 kg the dietary pigment level may then be reduced to 30–35 mg kg^{-1}. Before the farmer takes the decision to reduce pigment, it is highly recommended that at least 30 fish, randomly selected, are first sampled for flesh colour by chemical analysis and by visual methods in order to establish that the carotenoid level in the flesh has reached a minimum acceptable colour. The savings inherent in this strategy can be significant, but it is recommended that a flesh quality-monitoring programme—to detect any potential flesh colour problem developing—accompany the strategy. Where farmers are working in carcass quality-sensitive markets it may be advisable to maintain dietary pigmentation levels above 50 mg kg^{-1}. The start high/finish low pigmentation strategy has the benefit of developing a marketable flesh colour early in the growth cycle. When significant percentages of grilse are anticipated it is advisable to delay reducing the dietary pigment levels until all these are removed. Before reducing dietary pigment levels the farmer should consider the balance of the potential savings against the potential premiums as very well-pigmented salmon often command a higher price in the marketplace.

Figure 4.14 shows the increase in flesh astaxanthin concentration plotted against fish weight for Norwegian Atlantic salmon. It can be seen that some individual fish of less than 2 kg have flesh levels of astaxanthin reaching near the maximum value expected in Atlantic salmon (12–14 mg kg^{-1}). The trend line shows that the average Norwegian salmon sampled in this survey, taken several years ago, has 6–7 mg kg^{-1} at a harvest weight of 3–4 kg. There is real potential for using genetic selection of family groups to achieve a higher consistency and overall flesh colour in farmed salmon. A number of studies have shown that neither the visual measurement of colour nor colorimetry results have a linear relationship with the astaxanthin concentration in the flesh (Smith *et al.*, 1992; Christiansen *et al.*, 1995c; Nickell and

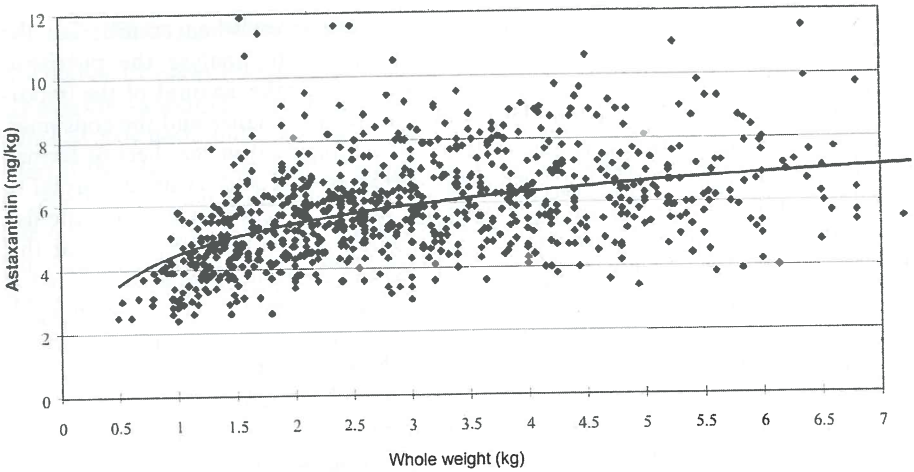


Figure 4.14. Relationship between Atlantic salmon weight and flesh astaxanthin content (NQC section).

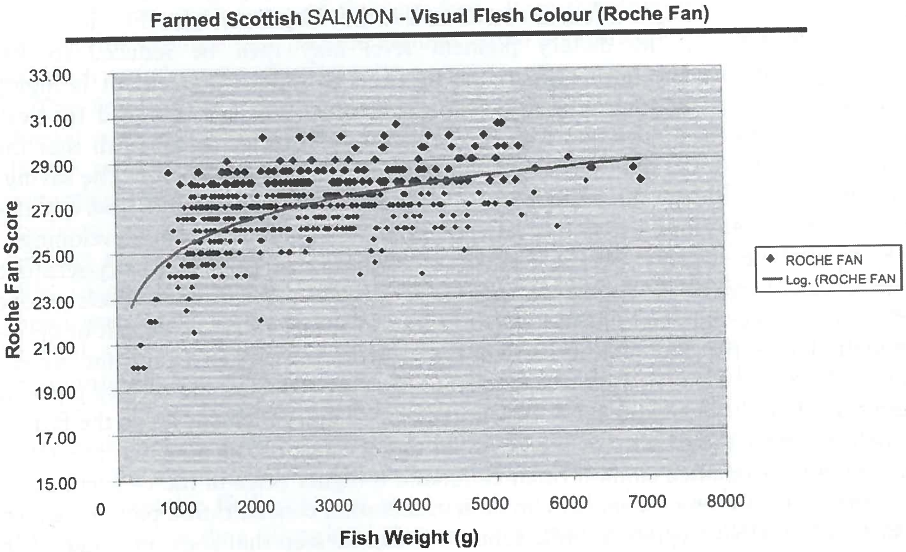


Figure 4.15. Flesh colour development in farmed Atlantic salmon measured by Roche SalmoFan™.

Bromage, 1998). It is the visual perception of flesh colour that is important to fish buyers and consumers alike. Figure 4.15 shows the development of flesh colour in Scottish farmed salmon, measured visually using a Roche *Salmo*Fan™. A score of 26 on the *Salmo*Fan™ would typically be the minimum required by many salmon retailers. The colour specification may also reflect the individual end product derived from salmon. Thus one would expect the raw material used in a smoked salmon product to have a higher colour specification than for fresh salmon products. Figure 4.15 clearly shows the rapid initial rise in flesh colour followed by a more gradual increase as the fish increase in weight. The wide variation in colour for any given fish weight is also clearly demonstrated; this variation is of great importance to farmers, processors and consumers as it may result in fish of unacceptable flesh colour reaching the market. In order to reduce the impact of this inherent variation seen in the flesh colour of Atlantic salmon it may be advisable to maintain a high concentration of dietary pigment.

4.13.7 Pigmentation problems

It was mentioned earlier that pigment deposition in salmon is affected by genetics, age, health status, stress and life-stage, but these are factors that lie outside the scope of this chapter. Sexual maturation is, however, by far the most common factor associated with pale flesh in farmed salmon. It is advisable to grade out and sell salmon well before maturation takes place.

4.13.8 Finishing diets

Several fish feed manufacturers market 'finishing' or 'harvest' type diets. These are designed to boost a number of desirable fish quality characteristics, such as the shelf life of fish and flesh colour. Researchers at Nutreco ARC found measurable improvements in flesh colour and flesh texture, and a slight, but significant, reduction in fat from feeding a 'maintenance' ration of a specialist, vitamin boosted diet to pre-harvest salmon for a period of 6–8 weeks. A maintenance ration is one that is designed to maintain the fish at a constant weight. However, these improvements in fish quality came at a considerable cost in terms of the loss of potential growth. Specialist 'finishing' diets are normally boosted with the antioxidants, vitamins E and C and typically contain elevated pigment levels.

4.14 TECHNICAL SUPPORT ACTIVITIES

Throughout the world of salmon farming, feed manufacturers employ technicians to assist farmers in a variety of ways. The most obvious service is the provision of advice on fish nutrition, but many feed companies also provide advice on fish health, carcass quality and fish husbandry. Most feed suppliers also employ fish veterinarians to help farmers keep diseases at bay and to arrange bacteriological testing of stocks and histopathological services. Feed companies may also offer salmon farmers help with computer programmes for daily record management and for predicting fish growth and feed usage. In addition, it is quite common for feed companies to assist farmers in monitoring fish quality and advising farmers in specialist areas, such as fish pigmentation.

4.15 SUMMARY

The manufacture of feed for farmed fish is now an international business, requiring high levels of investment in plants to service the continuing growth of the farming industry. While the technical demands of feed formulation and production have been addressed with increasing success, several major issues continue to present fresh areas of challenge for feed manufacturers. The ex-farm price of salmon has fallen sharply in recent years, making it difficult for farmers to remain profitable. Currency fluctuations have proved damaging to the profitability of a number of individual markets, placing extra pressure on the producers concerned. The sustainability of raw materials for fish feed is another major challenge, creating a need for further increases in the amount of plant proteins and oil used in the future production of fish feed. Nevertheless, the successful development of salmon farming during the past 25 years has been responsible for the revitalisation of many remote areas, bringing new employment and development opportunities to previously depressed communities. Associated employment in salmon processing, equipment supply and research has also boosted the economies of many countries. In addition, ongoing efforts to expand the successful farming of fish into new species is ensuring that the impact of aquaculture will continue to grow in the future. It is within that context, therefore, that our increasing understanding of fish nutrition is helping to drive the fish feed sector forward to the long-term benefit of the aquaculture industry and all who are associated with it.

Acknowledgements

I would like to thank my colleagues at Trouw Aquaculture, especially those in the Technical Department of Trouw Aquaculture and at Nutreco ARC for their support.

APPENDIX 4.1: GROWTH AND FEED PERFORMANCE CALCULATIONS

Specific Growth Rate (SGR)

The measure of percentage body weight increase per day.

Where the start and final weights are known:

$$\mathrm{SGR} = 100 \times (\ln \mathrm{W}_1 - \ln \mathrm{W}_0)/\mathrm{t}$$

Where: ln = natural log
W_1 = final weight (g)
W_0 = initial weight (g)
t = time interval (days)

For example, an Atlantic salmon which has grown from 2000 g to 2500 g in 30 days

$$\text{SGR} = 100 \times (\ln 2500 - \ln 2000)/30$$
$$\text{SGR} = 0.74\%$$

Growth Factor 3 (GF3)
Relates growth to the sum of daily water temperatures over a particular period

$$\text{GF3} = \frac{(\text{Final weight (g)})^{1/3} - \text{Start weight (g)}^{1/3}) \times 1000}{\text{Total sum temperature (degree days)}}$$

For example, using the same growth example as above but including temperature data for average water temperatures in Scotland in November (30 days)

$$\text{GF3} = \frac{(2500^{1/3} - 2000^{1/3} \times 1000}{349}$$
$$\text{GF3} = 2.77$$

GF3 can also be used to predict growth providing the temperature profile over a particular period can be anticipated.

$$\text{Final weight (g)} = ((\text{Start weight}^{1/3} + \text{GF3}) \times \text{Total sum temperature})/1000)^3$$

For example, using the previously calculated GF3 of 2.77 and a start weight of 2500 g projected forward by three months from November at average Scottish water temperatures:

$$\text{Final weight} = ((2500^{1/3} + 2.77 \times 642)/1000)^3$$
$$\text{Final weight} = 3617\,\text{g}$$

Note: 1/3 can be represented on a calculator by 1 divided by 3 = 0.33333333333333, retained in the memory using the 'M in' key and recalled using the 'MR' key.

Feed Conversion Ratio (FCR)
In its simplest form, FCR relates the amount of feed fed to weight gain of the fish:

$$\text{FCR} = \frac{\text{Weight of feed fed}}{\text{Weight gain}}$$

Typically, the calculation is made using the feed fed and total biomass figures for the whole pen over a defined period.

For example, again using the same example as above for a pen of 10,000 fish growing from 2 kg to 2.5 kg

Weight of feed fed over period = 6000 kg (from feed records)
Weight gain = (Total end weight – total start weight)
Weight gain = (10,000 × 2.5 – 10,000 × 2.0)
Weight gain = 5000 kg

$$\text{FCR} = \frac{6000}{5000}$$

$$\text{FCR} = 1.2$$

It has therefore taken 1.2 kg of feed to produce every 1 kg of fish.

Biological FCR

This calculation takes into account the feed used to rear any dead or escaped fish and is commonly used to evaluate feed and fish performance.

$$\text{B-FCR} = \frac{\text{Weight of feed fed (ep)}}{\text{weight gain} + \text{losses}}$$

If calculating B-FCR at the end of a rearing cycle, the following calculation is used

$$\text{B-FCR} = \frac{\text{Total feed fed during cycle (ep)}}{(\text{live weight} + \text{losses}) - \text{weight of smolt}}$$

where ep = extruded pellet.

Live weight for B-FCR on harvest fish is recalculated from gutted fish as a 'whole fish equivalent' or WFE where

Live weight = all harvested fish gutted weight + 18% (10% guts, 8% blood and starving). The recalculation figure of 18% will vary between companies and can have a large bearing on the final B-FCR figure.

For example, for a smolt input of 10,000 fish at 100 g grown up to a harvest size of 4 kg (gutted) with a total weight of mortalities of 200 kg (800 fish @ 0.25 kg average).

Number of fish at harvest: 10,000–800 = 9200 individuals at harvest

Total feed for cycle	= 50,000 kg
Total gutted weight	= 9200 × 4 kg
Total live weight (WFE)	= 36,800 kg + 18%
WFE	= 43,424 kg
Losses	= 800 kg
Weight of smolt	= 10,000 × 0.1 kg
Weight of smolt	= 1000 kg
B-FCR	$= \frac{50,000}{(43,424 + 800) - 1000}$
B-FCR	= 1.16

Economic FCR

Economic or E-FCR does not take farm mortalities, bleeding or starving into account and only includes fish of marketable quality. Again, the recalculation values may differ from company to company.

$$\text{E-FCR} = \frac{\text{Total feed fed over cycle (ep)}}{\text{Harvested fish (round/bled)} - \text{weight of smolts}}$$

Where harvested fish are accepted quality fish (Superior, Ordinary or production) gutted weight + 10%.

e.g., using the same figures as for B-FCR and assuming 95% acceptable quality:

Total feed for cycle	= 50,000 kg
Total gutted weight	= 9200 × 4
Harvested fish	= 36,000 kg + 10%
Harvested fish	= 40,480 kg
Acceptable fish	= 40,480 kg × 0.95 (38,456)
Weight of smolt	= 10,000 × 0.1 kg
Weight of smolt	= 1000 kg
E-FCR	$= \dfrac{50{,}000}{(38{,}456) - 1000}$
E-FCR	= 1.33

Note: Recalculated live weight varies widely between companies and countries, where FCR is calculated prior to harvest, results of sample weighing can be used for live weight.

(Calculations and data supplied by Dr Chris Beattie of Trouw Aquaculture)

5

Post-harvest handling and processing

5.1 INTRODUCTION

Farming of Atlantic salmon can now be considered as a developed system of food production. A great deal of research and development by the industry itself, and by associated industries such as feed manufacturers and the pharmaceutical industry, has resulted in an efficient industry that can produce fish at costs less than many species of fish caught from the wild. Aquaculturists, and the industries that support aquaculture, quite naturally and understandably, put emphasis on the economic production of salmon, but it must be remembered that production of fish is not an end in itself. The product is intended as food and the aquaculture industry will be successful as long as consumers find the product acceptable in terms of satisfaction given as a food and on price. Consumers in economically advanced countries are presented with a wide variety of foods, and have the economic means to be selective in what they buy, and salmon competes with other foods and not just other fish species. Customers for farmed salmon appear to like what they are buying, and over the last decade or so global Atlantic salmon production has increased by around 14%, compound, a year. This is a remarkably high rate of sustained growth for a food commodity.

Good quality begins at the farm and salmon farmers are well aware of the importance of good quality in marketing their products. A variety of quality assurance schemes have been developed by the industries in countries with significant productions of farmed salmon, both for the raw material and for processed products such as smoked salmon. This chapter discusses the harvesting and subsequent handling, processing, distribution and marketing of the salmon, and particularly of the interaction between husbandry practices and these processes. The quality of farmed fish and the effects of aquacultural practices, including feeding and slaughtering practices on quality, are discussed in the proceedings of a recent conference (Kestin and Warriss, 2001).

5.2 SLAUGHTERING AND IMMEDIATE *POST MORTEM* HANDLING

5.2.1 Slaughtering procedures

The methods most commonly used for slaughtering fish in commercial salmon farming are percussive stunning and carbon dioxide (CO_2) anaesthesia, though other procedures such as anaesthesia by drugs, electrostunning, chilling in ice water, spiking the brain, and taking the fish out of water to suffocate are available. These various procedures, other than the last, might not render the fish immediately physiologically dead, but at least unconscious and thus easy to handle. Considerations of humaneness in the slaughtering process require that the procedure be carried out swiftly with minimum stress to the animal, and that the fish be rendered at least deeply unconscious to the extent that they cannot recover consciousness (Farm Animal Welfare Council, 1996). The first two procedures listed above, percussive stunning and CO_2 anaesthesia, meet these requirements when carried out under good practices.

In percussive stunning, the culled fish, which have previously not been fed for up to 10 days to ensure that the gut is empty, are hit on the head with a small club—referred to as a 'priest' in Scotland—just behind the eyes. This operation requires some degree of skill and dexterity to carry out cleanly on a struggling fish; a misdirected blow can fail to immobilise the fish, can damage the head of the fish detracting from its appearance, or bruise the fillet behind the head. The stunning is usually carried out at the cages and the fish are brought ashore in tanks of water. CO_2 anaesthesia can be carried out at the cages, but it is more usual to bring the live fish ashore. The fish are transferred to tanks containing water saturated with CO_2 gas and usually the gas is also vented into the tanks. The salmon become quiescent and unconscious within a few minutes and can then be removed from the gassing tank.

It is common practice after stunning to cut the gill arches on one or both sides and to drop the fish into a tank of water to bleed. Preferably the water in the tank should be cooled by refrigeration or with ice. Though the salmon are irrecoverably unconscious after correct stunning or CO_2 anaesthesia, the heart continues beating for a time and blood drains efficiently from the flesh. Exsanguination avoids blood spotting of the fillet and is important for the quality of products sold as fillets or smoked fillets. A disadvantage of electrostunning is that it causes blood to lodge in the vessels, and sometimes causes bruising at the backbone.

5.2.2 Handling after slaughtering

Salmon intended to be distributed as gutted fish should be eviscerated as soon as possible after death, and before they have entered rigor mortis (see Section 5.3). The belly cavity should be opened by a cut from between the pectoral fins to the vent and the viscera removed cleanly. The swim bladder and underlying kidney tissues should be scraped and brushed out, and the belly cavity thoroughly washed.

The fish, gutted or not, should be iced as soon as possible. Before packing, the salmon should be sorted and graded for size and for quality according to the requirements of the intended markets. Sometimes the producer will grade to standards drawn up by a grower's organisation or similar trade organisation, sometimes to standards set by the buyer. Appearance will figure prominently in the specifications when salmon are to be displayed whole or gutted, which is often the case for retail markets. The fish must have a good conformation, a regularly-shaped head, clean, undamaged skin, and not show signs of maturity. Fish with misshapen heads, or with slight skin defects might be suitable for fillet products.

5.3 IMMEDIATE *POST MORTEM* CHANGES, AND EFFECTS OF SLAUGHTERING PROCEDURES ON THEM

The most obvious immediate *post mortem* phenomenon observed in the salmon is the onset and resolution of rigor mortis. The stiffening starts a few hours after death and increases in intensity to a maximum rigidity about 12–24 hours after death, followed by a resolution of the rigor taking a further one or two days. The biochemical events leading to rigor mortis and its resolution are complex and not fully elucidated. An important factor in the timing of onset of rigor, and its intensity, is the glycogen content of the muscle at death. Glycogen is the energy reserve in the muscle and is depleted during any struggling before death. Fish which are rested and unstressed before death will have high glycogen contents in the muscle, and the time into rigor mortis will be long and its intensity strong, compared with fish exhausted and stressed before death.

It is known from experience with catching fish in the wild that the capture method—trawling, seine netting, trolling, fish traps—and nutritional condition of the fish at the time of catching influence the glycogen content of muscle and hence the progress and intensity of rigor. It has been reported that stress associated with slaughter also affects the rigor process in farmed fish and, apart from any considerations of humane slaughter, fish should be slaughtered with the minimum of stress to give the best fillet quality. Most of the work on the effects of slaughtering method on rigor mortis and associated biochemical changes, and particularly on the spiking procedure (iki jima), has been carried out in Japan and many of the papers are in Japanese. None of the reported experimental work on the iki jima procedure has involved salmon, (though various laboratories have experimented with iki jima for salmon, the results have not yet appeared in the open press), but there is no reason to suppose that the general findings will not apply to this species. There are two variations of the spiking procedure. The simplest is just to stab through the skull between the eyes into the brain using a small knife or spike, or mechanically using a builders nailing gun (Boyd *et al.*, 1984). The other is to stab the brain as described then pass a thin wire into the neural canal of the spinal column to destroy the spinal cord (Nakayama *et al.*, 1996, 1997). Using red sea bream Nakayama *et al.* (1996)

showed that destruction of the spinal cord delayed full rigor tension until about 24 hours after death compared with 10 hours in the fish spiked without spinal cord destruction.

Stress in the context of depletion of muscle glycogen can be related to the amount of activity just prior to death. Spiking and neural cord destruction result in complete relaxation of the muscle and maintenance of high glycogen contents; the opposite extreme of considerable depletion of glycogen is given by removal of fish from the water and allowing them to struggle and suffocate to death without any prior stunning or anaethetisation. Highly-stressed fish go into rigor very quickly, and the duration of rigor is short compared with procedures in which fish die in a relatively unstressed condition (Berg *et al.*, 1997). Of course, any method of slaughtering will involve some stress and it is a matter of degree. A fish that suffocates to death out of water will struggle considerably; one which is stunned will struggle less so. Reflex muscular activity might not cease entirely with stunning; the muscle can twitch and the fish might show swimming movements in the bleeding tank. Destruction of the spinal cord after spiking inhibits even this reflex muscle activity (Nakayama *et al.*, 1996, 1997) and results in the least exercise stress of any of the slaughtering procedures referred to here.

There is little or no advantage in having long times into and through rigor for most systems of handling, processing and distribution of salmon after harvesting. Salmon should not be handled while in rigor, and the 2–3 days it usually takes for complete resolution of rigor can sometimes be a nuisance. In many countries times of delivery of salmon from farms to processing plants are often short and usually less than that required for resolution of rigor. Consequently, the salmon might have to be held back in a chill store for a day or two before it can be processed. However, if the salmon is to be sold entire to the customer, for example a catering outlet, the fact that the fish is still in rigor would be an indication that it is very fresh. For some specialist outlets, for example Japanese-style sashimi restaurants, the product should be prepared from pre-rigor fish, and spiking followed by spinal cord destruction would be the preferred slaughtering procedure. Other than the extremes of the iki jima process and of death by suffocation, the length of time into and through rigor mortis, does not differ much among slaughtering procedures, and probably does not need to be taken into account when selecting the most convenient procedure.

Any gutting and packing of the salmon should be carried out before the fish goes into rigor as handling salmon in rigor can result in damage to the fillet. Salmon should not be filleted until the rigor process is fully resolved. A fillet removed before rigor is fully resolved will later have a rough, sandpaper-like appearance, will not take on a good gloss if it is smoked, and the cooked product will have a tough, rubbery texture. The times for onset and resolution of rigor referred to above are for salmon stored in ice and times are shorter at ambient temperatures around 20°C, but warming fish up to hasten the rigor process is inadvisable as the rigor process at high temperatures can cause vigorous contraction in the muscle that can result in severe gaping (breaking of the tissue at the junction of the blocks of muscle), in the fillet.

5.4 EFFECTS OF HUSBANDRY PRACTICES, INCLUDING SLAUGHTERING, ON COMPOSITION AND QUALITY OF SALMON

5.4.1 Comparison of farmed and wild fish

Food writers often claim that the culinary properties of farmed salmon are inferior to those of wild, but there does not seem to be any basis for this proposition based on consumer studies, and it must remain an opinion of the particular writer. According to FAO fishery statistics, only about 1% of Atlantic salmon is produced from the wild and the great majority of its consumers would not have had the opportunity to make any comparison between farmed and wild salmon. My own experience of evaluating both wild and farmed salmon is that there is no systematic difference in eating quality of the two varieties. Schallich and Gormley (1996) reported that a panel of 28 persons showed no significant preference for either wild or farmed steamed Atlantic salmon caught/cultured in Ireland in a preference test. Sylvia *et al.* (1995) compared wild and farmed chinook salmon in a consumer study (189 consumers), and found only a small preference for the wild variety.

5.4.2 Fat content

There is one aspect of the composition of farmed salmon for which the farmed product can be markedly different from wild salmon, and that is in the fat content. Surveys of fat content of farmed salmon grown in Scotland, Ireland and Norway gave average values of 10.1% (n = 495), 11.9% (n = 587) and 15.0% (n = 145) respectively (Schallich and Gormley, 1996; Bell *et al.*, 1998; Refsgaard *et al.*, 1998) (n = number of fish sampled). The fat content of wild Atlantic salmon varies with biological factors such as season and maturation, but wild salmon caught in Scotland have fat contents of around 8%. Schallich and Gormley (1996) reported an average fat content of 12.3% in 295 wild salmon marketed in Ireland. Fat content affects the quality of both unprocessed and processed products. Salmon with very high fat contents will exude oil from cut surfaces or when minced. High fat contents give rise to a soft texture to the feel of the raw fillets, and to soft texture on the palate and an oily mouthfeel in the cooked product. The fat content affects the uptake of salt in preparation of smoked products—the higher the fat content, the slower the uptake—and the eating quality of the finished product. Smoked salmon prepared from high fat-content fish, more than about 10% fat in the raw fillet, will have a soft texture, an oily mouthfeel, and will weep oil into the package in the case of packaged products. A typical process specification for processors will ask for a fat content of 8–12% in the flesh.

Several factors influence the fat content of farmed salmon. One is the oil content of the diet. On average, in Scottish farms, a feed of 15% oil content gives fish with about 7% fat content in the flesh, one of 30% gives about 11% fat content. There is an annual cyclic effect; fat content is highest in winter, lowest in late summer. The range, on average over the year, is about 4 percentage units. Salmon tend to get more fatty as they get larger; the range, on average, between salmon of 2.5 and 4 kg, is about 4 percentage units (Bell *et al.*, 1998). A more detailed account of the effects of ration on fat content of salmon is given in Chapter 4.

Apart from the high values of average fat content, the variation in fat content among salmon is large. In the three studies on fat contents referred to above the standard deviation of fat contents over all of the salmon tested approached 3 percentage units. This means that, over all the fish analysed within a survey, 95% of the values lay between ±6 percentage units of the average value, that is between 4% and 16% for 95% of individuals in the survey of Scottish salmon referred to in Bell *et al.* (1998). This variation includes various factors that can affect fat content, including variations between farms; the variation within a particular batch from one farm, within a restricted size range, and harvested together will of course be smaller, around ±3 percentage units of the batch mean for 95% of the fish. A processor can therefore expect the fat contents of individual fish within a batch of farmed salmon from a single source with an average fat content of 10% to range from 7% to 13%.

A processor for whom fat content in the processed product is important should bear these factors in mind when sourcing supplies. For example, a salmon smoker should avoid supplies from farms using high oil-content feed, particularly large fish harvested in the winter. A satisfactory raw material is more likely to be obtained from a farm using low oil-content feeds, but then smaller fish from such a farm harvested in late summer could have fat contents too low, approaching 5%, for optimum quality in the smoked product. There are instruments for non-destructively measuring the fat content of salmon with sufficient accuracy and speed for processors to scan individual fish within a batch and select for optimum fat content (Kent, 1990; Kent *et al.*, 1996).

5.4.3 Composition of the lipids

The nutritional benefits of fish oils are well established, and nutritionalists recommend consumption of fish or fish oils as a preventative for some degenerative diseases and inflammatory conditions. The protection comes from the polyunsaturated fatty acids (PUFAs), which are present in higher concentrations in fish oils than in vegetable oils. Many studies have shown that oils from farmed fish are also high in PUFAs, and to a small extent their amounts are affected by diet. The effect of diet on the composition of oils in farmed fish is complicated, but it has long been known that the fatty acid composition of muscle lipids reflects that of the diet, and a formulated diet containing fish oils will produce oils with high PUFA contents in the farmed fish. Vegetable oils are deficient in the long chain length PUFAs, but fish are capable of elongating and desaturating fatty acids, and studies have shown that the lipids of fish fed on vegetable diets or on diets containing vegetable oils have high levels of PUFAs, though perhaps not quite as high in those fed diets in which the oil is derived solely from marine sources (Henderson and Tocher, 1987).

The high content of unsaturated fatty acids in fish oils does not have a direct influence on the processing of salmon, but does have a bearing on the stability of the lipid during storage, particularly frozen storage. The unsaturated nature of the lipids makes them prone to oxidation and development of rancid flavours during frozen storage. Vacuum packaging in oxygen-proof film, as is often done for smoked salmon, is effective in protecting against oxidation, but is not always feasible as a process for other products. A natural chemical present in fish flesh, vitamin E, is an effective antioxidant. Studies on incorporation of vitamin E in the form of α-tocopherol into diets of farmed fish have shown that it is taken up in the flesh and provides some protection against oxidation of the lipids in the flesh even when the PUFAs have been enhanced by the diet (Sigurgisladottir *et al.*, 1994; Bell *et al.*, 1998).

5.4.4 Other components

Once past the juvenile stage the protein content of salmon flesh is little influenced by the amount or composition of the diet, or by husbandry factors short of extended starvation (Shearer, 1994). It is common practice to cease feeding salmon a few days prior to culling, but this has no appreciable impact on the protein content of the flesh. The reasons for withdrawing food seem to be to allow the gut to empty in order to give a cleaner evisceration, and to purge any off flavours induced in the flesh by the feed. The water content of the flesh is inversely related to the oil content such that the sum of the water and oil contents in salmon flesh is approximately constant at 79% (Figure 5.1).

Hence feeding practices will affect water content of the fillet because they affect oil content. The variation in water content will have some effects on properties of the fillet during processing. The fillet will take up less salt in total in low water

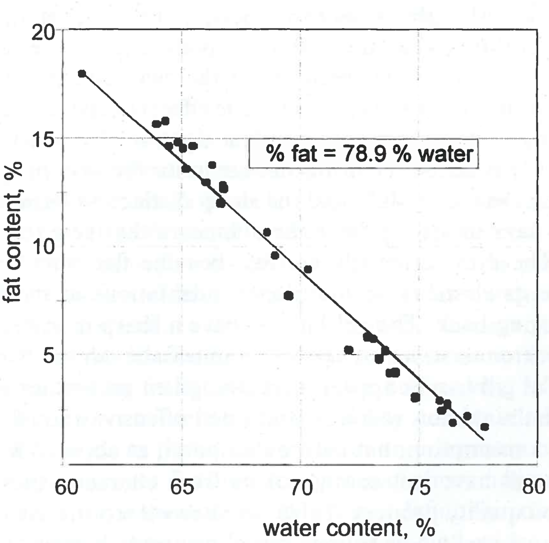


Figure 5.1. Water/fat relationship of flesh of Scottish farmed Atlantic salmon. Author's unpublished data.

content fillets during the brining process, but this will be a minor factor compared with the effects of oil content on the rate of penetration of salt and on the rate of drying in the kiln. The variation in water/oil contents will also influence physical properties like thermal conductivity, but these effects will not be of any practical significance.

The colour of farmed salmon is imparted by the carotenoids, astaxanthin and canthaxanthin, in the feeds. The amounts of these pigments fed to the salmon is carefully controlled by the feed manufacturers and the farmers as to the amount in the feed and the timing of their use in order to achieve the required colour in the fillets, respectively. Pigmentation of the flesh is checked by reference to standard colour cards. A full account of the use of pigments in feeds is provided in Chapter 4.

5.4.5 Effects of slaughtering practices on *post mortem* quality

The effects of slaughtering methods on the rigor mortis process has been discussed in Section 5.3. Once rigor has resolved, neither the quality of post-mortem salmon flesh, nor the behaviour of salmon flesh during subsequent handling, storage and processing are affected by the slaughtering procedures used.

5.5 HANDLING, STORAGE, DISTRIBUTION AND PROCESSING OF CHILLED SALMON

5.5.1 Loss of freshness and spoilage

In common with all fish, salmon lose freshness, and they spoil during storage after harvesting. Temperature has a large effect on spoilage rate—the rate approximately doubling for each 5°C rise in temperature of the fish—and it is very important to maintain the fish as near to 0°C as possible. The effects of spoilage can be observed in various characteristics of the salmon. The first signs are the onset and resolution of rigor mortis already described. During storage in ice the skin progressively loses its bright appearance, becoming dull, and the sharp distinction between colours is lost. After about ten days in ice a yellow slime appears that gets thicker as the fish is further stored. The eyes, originally convex, become flat, then sunken. The flesh softens and loses its elasticity so that finger indentations in the flesh are retained rather than springing back. The gills at first have a sharp marine smell which fades over the first week or so in ice. After that, unpleasant odours formed by bacterial degradation of the gill tissues appear, and strengthen on further storage. By about 15–18 days in ice the salmon will look and smell offensive enough to be considered unfit for human consumption, but before that point, at about 7–8 days, the appearance of the fish will have lost enough of its fresh characteristics for it not to be considered a good quality product. Table 5.1 shows a scoring system for evaluating the freshness of raw iced whole salmon based on these changes.

These are the characteristics of the raw salmon; the eating properties change as well (Table 5.2). After cooking fresh, post mortem salmon has a slightly sweet,

Table 5.1. Sensory scoring sheet for freshness of iced salmon—raw fish.

Score	Odour of gills	Appearance of eyes	Appearance of gills
10	marine, shellfish, seaweed, sharp	convex, clear, bright	dark red
9	freshly cut grass, fresh fruit, floral		
8	oily, freshly cut grass		
7	musty, muddy, mousy	flat, clear	red/brown, slight bleaching
6	leathery, beery, yeasty		
5	sour milk	flat/slightly sunken,	brown, bleached
4	sour, stale fruit, stale vegetable	cloudy	
3	sour, rancid	sunken, cloudy,	brown, bleached,
2	ammonia	discoloured	yellow slime

Table 5.2. Sensory scoring sheet for freshness of iced salmon—fish cooked by steaming or in microwave. Assessors should interpolate between these scores as required by the perceived odour and flavour.

Score	Odour	Flavour
10	baked, meaty, fresh oil	strong meaty, sweet, fresh oil, metallic
8	earthy, musty	loss of sweetness and meatiness, slightly musty
6	musty, sour	musty, sour
4	sour, stale fruit	sour, bitter
2	rancid, sweaty	putrid, nauseating

metallic, meaty flavour. The texture is firm and succulent, though there can be an oily mouthfeel in high oil-content salmon, above 10% fat content. The intrinsic fresh flavours are maintained over the first week or so of storage, though they decrease in intensity to some extent. Indeed, it is difficult even for experienced sensory assessors to detect consistent changes in flavour of stored salmon in this period. Unpleasant flavours are due to the action of bacteria and appear at later stages of storage. Fish flesh, unless the fish is diseased, is sterile, and spoilage flavours will appear in the flesh by diffusion of compounds from the growth of bacteria on the skin, and by the action of bacteria penetrating from the skin and the belly cavity. In salmon, this will occur after about 8–10 days in ice when slight musty and stale oil flavours can be detected. Chemical changes in the oil component can contribute to the unpleasant flavours. The spoilage flavours become stronger and more unpleasant on further storage, and by 15–18 days the cooked fish tastes definitely sour. Salmon fillets and steaks will spoil faster than whole fish, gutted or not, and it is good practice to store salmon in the whole form and leave preparation of products until as late in the supply chain as possible.

5.5.2 Chilled storage and distribution

Following sorting, and gutting if specified, the salmon should be packed in ice made from potable water or clean seawater. The fish should be handled carefully to avoid damage to the skin and flesh and laid out straight. Allowing the salmon to go though rigor bent or twisted can give rise to gaping and breaking of the connective tissue between muscle segments so that there are gaps between the segments. The salmon should be allowed to go through rigor mortis without any further disturbance, as handling salmon in rigor can also cause gaping of the fillet. It is common to stow the salmon in boxes and these should be long enough to take the salmon without having to bend the fish. The salmon can be stowed in bulk in layers of fish and ice, but the layers should not be more than about 50 cm deep without support to prevent pressure damage to the flesh. The salmon should be mixed with an adequate amount of ice to cool the fish down and keep it chilled during storage and distribution. About 2.5 kg of ice are required to cool 10 kg of salmon at about 15°C to ice temperature, but it is not always easy to estimate the extra amount required to keep the fish chilled during subsequent distribution and storage; the degree of insulation of the transport boxes, the insulation or refrigeration of the carrying vehicle, ambient temperatures, and the length of the distribution chain are important factors. Experience is a better guide than trying to estimate these factors, but generally salmon would be iced in a ratio of 3:1 to 2:1 fish:ice for a journey of a few days in insulated or refrigerated vehicles.

Ice can be manufactured in various forms, but as far as cooling capacity is concerned there is no difference between them. Criteria for selection are ability to make good contact with the fish, avoidance of physical damage to the fish, and ease of application. Flake ice meets all these requirements; its small, flat plates make good contact with the surface of the fish, effect rapid cooling and do not damage the skin of the salmon. Flake ice is readily available in bulk and can be conveniently made on the premises by small ice-making machines. Another form of ice that has some advantages is slush ice. This is prepared from water to which some salt has been added and is prepared as a slurry of ice in dilute brine. This material can be pumped, makes excellent contact with the fish, and does not cause any physical damage, apart perhaps of some dulling of the appearance of the skin. When first prepared, slush ice has a temperature a little below 0°C because the salt lowers the freezing temperature of the mix. This lower temperature slows the rate of spoilage slightly compared with storage in normal ice, but this advantage wears off during storage as the ice melts and the brine drains away.

Typically, salmon are distributed in non-returnable expanded polystyrene boxes custom-made to hold salmon. The salmon should be iced in the boxes by distributing about a third of the anticipated amount of ice required on the bottom of the box, laying in the salmon, then adding the rest of the ice. In some countries legislation already in force or intended, requires companies to recover and recycle waste, though at present most fish processing companies and merchants are probably below the threshold of turnover at which the regulations apply. Expanded polystyrene is difficult to recycle or recover economically and it is possible there could be a move towards the use of returnable plastics boxes. Unfortunately, the fish boxes currently used for distributing fish are too short to take whole salmon, other than perhaps for the smaller size ranges, without bending them, and it might be necessary to use custom-made returnable boxes for the purpose of transporting salmon. The normal fish box is not insulated, and it would be necessary to use at least insulated, if not refrigerated, vehicles for distribution.

5.6 FREEZING AND FROZEN STORAGE

Fish spoil rapidly even when chilled, and in situations where fish are caught at long distances from ports or where supplies can fluctuate they must be frozen for transport or long-term storage. A major advantage of aquaculture over catching fish from the wild is that the farmed fish can be produced near the markets and be supplied as the market demands. Consequently, the need for freezing and frozen storage of farmed fish is much less than it is for fish from wild stocks. Nevertheless, some salmon is frozen, particularly by processors, to even out seasonal variations in supplies from farms and to provide buffer stocks for times of high demand. In addition, some consumer products are sold as frozen products. Freezing and frozen storage of fishery products have been practised for decades—indeed, wild salmon was among the earliest fishery products to be frozen and stored—and the technologies involved are well understood.

Good manufacturing practices require that fish be frozen rapidly in equipment designed for the job, and be stored at a low temperature to avoid deterioration in quality during storage. Whole salmon are typically frozen in air blast freezers in which cold air at around −40°C is blown over the fish in a recirculating tunnel system. The salmon are laid out singly on trays or racks in the tunnel, or perhaps hung from rails. The core temperature of the fish, that is at the centre at the thickest part, should be reduced to below −20°C before it is taken out of the freezer for transfer to the cold store. A salmon 12.5 cm thick will take about five hours to freeze in an efficient air blast freezer (Aitken *et al.*, 1982). Fillets, including closely-wrapped fillets in vacuum packs (described below), can also be frozen in air blast freezers. Products in regularly-shaped packs, such as convenience products, are typically frozen in plate freezers. In these, the packs are frozen between hollow plates through which refrigerant, again at about −40°C, is circulated. The plates are brought together under slight pressure so that the product is frozen from two sides. A pack of fillets 4 cm thick in a carton will take about 1.5 hours to freeze in a plate freezer.

Frozen salmon, in common with other fishery products, are not completely stable during frozen storage, and appearance, flavour and texture can change. The rate of deterioration depends on several factors, but after a few weeks or months under poor storage conditions, after thawing frozen fillets and fillets cut from frozen whole fish will exude liquid, have a coarse appearance, and will be paler than the original. Oil and fatty tissue will take on a bronze appearance and have a rancid odour. The cooked product will have a tough and stringy texture, and a bitter, rancid flavour. The flavour changes, which are usually the limiting defects determining the storage lives of frozen salmon products, are due to oxidation of the unsaturated oils. This oxidation can be reduced considerably by excluding air from the frozen product by heavy glazing, that is by spraying the frozen salmon with water or dipping it briefly in water after freezing and before storage or, in the case of smaller products, by tightly wrapping in plastic film. Salmon frozen for buffer stocks and later processing should be frozen as whole fish rather than as fillets. Storage temperature considerably affects the rate of deterioration of frozen fish such as salmon, which together with its propensity for rancidity development should be stored below −25°C and preferably below −30°C. Under these conditions, assuming protection against oxidation, salmon products should have a storage life for good quality of between 6 and 12 months, and perhaps longer, depending on the product.

5.7 PROCESSING AND PACKAGING FOR RETAIL SALE

Typically, salmon is distributed from the farms to processors or wholesale markets as intact or gutted fish; processing at production sites is uncommon. Merchants at wholesale markets pass on the salmon to retailers or catering outlets, and might carry out simple processing operations such as gutting if necessary, filleting and steaking. It is important to keep the salmon chilled during all stages of distribution and marketing in order to maintain quality. Customers at the retail level will expect otherwise whole salmon to be gutted, which might be carried out at the retail premises. Outlets such as traditional fishmongers or fish counters at supermarkets will offer salmon as steaks—a common form for retailing and cooking salmon—or as fillets, which often prepared on the premises but possibly at the wholesale merchant's factory. Fillets might be further portioned as required by the customer into pan-sized pieces of one or two servings. This is all traditional fishmongering practice.

Prepackaged salmon and salmon products are now common in supermarkets and multiple stores. There are various ways of packaging for retail sale. The simplest is the overwrap. For this, the salmon, ranging from whole fish to steaks and fillet portions, are laid in a shallow tray, typically made of expanded polystyrene, and wrapped in clingfilm. The pack is catch weighed and labelled. This packaging can be done in the store or fishmonger's shop and is a convenient way for the product to be picked up and carried by the customer. Another form uses a deep, rigid tray made of clear plastic. The product, usually one or more pieces of steak or fillet portion, is laid in the tray, usually on an absorbent pad to take up exuded liquor, and a transparent lid is heat sealed on. A label is fixed onto the lid or the whole tray can be inserted into an outer sleeve which is printed with brand information and nutritional and culinary information. These types of packs will be prepared in factories and delivered to the retail outlets.

An extension of packaging in the rigid tray is modified atmosphere packaging (MAP). In this, the air in the pack is replaced by a mixture of gases intended to extend the storage life of the product (Davis, 1993). For example, a common mix used for fish products is 30% nitrogen, 40% carbon dioxide and 30% oxygen. Under appropriate conditions carbon dioxide suppresses growth of spoilage bacteria and extends the storage life of the products. Higher concentrations of carbon dioxide are more effective in extending storage life, but lead to problems with the sensory properties of the fish (acidic tastes and a tingling mouthfeel) and with collapse of the pack as the carbon dioxide dissolves in the fish product. Forty percent carbon dioxide in the mix is a suitable compromise between storage life extension and consumer acceptability. Sometimes a mix of 40% carbon dioxide/60% nitrogen, i.e., without any oxygen, is advocated for packaging fatty fish like salmon to reduce potential for rancidity, but that rancidity should not be a problem over the times the products are likely to be on display. Though MAP in 40% carbon dioxide under appropriate conditions can extend acceptable storage life of fish by 50% or so compared with air packs, this potential is not realised in practice. Studies demonstrating this extension have been carried out under laboratory conditions with the packs stored at 0°C. The effectiveness of carbon dioxide for extending storage life drops off rapidly with increase in storage temperature and is insignificant above about 5°C. It is difficult to operate chill display cabinets in stores below 4°C and consequently MAP under these conditions provides little benefit over packaging in air.

There is perhaps little justification for trying to extend the storage life of chilled salmon products under the conditions for processing and distribution in Britain, and indeed in many other countries. Salmon can usually be delivered to processing plants and merchants within a day or two of slaughter, hence they are very fresh at this point in the supply chain. Indeed, perhaps too fresh as the salmon could still be in rigor and the processor would have to wait until rigor is resolved before the fish can be filleted. Simple filleting, steaking and packaging can be accomplished easily within a working shift, and given good transport systems, products can be on the supermarket shelves the following day, that is within three or four days after harvesting. The policy of supermarkets, at least in Britain, is not to hold chilled fish products for more than two days so the total time from farm to sale is less than six days. Given good chilling practices throughout the processing and distribution chain this is well within the good-quality storage life of chilled salmon without resource to any process to extend storage life. Though packaging in MAP might not be of any advantage in retailing chilled salmon products, packaging in rigid containers is an attractive way of marketing the product, and a convenient way for the customer to buy and carry the product.

Another common form of packaging for retail sales is vacuum packaging. The product is laid on a coated paper board, inserted into a plastics sleeve, the air evacuated from the pack, and the sleeve sealed. The pack looks attractive and vacuum packaging is particularly useful for products that might have extended storage life with regard to microbiological spoilage but for which storage life is determined by lipid oxidation and development of rancid flavours. Smoked salmon is an example, and vacuum packaging of this product is widely used for both chilled and frozen storage.

5.8 PROCESSED PRODUCTS

The best known processed salmon product is smoked salmon. The salmon is salted before smoking and the most commonly-used procedure is dry salting. Skin-on fillets are prepared and the skin is slashed, or a few small areas of skin are removed to facilitate salt penetration from the skin side. The fillets are laid, skin side downwards, on a layer of fine grained salt 2 cm or so deep. More salt is spread over the cut surface. The amount to use is determined from experience: more for a thick fillet than a thin one. The salt is graded for amount from head to tail of the fillet to even out uptake of salt throughout the fillet, about 1 cm thick at the head end, a sprinkling at the tail end. The fillets are allowed to take up the salt in a cool or chilled room for 12–18 hours depending on size of fillet (Aitken *et al.*, 1982). High fat content in the fillet slows down uptake of salt and needs to be allowed for. Salty liquor will drain off the fillets which will lose 8–10% of their weight in the process. The salted fillets are washed to remove adhering salt and allowed to drain on racks. The fillets are then smoked for up to 12 hours, depending on their size, at a temperature of 27°C. This is cold smoking; more rarely salmon is hot smoked, i.e., smoked under conditions where the temperature rises to around 60°C so that the product is cooked. Traditionally, fillets were hung up to smoke in a naturally-ventilated smoke house, but nowadays they are smoked on racks in mechanical smoking kilns. The fillets will dry during smoking and this is important for imparting the desired texture to the finished product. Typically there is a further weight loss of about 9% at this stage. The smoked product is allowed to cool, inspected and packaged as sides or sliced and vacuum-packed.

There are variations on this basic procedure. The fillets can be brined in strong salt solutions rather than being dry salted, and flavourings like molasses, whisky and rum can be added to the dry salt or to the brine bath. The smoking time, the smoke density, and weight loss during smoking can be varied to produce various degrees of cure. Traditionally, salmon, as with other fish, was smoked as a means of preservation without refrigeration. The tendency now is for consumers to want less strongly flavoured and less salty products, which leads to lighter cures being made currently than was the case 20–30 years ago. Less hard cures result in shorter storage lives, and the current typical cures require that smoked salmon should not be considered as a long-life product that can be held without refrigeration and it should be held under refrigeration below 5°C.

Smoked salmon is intended to be consumed without any cooking and the product must be prepared under hygienic conditions to ensure it is safe to eat. One hazard is the possibility of the growth of *Clostridium botulinum* organisms and the production of botulinum toxin. It is therefore recommended that smoked salmon be prepared to contain at least 3.5% salt content in the water phase and held below 5°C to inhibit toxin production. If smoked salmon is to be held or distributed above this temperature for any appreciable time, for example because it is to be delivered by mail order, the cure should aim for 6% salt in the water phase.

Gravlax is a lightly-cured salmon product originating from Sweden and popular in Scandinavia, though obtainable much more widely. It is prepared by sprinkling the surfaces of a pair of fillets with some salt, sugar and white pepper. The fillets are laid together, cut side to cut side, head to tail with a layer of dill between them. The pair of fillets is put under light pressure and allowed to marinade in chill conditions for 1–2 days. The fillets are then thinly sliced and served as a delicatessen product. Gravlax does not have a long storage life, and should be chill-stored and consumed soon after preparation.

A feature of the retail marketing scene in Britain in the last two or three decades, as well as in other countries, is the increasing sales of ready-prepared meals which are already cooked and just need reheating, or no more preparation than cooking in an oven or a microwave. They can be presented as just a single component of a meal or as part of a complete meal. Farmed salmon is well represented among convenience fish products.

5.9 OPPORTUNITIES FOR MARKETING FARMED SALMON PRODUCTS

Farmed salmon has advantages over species from capture fisheries in that it is available throughout the year in amounts that can be tailored to production schedules, and in specified sizes. It can be assured of being very fresh, and meeting trade specifications for quality. Quality assurance, consumer satisfaction and regularity of supply, which are so important for multiple retailers, are much simpler to arrange in the case of farmed salmon than for fish caught in the wild. Salmon has an attractive appearance and a luxury image. The increased interest in cooking, fostered by television programmes and magazines, is stimulating an interest in the use of species of fish less familiar than the standard cod and haddock, and salmon often features in the recipes. Convenience fish dishes incorporating traditional white fish are often prepared from portions sawn from frozen blocks (usually incorrectly referred to as 'steaks'), which gives the product a factory-made appearance, whereas the convenience salmon products are prepared from natural fillet portions or from natural steaks. Supermarkets report an increasing support by the consumer for more natural, less processed foods, and farmed salmon products meet this demand. Some salmon farms can offer organically produced salmon.

Forecasts of fish supplies into the next decade or so show no, or at best a negligible, increase in supplies from wild stocks, but an increasing demand for fish (FAO, 1997, 1999). The level, or decreasing, supplies of fish from the wild accompanied by an increasing demand must inevitably result in increasing prices for the products. Indeed, over the last decade or so, retail prices of traditional fish products, at least in economically advanced countries, have increased faster than prices of food in general. At present, farmed salmon in general are slightly more expensive than traditional white fish species such as cod, haddock and some species of hake though the gap is closing, but it is distinctly less expensive than many other species of prime fish. A higher yield of edible flesh is obtained from salmon compared to fish such as cod: 60% of skinless fillets compared with 45% for cod.

It appears then that there are various factors related to both supplies and markets which are favourable to the marketing of salmon products. At present, farmed salmon are processed and marketed in the same way as wild fish. As the problems of producing salmon are solved, the industry perhaps should give some attention to matters related to post-harvest handling and the marketing of the product. There is scope for development of new products and new market outlets. The studies on the incorporation of α-tocopherol in the diet of salmon to stabilise colour and lipids during frozen storage are an example of the interaction between husbandry practices and post-harvest properties that can enhance the acceptability of the product. Ability to control fat content of the harvested fish within specified limits would be of benefit to processors. Selective breeding to produce fish more attractive to the consumer than wild counterparts could be considered. An example here is breeding to reduce the size and numbers of pin bones, which is known from consumer surveys to be a strong negative influence on purchases of fish.

6

Marketing farmed salmon

6.1 INTRODUCTION TO MARKETING

As the salmon farming industry has developed over the past 20 years or more, marketing has been the slowest discipline to be developed and be adopted wholeheartedly by the industry. Technology and production are the strengths on which the industry has been built; however, lasting success in any industry will always be reliant on meeting the market's needs. As production capacity has grown, so the industry has begun to appreciate the importance both of the market and of marketing.

This chapter outlines the basic principles of marketing and market research, and suggests their practical application to the salmon industry.

6.1.1 Definition of marketing

Marketing is riddled with misperceptions. Is it trading? Is it selling to an unwilling buyer? Is it exploiting the customer? Simply, it is none of these—it is a means of making products more sought after and, ultimately, business more profitable. Marketing is an integral part of selling and trading; however, marketing has much more to offer your business.

There are three key principles of marketing:

1 *Identifying* the *needs* of your *customers*.
2 *Satisfying* customer needs within the *resources* of your company.
3 *Satisfying* customer needs *profitably*.

Marketing is not complex; it is a practical, customer-focused approach to business that, if executed effectively, will impact positively on the 'bottom line'.

The aim of this chapter is to outline the practical application of marketing, but for readers requiring an academic approach, there exists a plethora of excellent textbooks, such as Baker (1998); Brassington and Pettitt (1997); Jobber (1998); Kotler (1997); Lancaster and Massingham (1999).

6.1.2 Marketing versus selling

The aquaculture industry is often criticised for being a production-driven industry. What this means is that great importance has been placed on the capabilities of production, and maximising those capabilities without considering the customer. Are there customers for the product? Who are they? How much will they buy? At what price? What features are they looking for in the product?

Historically, many operators in the sector have focused on 'loving the product' and not 'loving the customer'. In reality, they should have been asking: 'Does the customer really want that species, in that size, at that price?' In practice, being a production-driven business means that there is no attempt to meet the needs of customers.

Is it better, then, that the industry becomes more sales-driven? The answer to this has to be a resounding 'NO'! For an industry to enjoy long-term, sustainable success, it is necessary for it to become 'market-driven'. Quite simply, this means focusing on the needs and wants of its customers.

There is a very clear distinction between selling and marketing, and this is illustrated by the following:

- Selling is getting someone to buy the product that your business produces.
- A sales-oriented company will focus on sales volume.
- If your aim is to sell, then all you want is a buyer.
- Marketing provides the salesperson with a product they can sell.
- Marketing looks to the market for guidance as to what the customers' needs and wants are—this facilitates a longer-term view and ensures that the product meets customer needs and ensures customer satisfaction.
- A marketing-oriented company will place emphasis on profit and keep growth and profits in balance.
- The marketing-oriented company will monitor the market place, identify trends and plan production and the development of the business accordingly.
- If the aim of the company is to market effectively, then customers' needs and wants need to be anticipated.

If the inherent advantages of aquaculture over capture fisheries are considered, it is easy to identify how there are far greater opportunities for aquaculture to be market-led. Quite simply, aquaculture offers greater predictability of supply, control over quality, production planning, steadier pricing, price forecasting ability and greater potential to meet customer specification than capture fisheries. Fish farmers are able to adjust supply to demand, thereby providing for a more orderly market and a more stable price structure. With more control over the production process, they can provide products within a small range of size and intrinsic quality and, to some extent, can match their products to the requirements of the purchaser. Conditions for handling and packing of fish on land are easier to control than they are at sea, and farmed fish can be delivered to the user in much better condition than can fish from capture fisheries.

6.1.3 Marketing's role in business development

Marketing impacts across the full range of business activities. It provides an operating environment that aims to achieve organisational goals through the ability to determine the needs and wants of target markets, and by delivering the product that is desired by these markets more effectively than competitors (Kotler *et al.*, 1996). This is the marketing concept of business management and, by following such a concept, the company's vulnerability to changes in the business environment will be reduced and each and every profit opportunity that is presented to the business can be evaluated. It increases the opportunities for effective control of business activities by improving communication, coordination and planning. With all functions of the business working towards the same goal of meeting customer demands, a successful outcome is much more likely.

A recent newspaper article highlighted how one company is taking a market-led approach to altering their operations (from Kennedy, 1999):

> *Example 6.1*
> A Shetland salmon producer claims that it can cut processing times to less than an hour, ensuring improved quality.
>
> Lerwick Fish Traders Manager Joe Hottinger said the salmon would be filleted before rigor mortis set in, giving the product a huge marketing advantage. Mr Hottinger said, 'We want to have a fresher fish than all the other companies on the market. We achieve this by cooling the fish down at the right time and to the right temperature. This is being done very fast.
>
> We also want to eliminate the use of carbon dioxide before killing because it is very stressful, and ensure the fish has enough cool energy during the whole process, so that we have a controlled temperature throughout.'
>
> The key to the new system is liquid ice, normally used when handling filleted fish but not used before, according to the company, when dealing with live fish.
>
> The liquid ice makes sure the fish gets a temperature shock when entering the plant, is easy to handle and never gets warmer than 5°C during processing.

Lerwick Fish Traders (LFT) sell most of their produce for smoking before being distributed worldwide, so this means that they are selling into a commodity market. In the broadest terms, within such a market there is little to differentiate one product from another, unless there exists a demonstrable difference in some aspect of the product, its price or its availability. It is evident that a unique selling point (USP) such as fresher fish would give a company an edge in the market.

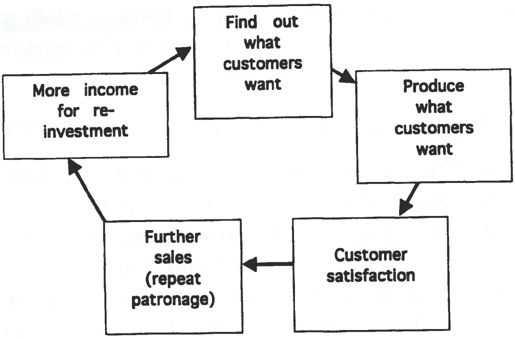


Figure 6.1. The cycle of virtue. *Source:* Saunders and Wong (1989).

LFT have looked at what the customer demands, and have made changes to meet those demands. Those changes have required considerable investment and changes in working practices, but if it means that LFT meet their customers' needs more effectively, thereby increasing sales, market share, price or profit margin, it will have a positive impact on the business.

As marketing impacts across the whole of the business, so it will create a 'cycle of virtue', as demonstrated in Figure 6.1. This 'cycle of virtue' demonstrates the positive impact marketing can have on a business.

6.1.4 Marketing success stories from the aquaculture industry

Example 6.2

In 1998, with production running at approximately 115,000 tonnes, and with a first sale value of in excess of £250 million, half of which is exported, the salmon farming industry supports over 6000 jobs throughout the Scottish economy. The industry is a significant contributor to employment and income generation in the most remote communities, particularly in the Highlands and Islands, and helps to sustain traditional patterns of economic activity in these regions. Some £60 million in wages and salary contributions are pumped into these local economies.

In the market, the Scottish industry has a reputation for producing the highest-quality fresh chilled product and, together with the Scottish salmon smoked in Scotland, it is estimated the retail value of sales is in excess of £550 million.

During the early stages of the industry, it was recognised that quality assurance in the food sector was a critical necessity to provide consumer confidence and advance sales. Since 1985 the industry's quality scheme has been a dynamic instrument embracing all aspects of quality control from farm through to processor and retailer, with trace-back a central feature.

The quality assurance scheme enjoys independent certification and accreditation to the European standard (EN45011) and has Label Rouge superior status from the French authorities. Changing consumer habits have meant that more salmon is processed into added value products and this is a continuing development with very exciting areas of recipe development gathering momentum. Much of the further processing is done to a very high standard by Scottish-based companies.

Scottish salmon benefits from its healthy eating qualities containing Omega-3 and Omega-6 fatty acids. In the UK alone, salmon consumption has nearly quadrupled in the last eight years and in many fishmongers' shops; their salmon trade amounts to some 50 per cent of total fish sales. Increased frequency of purchase by consumers underlines the ease of preparation and versatility of salmon which fits modern lifestyle cuisine.

The industry developed during the 1980s at a time when many other food products were in surplus and it has largely been the resources of the industry itself, collectively invested, through its own research and development programmes which has generated productivity gains.

Source: Scottish Council for Development and Industry (SCDI) (1999).

6.2 THE MARKETING ENVIRONMENT

No business operates in a vacuum. Businesses operate within an environment that is ever-changing. In order to compete effectively within that environment, it is imperative to:

(i) understand what constitutes the business environment;
(ii) monitor all aspects of the business environment;
(iii) define how best to maximise the opportunities and minimise the threats that the environment presents to the business.

6.2.1 Defining the marketing environment

According to Kotler *et al.* (1996), the business environment includes any actors or forces outside of the company that affect its ability to develop and maintain successful transactions with its target customers. The business environment can be split into two main components:

- the Micro-environment (forces close to the company, over some of which the company may have an element of control);
- the Macro-environment (larger societal forces over which it has no control).

The Micro-environment includes:

- Competitors: firms that supply the same or similar goods to the organisation's target market.

- Suppliers: firms and individuals that provide the resources needed by the organisation to produce its goods and services.
- Marketing intermediaries: firms that help the company promote, sell, and distribute its goods to final buyers.
- Transportation systems: systems that bring customers to the business or organisation, or that take the organisation's products to its customers.
- Marketing services agencies: marketing research firms, advertising agencies, media firms, and marketing consultants.
- Financial intermediaries: banks, credit companies, insurance companies, and other finance companies.

The Macro-environment includes more general aspects of the business environment, which impact on a firm's operations in a less direct fashion and are often uncontrollable by the firm. It includes influences from the economic, demographic, natural, technological, political and legal environments. Table 6.1 illustrates some of the external factors that may affect business within the Macro-environment.

Examples of the impact of different types of change on the industry are given below.

A political change in the Macro-environment that had a large impact on the Norwegian salmon farming industry is the 1997 anti-dumping case instigated by the

Table 6.1. Factors within the Macro-environment that may influence business operations.

Political and legal	Economic and demographic
Consumer legislation	Growth in national and world economy
Health legislation	Interest rates
Environmental laws	Tax rates
Workforce legislation	Inflation rate
Privatisation legislation	Exchange rates
Political shifts	Consumer spending
Pressure group actions	Income and changes in the distribution of income
EU influences	Demographic changes
	Market concentration
	Increasing/decreasing importance of different sales outlets
Social and cultural	Natural and Technological
Consumer preferences	New production methods
Social values	New products
Immigration	New ways of selling
Lifestyle changes: more eating out	Information systems
Education	Patents
Consumer concerns: health scares	Climate change
	New processing technology

Source: Baker (1998).

EU. The main provisions of the agreement included: the imposition of a marketing duty of 2.25%[1] on Norwegian salmon entering the EU market; an agreement on a minimum price; and a 10% maximum increase per annum on the total quantity of exported farmed salmon from Norway to the EU market. In essence, the trade agreement increased costs for Norwegian salmon farmers and limited the growth potential of one of their main export markets.

Economic changes in the Macro-environment are perhaps most likely to have direct impacts on a salmon farming business. The high value of sterling in 1999, resulting from a strong British economy, had major impacts for most businesses in the UK. Scottish salmon farmers, with a heavy reliance on export markets for sales, were particularly affected. The strong value of the pound made UK products relatively more expensive for importers to purchase.

Increasing consumer concerns over food safety and environmentally-friendly food production methods—an example of a social change in the Macro-environment—may have a positive impact on the sales of farmed salmon, providing the industry ensures that consumers perceive that production techniques used on salmon farms pose no risk to their health or to the environment.

A technological change, such as the development of automatic feeders, will affect the costs of production for a farm, and will therefore impact upon the profitability of production. This could, in turn, affect the success of the business.

From the above examples, it is easy to see how important it is that a successful company has a solid understanding of the business environment in which it operates, and keeps up-to-date on developments within that environment. This knowledge will allow it to be able to determine the likely impact of changes on its business, and be proactive in adapting to the changes.

6.2.2 Analysing the marketing environment

A simple way to ensure that all types of change are taken into account is to undertake a SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis and a PEST (Political, Economic, Social and Technological) analysis of the market environment. The SWOT analysis allows an objective examination of the Micro-environment, while the PEST is an audit of changes in the Macro-environment. It is also worthwhile considering the marketing environments of customers and of suppliers.

Organisations should continually monitor what is taking place in the environment in which they operate. This process is known as environmental scanning and should be an integral part of market-led business activities. Such environmental monitoring allows the business to identify future opportunities and threats in the market, to be aware of its competitive advantages and disadvantages, and to have an understanding of external forces that may impact on its operations.

An example of the application of environmental screening and its subsequent impact on business can be seen within the capture fisheries market. The fluctuations

[1] This is in addition to the 0.75% duty that was already in place.

of supply volume, quality and price have led two of the UK capture fisheries market's most significant customers—the major multiples[2] Asda and Tesco—to operate their own fishing vessels. This route should, in part, offer them some of the inherent advantages enjoyed by aquaculture, namely guaranteed supply, contract pricing, and tighter quality specification. Without a doubt, Asda and Tesco will have continually monitored their supply sources, as well as their customers. As a result of this, they will have recognised the limitations of the capture fisheries market and, by operating their own vessels, are trying to circumvent those difficulties.

> In a £1.5m deal, Asda has purchased four boats and their crews to ensure availability of cod supplies. The boats are expected to supply up to 100 stores with more than 500,000 cod per year.
>
> Tesco have chartered three boats since October 1998 and aim to have 30 vessels in its own dedicated fleet by the end of June [1999]. The boats will be flying the 'Fishing for Tesco' flag.

Source: IGD (June 1999).

This development demonstrates recognition by the major multiples of the limitations of the capture fisheries market in the UK. Having recognised the needs of their customers (i.e., to be guaranteed a supply of cod, within a given price band, throughout the season), Asda and Tesco have changed their business practices to overcome the weaknesses of supply, to better meet the demands of the market.

The knowledge obtained through environmental scanning provides the required information to adjust operations where possible in order to achieve the firm's objectives. Having identified the current situation within the market (SWOT), and the external forces that may impact on operations, it is now possible to develop a strategy for maximising the potential for the business to meet its marketing objectives.

In order to achieve this, a strategy is required that includes the various parts of the 'marketing mix'. This mix is a combination of what is commonly known as the **four Ps**: product, place, price and promotion.

More recently, these have been 'repackaged' to suit the more customer-oriented approaches to marketing management, and may be referred to as the **four Cs**. Developed by Robert Lauterborn (1990), they are:

- convenience (place);
- cost to the user (price);
- communication (promotion);
- customer needs and wants (product).

[2] In the UK, the major multiples are food retailers with annual sales of £1billion or more, such as Safeway, Sainsbury, Asda and Tesco.

6.3 KEY ELEMENTS IN MARKETING: THE PRODUCT

A great many of the activities that take place within a business can be said to revolve around what is commonly referred to as the 'product'. Firms purchase inputs, hire labour, rent land and buildings, design advertising campaigns, plan inventories and sales, and enter into various contracts in order to make, store, and sell their 'product'. So what is this 'product'? The easy answer is that it is the fish being produced and sold. It is considered by some to be the most crucial component of the marketing effort. It is the basis for satisfying consumers' needs, and for generating the revenue for the business.

6.3.1 What makes up the product?

A 'product' is anything (not necessarily a physical item) that serves to meet the needs of a customer, be it a physical good such as a fish, a service (i.e., transporting the fish to the processing plant) or something less tangible such as a feature (this could be the day on which the fish is delivered or the location of the retailing unit).

'Product' therefore can be defined as an amalgamation of attributes that are desired by the customer. Some of the attributes looked for in a fish product may be:

- size
- flavour
- price (value for money)
- quality (i.e., colour, freshness)
- quantity
- packaging
- shelf life
- name (i.e., brand, location, organic)
- availability
- after-sales service
- cooking guidelines

The purchaser will look for all or some of these attributes when making their decision about which product to purchase. In addition, some attributes will play a more important role in this decision-making process than others. The key to a successful product is a full understanding of which attributes are demanded, and the relative importance of each.

6.3.2 Identifying and satisfying customer needs

Having said that the key to a successful product—and therefore a successful business—is knowledge regarding what consumers are looking for, it then becomes necessary to be able to identify these demands.

Given the diversity of individuals, how does one go about identifying customer needs and demands?

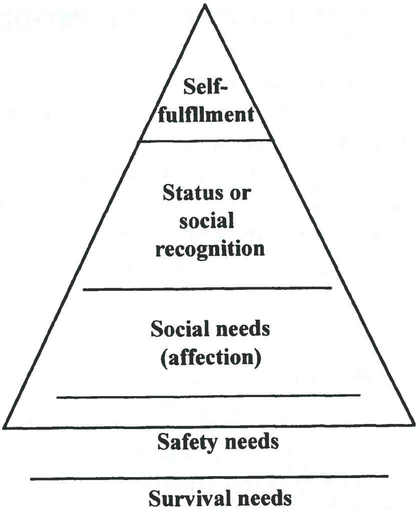


Figure 6.2. Hierarchy of needs. Adapted from Maslow (1970).

Maslow's Hierarchy of Needs (1970) is often used to emphasise the diversity of customer needs. The model, represented in Figure 6.2, suggests that once basic needs such as survival, food and shelter are satisfied, more sophisticated needs are demanded.

The significance of this model is in applying it to markets. A company should identify the kinds of needs most required by its principal group of buyers. In general, more sophisticated needs tend to come from consumers with higher standards of living.

> *Example 6.3*
> A low-valued fish, such as carp, may be offered and promoted as a basic food source in Eastern Europe, at a price the local market can afford, whereas in a more advanced economy such as the UK, most consumers want something extra and will be prepared to pay for it. These consumers have moved beyond the requirement to satisfy their basic need for food.

Consumer needs arise in order to satisfy some purpose. This purpose may be either:

- *rational*; based on objective benefits, or
- *emotive*, based on fulfilling a psychological or social need.

When needs are emotive, an individual's feelings and attitudes play a significant role in their decision to purchase a product.

Example 6.3 (continued)

Once a consumer has decided to satisfy their rational need for food with the purchase of fish, the next decision is 'What type of fish?' The choice is more highly influenced by emotive needs; a consumer will search for a particular type of fish that satisfies these psychological or social needs.

A prime example of this in fish markets is the success of 'dolphin-friendly' tuna. In today's market, consumers buying tuna are looking for more than simply a fish that is relatively cheap and ready to use. They are also interested in other aspects of the product such as the impacts of tuna fishing on dolphin populations—there is an environmental issue involved in the consumer's decision to purchase tuna products.

In the UK fish market, research has shown that consumers are looking for the following characteristics when they purchase fish:

- ease of preparation;
- quick and convenient cooking methods;
- good flavour qualities;
- value for money;
- lack of bones, eyes and smell;
- long storage life;
- attractive appearance.

Market research is required to identify consumer needs and whether they are objective or emotive. In addition to knowing what the demands of the market are, it is essential to have information on the people who are buying the product.

- What are their characteristics?
    - Age?
    - Gender?
    - Income?
    - Occupation?
    - Location?
- What are their preferences?
    - How often do they eat the product?
    - What else do they eat?
    - What are the characteristics of the product that they desire?
    - What price are they willing to pay?
- How are these changing over time?
    - Changes in eating habits.
    - Changes in working patterns.
    - Changes in incomes.
    - Changes in lifestyles.

Example 6.4
Consumers in the UK are very sophisticated. Returning to Maslow's Hierarchy of Needs (Figure 6.2), and the original example of carp, the philosophy behind marketing carp in Eastern Europe would not be profitable in the UK.

UK consumers have moved beyond the requirement to satisfy their basic need for food, as they have a high standard of living and are looking to satisfy needs further up the hierarchy such as self-fulfillment, social recognition, or social needs.

Most consumers in the UK want something extra and will be prepared to pay for it. Their choice is more heavily influenced by emotive factors such as fulfillment of psychological or social needs. *What type of fish will satisfy these needs?*

A wide choice of wet, smoked, cooked, chilled, frozen and ready-prepared fish is now on offer as a result of consumer demand that these social and self-fulfilling needs be satisfied.

For example, whole salmon would satisfy basic food requirements only, whereas hot smoked peppered salmon would be fulfilling social recognition needs.

Broad social change since the Second World War has heavily influenced eating habits in the UK. Meals are more casual, with families no longer regularly sitting down together for traditional formal meals. With women's roles changing from housewives to becoming coearners, time pressures have resulted in snacking and casual light meals becoming the norm.

For children and young adults, snacks are beginning to replace regular meals. The trend for light meals is even more pronounced. Lunch, which previously consisted of a formal hot dish, is now more likely to consist of a cold eating snack. The Taylor Nelson Family Food Panel reports that there was a 35% increase in this type of meal occasion in the 6-year period 1991–96 (Seafish Industry Authority (SFIA), 1998).

As a result, food has been adapted to become more convenient in terms of preparation, so it can be delivered prepared, direct to your home or bought ready prepared from the supermarket. This, together with the increasing ownership of freezers and microwaves, means that convenient, quickly-prepared food is available 24 hours a day, 365 days a year.

Approximately 37% of UK households buy chilled, fish-based ready meals at least once a year, with fish-in-auce products being the most popular, followed by fish and chip meals. The SFIA reports that the ready-meals sector is gaining recognition of an opportunity to bypass consumer lack of confidence, knowledge and/or willingness to deal with fish in unprepared form (Agra Europe (London) Ltd., 1999).

Illustrating some of the trends noted above are the findings of a recently-published report, *Eating Out Habits* (Mintel, 1999). Mintel estimates the value of the UK eating-out sector in 1999 at £20.6 billion. This market has suffered in past years from the effects of recession, but has performed better in more recent times. The development of a new eating-out culture among UK consumers is assisting this revival. People are eating out more often, food is in fashion and the new demand is coming from a wider cross-section of society, giving the market a mass base.

Most dining out is no longer prompted by a special event. People eat out or purchase takeaways for a variety of reasons: utilitarian, social and for relaxation. Mintel has established that only 34% of those who dine out do so for special occasions only (Mintel, 1999).

As a result of the rising numbers of women entering the workplace, and value placed on having real leisure time, there has been a rise in the one-stop weekly, fortnightly, or even monthly shop in the supermarket multiples, encouraged even more so with the introduction of store loyalty cards. This has had a devastating effect on the independent fishmongers, whose numbers are now in rapid decline.

6.4 KEY ELEMENTS IN MARKETING: DISTRIBUTION

6.4.1 The distribution model

The model for distribution of farmed fish is relatively simple. It is unlikely that a farmer will be trading directly with the end consumer. Rather, it is more likely that the farmer's customer will be a wholesaler, retailer or caterer. The distribution model is illustrated in Figure 6.3.

The different players in the distribution chain will have different needs and wants, and these will be best suited to different types of farmers. The key things that should be considered when selecting distribution channels are: the needs of the customer; the capabilities of the business; and the costs of distribution. Each option will have benefits and disadvantages and each will be more or less suited to the business. It is important not to simply select what is the simplest method of distribution, but rather to consider what is the best option to meet the other requirements noted above.

A description of the format and the needs and suitability of the different main options for distribution within the farmed salmon market are noted in Table 6.2.

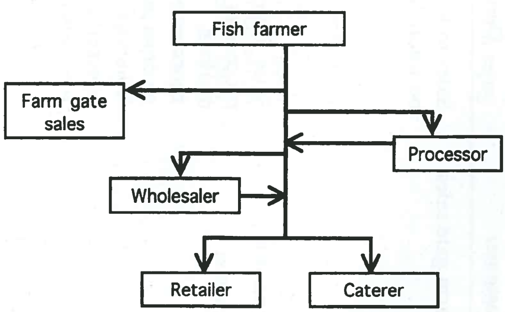


Figure 6.3. Distribution options. Adapted from Shaw (1990).

Table 6.2. Outline of distribution channel options for salmon.

Customer	Description	Suitability	Requirements
Farm gate sales	✓ Sales to local customers and, occasionally, consumers.	✓ Requires good passing trade. ✓ High margins on relatively small volumes—most suited to well-located small farmer.	✓ May be very seasonal depending on location. ✓ Range of related products an advantage. ✓ Shopkeeping skills needed. ✓ Food hygiene skills.
Processor	✓ Sales to primary and secondary processors in home and overseas markets.	✓ Variety of types of customer with regard to price requirements, product specification, quantity and quality requirements.	✓ Smaller processors tend to practise less-structured business (i.e., will shop around on a daily basis, and have less stringent standards). ✓ Increasingly stringent product specifications, particularly if selling on to multiple retailers. ✓ Increasing use of contractual agreements with larger processors.
Wholesaler	✓ Traders: buy fish from farmers and sell on to other wholesalers, retailers or caterers.	✓ Huge variety within market in terms of business size and trading practices and requirements.	✓ Dependent upon business-some prefer close liaison with grower, others tend to 'shop around'. ✓ Some contracts.
	✓ Inland wholesalers: group of wholesalers (e.g., Billingsgate Market, London) selling primarily to local users, but also to other wholesalers and processors.	✓ Outlets for large or small volumes. ✓ Group of dedicated suppliers. ✓ Market with high entry barriers.	✓ Consistency of quality preferred. ✓ No contracts or fixed prices.
Retailer	✓ Sales direct to retailers, with deliveries direct to store for fresh fish and into regional distribution centres for packaged fish.	✓ High volume orders. ✓ Aiming for consistency in quality. ✓ Increasingly concentrated market. ✓ Prefer to source from narrowing customer base.	✓ Regular supplies on on-going basis. ✓ Minimal price fluctuations. ✓ Increasing use of contractual agreements. ✓ Require consistency and flexibility. ✓ High and carefully-monitored quality standards.
Caterer	✓ Sales direct to caterers only for larger customers (e.g., Brake Brothers). ✓ Otherwise via wholesalers.	✓ As per retailers where buying direct.	✓ As per retailers where buying direct.

Source: Adapted from Shaw (1990).

6.5 KEY ELEMENTS IN MARKETING: PRICE

The price of a product is the exchange value of a product. In strict terms, it is the amount of money or other products needed to acquire a product. The price attached to your good, however, represents more than the amount of money a customer must pay to obtain it. It reflects the 'value' of the product among potential purchases.

'Value' is a relative concept; a customer will perceive a product to be of good value if the perceived benefits of the product outweigh the price of the product plus any other costs associated with it (i.e., time associated with shopping, environmental impacts, etc.). The price should indicate to the customer that the product has the kinds and amounts of benefits expected at that price (Allen, 1999).

6.5.1 The elements that make up a price

In market-based economies, prices are primarily determined in the market through the interactions of supply and demand. Supply refers to the total quantity of a product that is made available for sale in the market. Demand is the total quantity of a product that consumers wish to purchase.

The market can be defined as the place where exchange occurs, and it is in the market that prices are determined. Suppliers arrive with their products, wishing to sell as much as possible at as high a price as possible. Buyers, on the other hand, arrive at the market wishing to purchase a certain amount of the product for an amount of money that they deem to represent the correct value. If the buyers think the price is too high, few of them will purchase the product. Alternatively, if the price is too low, the demand for the product may well outstrip the available supplies, or a low price may suggest poor quality. Through negotiations and the transfer of information from buyer to seller, a price is determined at which the producers will be willing to sell all of their goods, and the buyers will be willing to purchase them all.

However, prices are never stable for long. This is particularly the case for fresh products such as fish and shellfish, primarily due to the perishability of the product, and the resulting need to sell within a short time period.

Market prices fluctuate as a result of changes on both the customer side (demand) and the producer side of the equation (supply). As demand increases, there will be a temporary shortage in the market and prices will increase. Increases in supply will remove any shortages, or create surpluses on the market. The effect of a surplus is that firms will compete with each other for sales, and prices will fall.

Fluctuations in demand and supply arise due to a number of factors[3]:

6.5.5.1 Supply

- Costs of production: if input prices increase, the cost of supplying the product will increase, and without a subsequent increase in price, firms will change the amount they supply in an attempt to reduce costs.

[3] Refer to Chapter 7 for more details on demand and supply.

- Seasonal factors: given the nature of the aquaculture industry, production is tied to a biological process that will affect the quantity supplied to the market at certain times of the year.
- Changes in technology: new production processes are continually being developed in an attempt to better satisfy customers and/or to reduce costs. An example of a technological change was the discovery that by manipulating the amount of light, smolts could be produced out of season. With a steady supply of smolts, salmon farmers were no longer restricted by the natural biological process of the salmon, and could produce more salmon by putting smolts to sea more often. Changes in technology generally lead to an increase in the amount of a product that is ultimately placed on the market.
- Random shocks: disease outbreaks, storms or unseasonable temperatures can impact on the amount of fish produced on a salmon farm, and will therefore affect the total supply to the market.

6.5.5.2 Demand

- Price of the product: in general, the higher the price of the product on offer, the less demand there will be for that product. Conversely, the lower the price of the product on offer, the greater the demand will be.
- Prices of competing products: this may be other fish in similar market sectors, or other food products. Substitute products will influence the demand for the product you have on offer, as their relative 'values' will inevitably be compared at the point of purchase. For example, whether a consumer is buying salmon as a 'fish component' or a 'protein component' for a meal will have a strong influence on their decision-making process.
- Consumer spending power: increases in consumer income and spending power generally increase the demand for a product. However, food is a special case, in that demand for food does not necessarily increase along with income. In areas where people have a high disposable income, additional money is generally spent on luxury items such as houses, clothes or holidays rather than food. However, people do tend to buy highly-priced or higher-quality foods as their incomes grow, thus increasing demand for these types of products. Where people are less well-off, demand for these same foodstuffs will fall.
- Marketing and consumer choice: there are numerous complex factors involved in what people decide to buy. Some examples of these include:
  - The packaging: whether or not it is eye-catching; looks relevant to the meal occasion for which the product is required; is practical for the storage conditions it will be subjected to; gives the impression that the product is value for money; looks hygienic. All these factors can affect the demand of the product.
  - The time of year: cold eating products are not popular at cold times of the year, such as winter, causing demand for these types of products to drop temporarily. Demand rises again, however, in summer when salads, cold

buffets and barbeques are very popular. For products such as smoked salmon, demand in the UK reaches its peak during the Christmas season.

- The ease of preparation and cooking: consumers perceive fish as difficult to prepare and cook. If the fish comes ready to cook with little or no preparation required, it is going to be viewed advantageously and demand is likely to increase. Salmon '*en croute*', traditionally seen as a complex dish to prepare, can be bought pre-prepared, simply requiring heating up—this encourages consumers not only to purchase fish, but also to experiment with more difficult preparations of fish.
- Organoleptic qualities (taste/texture/appearance/aroma): any food that tastes fresh, looks attractive and appealing and gives off a delicious aroma is likely to be popular, thus demand will increase. Conversely demand will decrease if the product does not smell fresh, taste good or appear attractive.

6.5.2 Influencing the price

Price is a determinant of the market supply and demand for the product. Most firms, unless they have market power[4], do not have a great deal of control over the price they will receive for their product. Individual companies may not be able to influence price on their own, but they can increase their market power by acting in cooperation with other firms. By pooling production and marketing as a group, the 'cooperative' will have access to a larger total supply of the product, and therefore may be able to influence the price on the market.

Companies can also direct some influence over the price they receive by competing in a smaller market. Non-price features of the product such as branding, quality and convenience can differentiate a product from its competitors, and therefore can decrease the size of the market in which it competes. This then allows a firm to have some influence on the price of a product, as they have the largest market share.

An example of companies attempting to operate in a smaller market (or finding what is often referred to as a 'niche' market) is the introduction of organic salmon into the UK market. Some small salmon farms, operating in the Orkney Islands, have converted to organic production of salmon in an attempt to enhance the profitability of the business. Increasingly, salmon farming in the UK is highly competitive and concentrated, and economies of size are required to ensure an operating profit. Small firms find it difficult to compete with the large companies in a very competitive marketplace. To reduce the size of the market, these Orkney-based farms chose to produce a product which does not compete for the same customer base as the large farms. Consumers of organic products demand products that have different features

[4] Market power allows a firm to influence price. This generally occurs if it can manipulate the total supply on the market (i.e., if it has a large enough production volume to influence the market supply).

than conventially-produced salmon, and are willing to pay a premium for these features.

6.6 KEY ELEMENTS IN MARKETING: PROMOTION

Promotion is vital to the success of any business; however, it really should carry a health warning! Often businesses will embark on costly promotional campaigns that are suited neither to their business' objectives nor to their market. What good promotion means in practice is letting existing and potential customers know, via a medium they respect and understand, about the organisation and its products.

6.6.1 The different elements of promotion

The elements of the marketing communications mix are described together with their advantages and disadvantages in Table 6.3.

6.6.2 Key considerations of a promotional campaign

Before embarking on any form of promotional activity, it is important to define why it is being done, i.e., define the promotional objectives. There are a huge variety of reasons why an aquaculture business might consider promotional activity, and some examples are listed below:

- increase sales by X%;
- introduce your company and its products to potential buyers in a new overseas market;
- inform existing and potential customers of your intention to commence the farming of organic salmon;
- create brand recognition for a new collaborative branding scheme;
- inform customers of recent acquisition of neighbouring farm and resulting increased production capabilities.

Having defined the objectives for embarking on a promotional campaign, it is important then to identify the resources, in terms of staff skills, finance and time, which are available to the campaign. Many businesses will have the resources to undertake direct mail and personal selling themselves, but it is highly likely that they will hire expert help if considering an advertising campaign, sales promotions, or a high-profile PR campaign.

Prior to defining the structure and elements of the campaign it is worthwhile undertaking some research to establish the level and type of promotional activity in the target market, the promotional activity of your direct competitors, and which promotional activity target customers respond to. If you think about the purchase decision from the point of view of your customer, this may well help guide you: for example, does the customer buy on price? If so, price promotions may be of value.

Table 6.3. The promotional (or marketing communications) mix.

Promotional form	Description	Advantages	Disadvantages
Advertising	Paid form of non-personal media presentation promoting ideas, concepts, goods or services by an identified organization. Can use any form of media, e.g., TV, press, billboard, WWW, radio.	✓ Can be highly effective.	✓ Costly.
Sales promotion	Point-of-sale material or inducements aimed to stimulate purchase, e.g., leaflets, money-off coupons, 'buy one get one free' offers, shelf talkers. Paid for by producer or promoting organisation or selling outlet.	✓ Can 'sell in' (to trade), or 'sell out' (to public) product. ✓ Reinforces brand image.	✓ Cost. ✓ Requires sophisticated measurement techniques.
Personal selling	Any conversation or correspondence between seller and customer aimed at making sales, e.g., sales presentations.	✓ Develops one-to-one relationship more quickly than other forms.	✓ Time consuming. ✓ Costly.
Public relations (PR)	Planned communication activities aimed at promoting understanding between an organisation and its public in order to help achieve its long- and short-term goals, e.g., news stories in local press, company profiles, political lobbying.	✓ Seen as independent source of information by many customers.	✓ Requires strong understanding of media.
Direct mail	Mailshots targeted at specific groups of existing or potential customers. Recipients likely to have been selected from database (organisation's own or bought-in) of potential recipients.	✓ Quick. ✓ Cheap. ✓ Easily organised. ✓ Easy-to-measure impact.	✓ Increasingly viewed as 'irritating'. ✓ Often ends up in bin.
Web-based marketing	Any online promotional activity. This can include: developing own website; joining relevant online market places and information portals; developing network of links to other relevant sites' (synergistic links to other non-fish sites) online advertising; online public relations.	✓ Low cost ✓ Ability to establish and maintain direct dialogue with customers. ✓ Potential global reach.	✓ Requires technology skills. ✓ Increased competition (global). ✓ Fragmented customer base.

However, if supplier reputation and prestige more heavily influence buying decisions, then PR is likely to play a bigger role.

Promotional campaigns may include combinations of all the elements of the promotional mix, i.e., advertising, sales promotions, personal selling, public relations, direct mail and web-based activities.

Think about your customer(s) and their objective(s). For example, if dealing with the major multiples, who are very experienced in promotional activity, consider their promotional objectives. They will be interested in increasing the efficiency of their promotions. They do not want promotions that simply shift sales from one supplier's product to another or that mortgage next month's sales, but rather promotions that increase total sustainable sales in the category.

Promotions must also be consistent with the product's image. If a company is renowned for producing a consistently high-quality farmed fish, any promotion must enhance that image in order to increase sales. Any contradiction between promotional image and product/company image will confuse a customer, and may ultimately result in lost sales. For example, if a company is producing high-quality, premium, organic salmon, which traditionally enjoys a high price premium, a 'stack them high, sell them cheap' price promotion is unlikely to fit with the product's image. This type of promotion is more likely to damage the image of the firm and its products than enhance the long-term profitability of the company.

Having considered and formulated the objectives, available resources and the campaign structure, it is time to plan the operational activity of the campaign. It is useful to outline an annual promotional plan, in order to see how the activities can build on and complement each other. For example, if a company is considering exhibiting at the European Seafood Exposition in Brussels held each Spring, it might be useful to undertake a direct mail campaign in advance of the show to advise buyers of its presence at the show and invite them to its stand. Trade press advertising might also be considered as a means of building awareness of the company name. Perhaps the show could be launched to launch organic salmon to customers. After the event, some PR activity highlighting the success at the show might be useful.

Scottish Quality Salmon's (SQS) Tartan Quality Mark (TQM) scheme is widely acknowledged as a 'case study' example of the benefits of a collaborative marketing and promotion scheme. In addition to the TQM scheme, SQS have also directed their marketing efforts to the various levels of the supply chain, as illustrated below.

Example 6.5

In running any business, it's easy to forget that a little extra effort in promoting its product and services can result in increased sales and happy customers.

For this reason the Scottish Salmon Board[5] (SSB) launched the *Excellence in Marketing* initiative at the beginning of 1998 to encourage fishmongers to

[5] Scottish Quality Salmon was formerly known as the Scottish Salmon Board.

focus on marketing their business through promotion of their products and services. This aimed to not only reap rewards in terms of increased business, but also develop marketing skills that help to compete successfully in today's challenging trading environment.

Open to official retailers all over the UK, the *Excellence in Marketing* initiative was specifically aimed to recognise and reward fishmongers who actively and successfully promoted Tartan Quality Mark Scottish salmon, as well as their own business, over the traditionally slow period between January and March. Entries were judged on originality of the idea, display and merchandising skills, creative input, scope of activity and customer focus.

The competition attracted a healthy response and the standard of entries was so good that the judging panel had a very difficult decision on their hands. All the winners were featured in the SSB newsletter and benefited from further publicity in their local press at the time of the awards.

An example of a business putting the scheme into practice is Ward's Fish in Birkenhead. Having just refurbished their shop, they saw *Excellence in Marketing* as a great opportunity through which to promote the new shop and TQM Scottish Salmon.

Promoted as a more cost-effective and healthy alternative to meat was Ward's very own 'Sunday Road TQM Salmon' recipe. Three dishes were devised and all the staff held a tasting to select the winner—salmon stuffed with whiting. Customers were treated to a tasting at the counter to help encourage the less adventurous to try the 'Sunday Road TQM Salmon' before buying it.

The upshot of this promotion was a significant upturn in sales, with no adverse effect on the sales of other salmon cuts or, indeed, other fish. An interesting finding from this exercise was that most people purchased the Sunday dish ready-prepared despite the fact that a recipe was also available—proof that convenience food is an ever-growing market.

Source: SSB (1998).

6.7 MARKET RESEARCH

6.7.1 Definition of market research

In 1961, the American Marketing Association defined market research as:

> The objective gathering, recording and analyzing of all facts about problems relating to the transfer and sale of goods and services from the supplier to the consumer or user.

The procedure that is followed when market research is undertaken will be the same whether it is considering a new trade market, a new consumer market, the market for

Identify the problem/opportunity

↓

Create the research design

↓

Choose research method

↓

Select sampling procedure

↓

Collect data

↓

Analyse data

↓

Prepare report

Figure 6.4. The market research process.

a new species, or a new overseas market. The process is logical and sequential and is outlined in Figure 6.4.

At the first stage, 'identify the problem/opportunity', it is typical for a company to be faced with changes in the external environment and want to know whether to change some aspect of the product portfolio, pricing strategy, promotional efforts or distribution channels. The company will also want to know how they should change. It is fundamental that the problem is identified correctly, in order that the research will be appropriate to the company's needs. Taking the example of a fish farm interested in starting to farm abalone, initially the problem/opportunity may be defined as 'Can we farm abalone efficiently?' In fact, that is only one part of the problem or opportunity. Rather, what should be researched is a quantitative and qualitative assessment of the market for abalone, the requirements of that market and the ability of the farm to meet those requirements.

Having correctly identified the problem, it must then be decided how best to answer that problem. At this stage, the research team will consider the different market research methodologies such as surveys, focus groups and observation techniques.

If a company has decided to embark on the production of a new species, such as abalone, there would be little point in researching the problem with consumers if respondents were unlikely to have any experience of the 'new' species, its flavour profile or how it is typically eaten. Such a consideration would obviously influence both the research design and the research method chosen. In this case, a variety of research methodologies will be required. Desk research would be the first stage, followed by qualitative assessments via in-depth interviewing and perhaps focus groups.

There are two broad categories of market research: desk research and field research.

6.7.2 Desk research

Desk research is essentially exploratory research. It is a fundamental aspect of any research project, but only one part of it. It is a quick and cost-effective method for gaining insights into the research issue. Generally, desk research consists of collecting and summarising secondary[6] data in order to provide the background information required for the problem.

Performing this preliminary research may be all that is required for the problem at hand, or may be all that is affordable in terms of time and money given the importance of the problem. When this is not the case, desk research still serves an important role in that it should provide the researcher with the necessary background information to identify areas in need of further research and to refine the research objectives for the field research.

The secondary data used in desk research may not always be completely relevant to the problem at hand; however it does allow for a preliminary overview of the subject or problem.

The advantages of secondary data are that it is:

- inexpensive;
- readily available; and
- several sources are available, allowing for comparisons.

The disadvantages include:

- information may be out of date;
- data may not be suitable; and
- methodology may be inappropriate.

6.7.2.1 Sources of market information

Data about the problem must be gathered before a possible solution to the problem can be formed. Much of the required information may already be available inside the organisation from its own records. However, much secondary data has to be obtained from outside the organisation: the internet, libraries, trade associations, universities, private research organisations, and government agencies are all possible

[6] Secondary data is pre-existing, collected for another purpose. For example, the National Food Survey provides regular data on food consumption in the UK; Mintel produces reports on the market for fish and fish products in the UK; Food from Britain produces monthly reports on the trade in all food products to and from the UK. All the sources of data could provide useful quantitative data on fish consumption in the UK.

sources of market information. Appendix 6.1 gives a sample of some possible sources of market information for the seafood industry.

6.7.3 Field research

Although desk research is a cheap, quick way of gathering information, it would be inadvisable to base key decisions on the findings of desk research alone. It is necessary for researchers to gather data that is specific to the research problem at hand. This is known as field or primary research.

In some instances conducting field research will be a necessity, in other cases it may not be necessary or worthwhile. If a company wishes to assess demand for a new species before commencing production, it would be difficult to base such a decision on desk research alone. However, if a company has over-produced and simply wishes to dispose of product for minimal returns, then neither budget nor time constraints would suggest that undertaking field research would be worthwhile.

Table 6.4 indicates the different types and uses of field research.

Effectively conducted market research will enable a business to better define their customer, their target market, the behaviour within that market, the competition and the gaps within the market.

6.7.4 Marketing Information Systems

Aside from specific market research projects, there is also a need for companies to gather data for ongoing decisions where it would be neither feasible nor effective to commission bespoke research. This data should be organised into a marketing information system (MIS).

Kotler (1997) defines a marketing information system as consisting:

> ... of people, equipment, and procedures to gather, sort, analyze, evaluate and distribute pertinent, timely and accurate information to marketing decision makers.

An MIS that is well structured and fed information from across the company can provide the decision-maker with basic data for ongoing decisions.

Why is there a need for an MIS?

There is little point in finding information and not systemising it, making it as structured as possible to ease future access not only for the individual who originally gathered the information, but also for others in the organisation.

The information contained in the MIS can be used at both the strategic and the operational level. At the strategic level, information might be required from the MIS when identifying the following:

- opportunities and threats;
- new market opportunities;
- market entry and development strategy selection;
- performance in a given market.

Table 6.4. Types and uses of field research.

	Types of field research	Uses of field research
(i)	*In-depth interviews* between the researcher and carefully-selected individuals. Ideal for gathering depth of information from key individuals in a particular area, geographically or industrially.	If assessing the retail market for frozen fish in France, the three key frozen fish importers in Boulogne would be appropriate interviewees. Their knowledge of the market is extensive, their coverage of the market similarly expansive and their level of further contacts within the industry would be unsurpassable.
(ii)	*Surveys:* typically structured questionnaires are delivered. Useful when trying to gather quantitative data from a large group.	If assessing consumer opinion of products, a survey would be an appropriate means of gathering the information from the breadth of respondents necessary.
(iii)	*Focus groups:* a group of selected people (usually 7–10) discusses a topic with a trained moderator guiding discussions. Ideal for gathering information about perceptions, emotions, motivation and non-overt factors.	When gauging consumer motivation regarding, for example, organic produce (will they really pay more?), or attitudes towards farmed fish, a focus group would allow for understanding of motivations and perceptions.
(iv)	*Observation and projective techniques:* the researcher does not interact with the subject at all in the former, simply observes their actions and reactions to a given situation. In the latter, the respondent is required to react to a given stimuli and conclusions will be drawn from that reaction.	If trying to assess the understanding of a 'foreign' species, such as abalone, in a new market, this technique would enable the researching of behavioural dimensions.
(v)	*Experimentation:* the researcher typically alters one element of a situation and examines the impact of this change. This helps to determine the effect of an intervening variable and establish precise cause and effect relationships.	If trying to measure the impact of a packaging change on purchase behaviour, experimentation techniques would allow a manufacturer to 'try' and 'observe'.

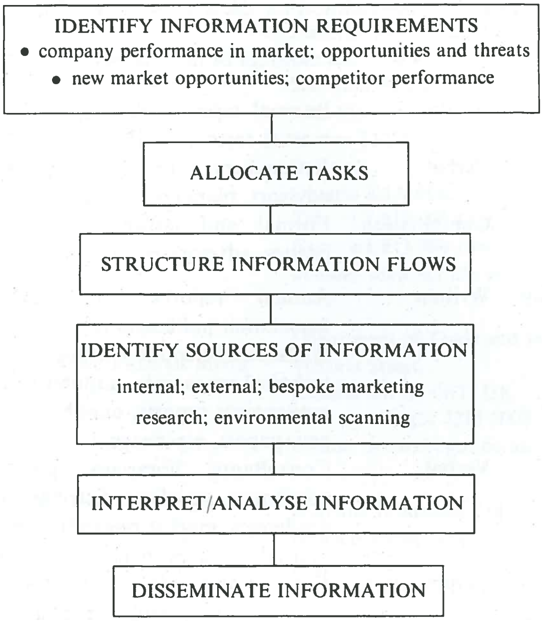


Figure 6.5. Setting up an MIS.

At the operational level, information might be required from the MIS to assist decision making in the following areas:

- product policy;
- price policy;
- promotion policy;
- distribution policy.

The stages of designing and setting up a MIS are illustrated in Figure 6.5. It is important to remember that this process is ongoing and will never be complete. Many companies will find that they already have a lot of information that is needed for their MIS; it is simply not structured or seen as a common resource.

As a result of empirical research, Brownlie (1987) cites the following sources of information on the business environment (Table 6.5).

6.8 ... AND THE END OF THE STORY

While there is a lot of detail to the practice of marketing, the principle of marketing is very straightforward.

Know your market. Know your customers. Ensure that all business practices, from production planning to promotions, are geared towards satisfying their needs—and that this is done profitably!

Table 6.5. Sources of information for the marketing information system.

Location	Types	Sources of information on business environment
Inside the company	Written	Internal reports and memos, planning documents, market research, MIS.
	Verbal	Researchers, sales force, marketing, purchasing, advisors, planners, board.
	Combination	Formal and informal meetings, (e.g., working parties, advisory committees).
Outside the company	Written	Annual reports, investment reports, trade association publications, institute yearbooks, textbooks, scientific journals, professional journals, technical magazines, unpublished reports, government reports, unpublished papers, abstracts, newspapers, espionage.
	Verbal	Consultants, librarians, governmental officials, consumers, suppliers, distributors, competitors, academics, market researchers, industry bodies, journalists, spies, bankers, stockbrokers.
	Combination	Formal and informal meetings, membership of government working parties and advisory boards, industry bodies, trade associations.

Successful businesses are in tune with the current needs of the market but, most importantly, they are able to anticipate and adapt to the future needs of the market.

APPENDIX 6.1 SEAFOOD MARKET INFORMATION CONTACTS

Agra Europe (London) Ltd.
25 Frank Road,
Tunbridge Wells,
Kent TN2 5JT, UK
Tel: +44 (0)1892 533813
Fax: +44 (0)1892 544895

Alaska Division of Trade and Development
(Seafood Industry)
PO Box 110804,
Juneau,
Alaska 99811, USA
Tel: +1 907 465 2017
Fax: +1 907 465 3767
website: www.dced.state.ak.uk/trade/seafood. htm

Alaska Seafood Marketing Institute
311 N. Franklin Street,
Suite 200, Juneau,
Alaska 99801-1147, USA
Tel: +1 907 465 5560
Fax: +1 907 465 5572
website: www.alaska.seafood.org

Aquaculture Magazine Online
PO Box 2329,
Asheville,
North Carolina 28802, USA
Tel: +1 828 254 7334
Fax: +1 828 253 0677
website: www.ioa.com/~aquamag/

Aquaculture Network Information Center (AquaNIC)
website: Ag.ansc.purdue.edu/aquanic/

Australian Seafood Industry Council
PO Box 533,
Curtin,
ACT 2605,
Australia
Tel: +61 (0)2 6281 0383
Fax: +61 (0)2 6281 0438
website: www.asic.org.au

Bord Iascaigh Mhara—Irish Sea Fisheries Board (BIM)
P.O. Box 12,
Crofton Road,
Cun Laoghaire, Co.
Dublin, Republic of Ireland
Tel: +353 1 284 1544
Fax: +353 1 284 1123
website: www.bim.ie

British Columbia Salmon Marketing Council (BCSMC)
Suite 1100–1200
West 73rd Avenue,
Vancouver,
British Columbia V6P 6G5, Canada
Tel: +1 604 267 3030
Fax: +1 604 266 3097
website: www.bcsalmon.ca

The British Food Export Council
123 Buckingham Palace Road,
London SW1W 9SA, UK
Tel: +44 (0)20 233 5111
Fax: +44 (0)20 7233 9515

Business Link Network Company (United Kingdom)
Tel: +44 (0)8457 467 765
website: www.businesslink.co.uk

Chilean Salmon and Trout Producers Association
website: www.salmon.chile.cl/sching/index.htm

The ComFish Index
(index to commercial fishing and seafood web sites)
website: www.comfish.org

Department of Fisheries and Oceans (DFO)
Fisheries and Oceans Canada Communications Branch,
200 Kent Street,
13th Floor,
Station 13228,
Ottawa,
Ontario K1A 0E6, Canada
Tel: +1 613 993 1516
Fax: +1 613 990 1866
website: www.ncr.dfo.ca

Department of Trade and Industry (DTI)
Victoria Street,
London SW1H 0ET, UK
Tel: +44 (0)20 7215 5000
website: www.dti.gov.co.uk

Dun and Bradstreet Ltd
Holmers Farm Way,
High Wycombe,
Buckinghamshire HP12 4UL, UK
Tel: +44 (0)870 243 2344
website: www.dunandbrad.co.uk

Euromonitor International
(global consumer market and business intelligence)
Customer Service—Head Office,
60-61 Britton Street,
London EC1M 5UX, UK
Tel: +44 (0)20 7251 8024
Fax: +44 (0)20 7608 3149
website: www.euromonitor.com

European Commission
Directorate General XIV (Fisheries)
Rue de la Loi 2000 / Wetstraat 2,
B-1049 Brussels,
Belgium
Tel: +32 2 299 1111
Fax: +32 2 295 2569
website: europa.eu.int/comm/dg14/dg14.html

Fish Farming International
Meed House,
21 John Street,
London WC1N 2BP, UK
Tel: +44 (0)20 7470 6403
Fax: +44 (0)20 7430 0337

Fish Industry Yearbook
The Oban Times Ltd,
Royston House,
Caroline Park,
Edinburgh EH5 1QJ,
Scotland, UK
Tel: +44 (0)131 551 2942
Fax: +44 (0)131 551 2938

FIS International Co. Ltd.
(index to fishing and seafood companies, markets and products)
12 Churchfileds,
Devauden, Chepstow,
Gwent NP6 6PN, UK
Tel: +44 (0)1291 650767
Fax: +44 (0)1291 650512
website: www.sea-world.com

Fish Trader Magazine
The Oban Times Ltd,
Royston House,
Caroline Park,
Edinburgh EH5 1QJ, Scotland, UK
Tel: +44 (0)131 551 2942
Fax: +44 (0)131 551 2938

Fishing Net
(Internet home of commercial fishing industry—US based)
website: www.schoonersolutions.com

Fishmonger
website: www.fishmonger.com

Food and Agriculture Organisation – FAO
(internation information on fisheries resources, production, trade, management, socio-economics, statistics)
website: www.fao.org/fi

Food From Britain
123 Buckingham Palace Road,
London SW1W 9SA, UK
Tel: +44 (0)20 7233 5111
Fax: +44 (0)20 7233 9515
website: www.foodfrombritain.com

Gadus Associates
(list of fisheries web sites—Canadian based)
RR#1, Musquodoboit Harbour,
Nova Scotia B0J 2L0, Canada
Tel: +1 902 889 9250
Fax: +1 902 889 9251
home.istar.ca/~gadus/

Grampian Seafood Project
Business Centre,
Glebefield House,
Links Terrace, Peterhead,
Aberdeenshire AB42 6XA, Scotland, UK
Tel: 01779 476611
Fax: 01779 471135

The Grocer Magazine
The Grocer Marketing Directory
The Grocer Marketing and Drink Directory
William Reed Publishing,
Broadfield Park,
Crawley,
West Sussex RE11 9RT, UK
Tel: 01293 613400
Fax: 01293 610310
website: www.c-store.co.uk

H. M. Johnson and Associates
Seafood Marketing Information and Analysis
P.O. Box 53146, Bellevue,
Washington 98015, USA
Tel: +1 425 747 2757
Fax: +1 425 747 2672
website: www.hmj.com/index.html

Highlands and Islands Enterprise (HIE)
Bridge House,
20 Bridge Street,
Inverness IV1 1QR, Scotland, UK
Tel: +44 (0)1463 234171
Fax: +44 (0)1463 244469
website: www.hie.co.uk

INFOPESCA (Latin America)
website: www.infopesca.org

Keynote Ltd.
Field House,
72 Oldfield Road,
Hampton,
Middlesex TW12 2HQ, UK
Tel: +44 (0)20 8481 8750
Fax: +44 (0)20 8783 0049
website: www.keynote.co.uk

Ministry of Agriculture, Fisheries and Food (MAFF)
Noble House,
17 Smith Square,
London SW1P 3JR, UK
Tel: +44 (0)20 7238 3000
Fax: +44 (0) 7238 6591
website: www.maff.gov.uk

Mintel
18-19 Long Lane,
London EC1A 9HE, UK
Tel: 020 7606 4533
Fax: 020 7606 6000
website: sinatra2.mintel.com

National Marine Fisheries Science (NMFS)
FX1—Office of Industry and Trade,
SSMC3 / 3rd Floor / Room 3670,
1315 East-West Highway,
Sliver Spring, Maryland 20910, USA
Tel: +1 301 713 2379
Fax: +1 301 713 2384
website: www.nmfs.gov/trade

Office for National Statistics (ONS)
Government Buildings,
Cardiff Road,
Newport. NP10 8XG, UK
Tel: +44 (0)1633 815696
website: www.ons.gov.uk

Organisation for Economic Co-operation and Development—OECD
(international fisheries statistics, information on international food markets and trade policy)
2, rue André-Pascal,
75775 Paris Cedex 16,
France
Tel: +33 (0) 1 45 24 82 00
website: http://www.oecd.org/agr/fish/index.htm

The Scottish Business Information Service
Scottish Science Library,
National Library of Scotland,
33 Salisbury Place,
Edinburgh EH9 1SL,
Scotland, UK

Scottish Enterprise
120 Bothwell Street,
Glasgow G2 7JP,
Scotland, UK
Tel: +44 (0)141 248 2700
Fax: +44 (0)141 204 3969
website: www.scotent.co.uk

Scottish Fish Farmer
The Oban Times Ltd,
Royston House,
Caroline Park,
Edinburgh EH5 1QJ,
Scotland, UK
Tel: +44 (0)131 551 2938
Fax: +44(0)131 551 2938

Scottish Quality Salmon
(formerly Scottish Salmon Board)
Durn, Islay Road,
Perth PH2 7HG,
Scotland, UK
Tel: +44 (0)1738 587000
Fax: +44 (0)1738 621454

Seafish Industry Authority (SFIA)
18 Logie Mill,
Logie Green Road,
Edinburgh EH7 4HG,
Scotland, UK
Tel: +44 (0)131 558 3331
Fax: +44 (0)131 558 1442
website: www.seafish.co.uk

Seafood Datasearch
430 Marrett Road,
Lexington,
Massachusetts 02421, USA
Tel: +1 781 861 1760
Fax: +1 781 861 3823
website: www.seafood.com

Seafood Industry Council (New Zealand)
Private Bag 24-901,
Wellington, New Zealand
Tel: +64 4 385 4005
Fax: +64 4 385 2727
website: www.seafood.co.nz

Seafood International Magazine
Quantum Publishing Ltd.,
Quantum House,
19 Scarbrook Road,
Croydon,
Surrey CR9 1LX, UK
Tel: +44 (0)20 8565 4340

Seafood Market Analyst
PO Box 564,
Narragansett,
Rhode Island 02882, USA
Tel: +1 401 783 8899
Fax: +1 401 783 8883
website: www.seafoodreport.com

Seafood Market Information Service
University of Alaska,
3211 Providene Drive,
Anchorage, Alaska 99508, USA
Tel: +1 907 786 7710
Fax: +1 907 786 7739
website: shiva.its.uaa.alaska.edu/smis

Seafood Network Information Centre
(SeafoodNIC)
website: seafood.ucdavis.edu/home.htm

Seafood Scotland
18 Logie Mill,
Logie Green Road,
Edinburgh EH7 4HG,
Scotland, UK
Tel: +44 (0)131 558 3331
Fax: +44 (0)131 558 1442

Statistical Yearbook of Norway
(production, price and trade figures for farmed
Atlantic salmon)
Statistics Norway,
P.O.B. 8131 Dep, N-0033,
Oslo, Norway
Tel: +47 (22) 86 45 00
Fax: +47 (22) 86 49 73
website: www.ssb.no/www-open/english/yearbook

Urner Barry Publications, Inc.
(US market news reporting service)
P.O. Box 389,
Toms River,
New Jersey 08754-0389, USA
Tel: +1 732 240 5330
Fax: +1 732 341 0891
website: www.urnerbarry.com

7

Economic and business issues

7.1 INTRODUCTION

The economic and business issues of salmon farming are considered under three headings: Demand, Supply and Analysis, Planning and Control. For any business venture, the essential first issue to consider is the demand for the product or service to be produced. The scale of that **demand**, its detailed features and trends, will be a primary determinant of the economic potential of that business. The second issue is the current and prospective **supply** to meet that demand, i.e., the competition in the market. How well placed is the business to compete with alternative suppliers? What opportunities are there to meet market demands better than alternative suppliers? Thirdly, if a business is to use its resources to best advantage to take those opportunities, there needs to be careful **analysis, planning** and **control**.

7.2 DEMAND

An understanding of the demand for a product, how it is determined and the various factors which may influence its level and growth are important concepts for any business manager. In this section, the factors influencing demand will be covered, as well as how to assess the impact of changes in the market on the demand for a product. An overview of the demand for salmon in the major consuming nations is presented to give a broad understanding of the main trends and what has driven the changes in demand.

7.2.1 What is demand?

Demand is the intrinsic desire of consumers for a product or service, combined with the financial factors governing their ability and willingness to pay for it.

It is the ability and willingness to pay that makes the essential distinction between demand and desire or need.

Demand can only be defined in quantitative terms in relation to a specified period of time—'per day', 'per week', 'per annum'—and a specified market or geographical area. Demand determines the market price at which a given supply of a product, available within a specific period of time within an identified market, will be sold. It must be appreciated that 'availability' is required before demand can become apparent, i.e., the supply has to be available to the consumers. If a particular salmon product is sold only in Norway, one cannot say there is no demand for it in the UK. That can only be determined if it is made available in the UK market.

Demand for a product is expressed both in terms of quantity and price

Demand for a product is often spoken of as if it is simply the quantity of that product purchased, but it is a more dynamic concept than that. We may speak of the amount sold at a given time as being the 'quantity demanded' at the price current at that time, and that certainly gives some indication of demand for the product, but to describe that demand more fully and usefully for business purposes we want to know what quantities of the product will be demanded at different prices. How many fewer fish fingers would be demanded if the price went up to £10.00 each? Or how many more packs of smoked salmon would be demanded if the price went down to £2.00 each?

An important way in which we can visualise more fully the character of demand for a product is by mapping out on a graph the relationship that exists between the price of the product and the quantity demanded in a specific time period, as shown in Figure 7.1 (a hypothetical demand curve for salmon). In constructing a demand curve, the intrinsic assumption is that all other market forces remain unchanged. The shape of that demand curve, in particular its slope, defines the primary characteristic of the demand for that product in the specified market. That slope is known as the price elasticity of demand.

7.2.2 Price elasticity of demand

This can be formally defined as follows:

$$\varepsilon_P = \frac{(Q_1^D - Q_0^D)/Q_0^D}{(P_1^D - P_0^D)/P_0^D} \quad (1)$$

where ε_P represents 'price elasticity of demand', Q_i^D is the quantity demanded at time i (in the equation two points in time are represented, time 0 and time 1), P_i^D is the price for the product at time i.

The demand for a good is said to be *elastic* when the percentage change in

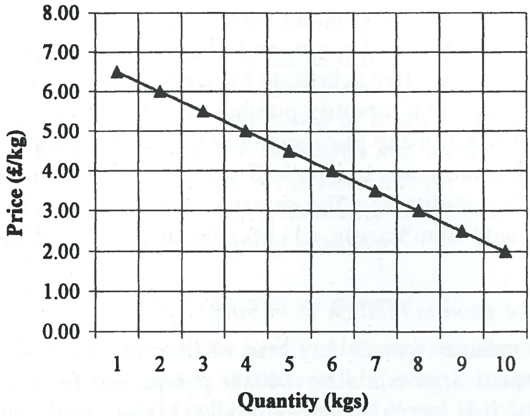


Figure 7.1. Monthly demand for salmon by households (hypothetical data).

quantity demanded is greater than the percentage change in price (i.e., $\varepsilon > 1$, but note that calculated values of ε are shown with a negative sign, because the basic 'law of demand' is that quantity demanded normally falls in response to a rise in price). Demand is *inelastic* ($\varepsilon < 1$) when the percentage change in quantity demanded is less than the percentage change in price, i.e., the demand is relatively insensitive to price changes. When a given percentage change in price leads to an equal percentage change in quantity demanded, then the demand for that good is said to be of unit elasticity ($\varepsilon = 1$).

7.2.2.1 Factors affecting the price elasticity of demand

The responsiveness of demand for any particular good to a change in its price is influenced by several factors:

- the availability of substitutes;
- the expenditure on the good in relation to income;
- the essential nature of the good;
- habits;
- time.

The availability of substitutes

For most processors, Norwegian farmed salmon is a good substitute for Scottish farmed salmon, although individual processors may prefer one or the other. If the price of Scottish farmed salmon increased by a small percentage, sales would probably fall by a relatively large amount because processors would switch to the other available sources of salmon, such as Norwegian, which would now be comparatively cheaper. The demand for salmon from a particular source is therefore highly price-elastic (elasticity significantly >1) due to the availability of close substitutes.

Alternatively, if the price of a product such as fresh milk increased, consumers might buy a little less fresh milk and buy more UHT or powdered milk. However, for many purposes there is no effective substitute for fresh milk, so if the price increased by a small percentage, the total quantity purchased would only decrease by a small amount. On the other hand, if the price were lowered, it is unlikely that consumers would buy a great deal more since there will be little demand transferred to milk from alternative goods (substitutes). The demand for milk is therefore *inelastic* with respect to price (elasticity significantly <1) because of the lack of substitutes.

The expenditure on the good in relation to income

The typical British consumer spends very little of their income on fish; in 1998, the average household spent approximately £40.00 per person for the year (MAFF, 1999). If the price of fish increased substantially, high-income consumers would probably still buy almost the same quantity because it would not represent a large change to their budget, even at the higher price. In contrast, to consumers on a low income, such as students, the cost of fresh fish could represent a more significant proportion of their budget, and they would be likely to cut down their consumption of fish more significantly if the price goes up.

The nature of the good

For products that are considered essential to a consumer, such as staple foods like bread and potatoes, an increase in price will have only a small impact on the quantity demanded. Equally, if the price of these products decreases, it is also likely that little extra will be purchased, because one can only eat so much of that type of staple food. The price elasticity of such basic necessities is thus low (<1).

On the other hand the less essential a good is to the life of the consumer, the more likely they are to reduce the total quantity demanded when the price goes up. Equally, if the product is inherently attractive, consumers will respond with a significant increase in the quantity demanded if the price goes down. The price elasticity of such non-essential/luxury products is thus high (> than 1). Salmon products tend to fall into this category, in that for most people they are not a 'staple' food—a standard or invariable element in the diet—but they are inherently attractive to many consumers.

Habits

Habits will also have an impact on consumers' buying patterns. Well-established habits will make the demand for that product less sensitive to price changes. It is for this reason that taxes on goods such as cigarettes and alcohol are good sources of government revenue, because the price increase arising from the tax does not significantly affect the demand for these products: if it did, and demand decreased, little revenues would be raised. The growth of salmon consumption in many countries could be making it more habitual, at least for some consumers, and thus the price elasticity of demand for salmon is likely to be falling.

Time

Finally, in determining how responsive demand is to price, we must be aware of the time frame under consideration. In the short term, consumer demand for a good will be less responsive to price changes than it will be in the longer term. This is because, with time, people have an opportunity to search and locate suitable alternatives to the higher-priced good. In addition, with time, people's preferences change and adapt to new market situations, the availability of goods, prices of goods and newly-available goods suited to changing lifestyles.

7.2.2.2 Significance of the price elasticity of demand

Food in itself has no substitute and is essential to our lives; also there is a limit to our appetite so the demand for food as a whole will be quite insensitive to price, i.e., the demand is inelastic (the price elasticity being <1). Some individual foods have very low price elasticity, for example staple foods such as bread, rice and potatoes as indicated above. However, demand for some food items which are not a habitual part of the diet, have ready substitutes, and/or are regarded as luxury items can be very responsive to price changes, i.e., the demand can be quite elastic (the price elasticity being well above 1).

The importance of the elasticity of demand for a product is that it determines the impact which increased levels of production can have on the revenue to the industry from selling its products, and hence on the incomes of the producers. This is illustrated by comparing Figures 7.2a and 7.2b.

Figure 7.2a shows the effect of an increase in supply of a product with an inelastic demand (elasticity <1, i.e., where the slope of the demand curve is more than 45°). In order to clear the market of the additional supply the market price falls by a larger proportion than the increase in supply, so the total revenue is actually lower with the increased supply than it was before: $P^1 \times Q^1$ is greater than $P^2 \times Q^2$.

In Figure 7.2b, however, with an elastic demand curve, the percentage fall in price required to clear the market of the added supply is less than the percentage increase in supply. Thus in this case, which is likely to be more representative of salmon, the increase in supply does increase the total revenue: $P^2 \times Q^2$ is greater than $P^1 \times Q^1$. However, it has to be noted that the price still falls, so the total revenue does not increase in proportion to the increase in production. This reflects the normal characteristic of demand that, all other things staying the same, a reduction in price will be required to clear the market of an increased quantity of a product.

The higher the price elasticity of demand the greater is the gain in total revenue from increasing production. The lower the elasticity the less is the gain in revenue from increasing production, and if the elasticity is <1, there is a reduction in total revenue from increased production.

7.2.2.3 The price elasticity of salmon and salmon products

A broad indication of the elasticity of demand for salmon can readily be drawn from examining the trend in salmon price in relation to the trend in salmon production, as

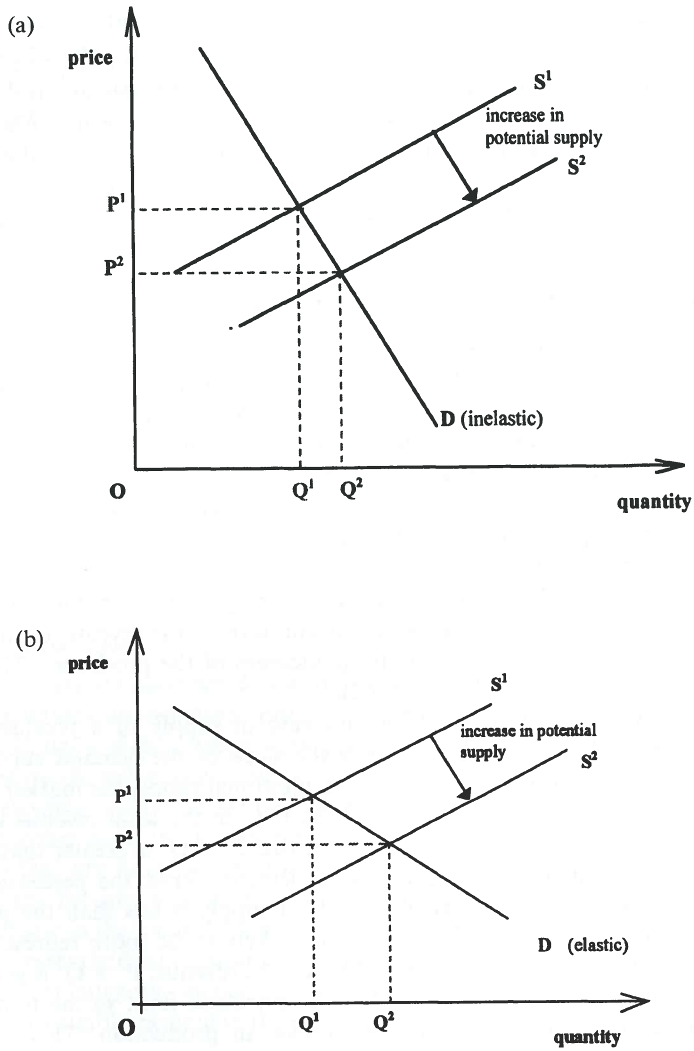


Figure 7.2. (a) The impact of an increase in supply for goods with inelastic demand; (b) The impact of an increase in supply for goods with elastic demand.

illustrated in Figure 7.3. This shows production in Scotland and Norway, the two main suppliers of salmon to the UK market, and the average price of farmed salmon at Billingsgate, the largest wholesale fish market in the UK. Of course total salmon production in Scotland and Norway is not exactly the supply to a specific market but, with the great majority of that production being sold on the European market and with the great majority of farmed salmon supply in Europe coming from those

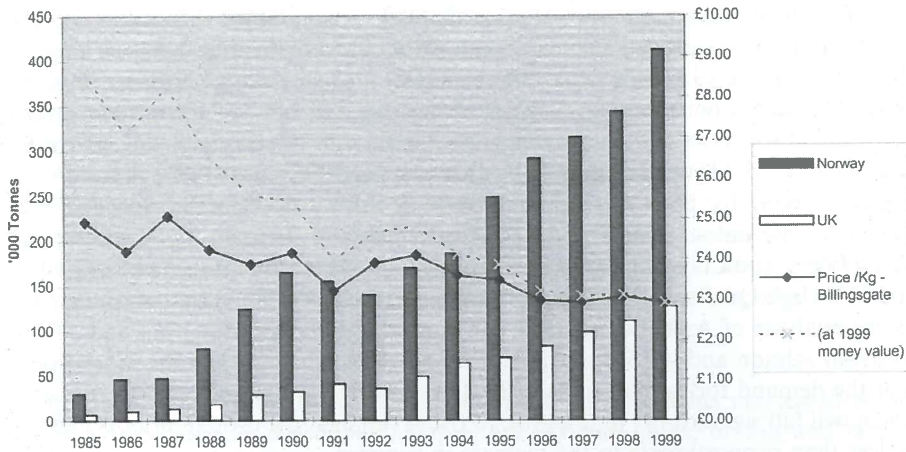


Figure 7.3. Farmed salmon production and prices. *Sources*: SOAEFD (1991–1998), SERAD (1999–2000), FAO (2000), FEAP (2000), Fishmongers' Company (2000).

sources, it is a reasonable indicator of the pattern of supplies to the European market. Similarly, the price on Billingsgate market is obviously not the price for Europe as a whole, but it has been shown that changes in salmon prices are closely interlinked not just in Europe, but across the world (Asche *et al.*, 1999), so the trend in price at Billingsgate, a well-established and significant market, can be taken as reasonably indicative of the general price trend in Europe.

It can be seen that over the last 15 years there was roughly a tenfold increase in the production of salmon in both Scotland and Norway, while over the same period the salmon price at Billingsgate fell by rather less than 50%, which would appear to suggest a price elasticity of $-10:1/2:1 = -5$.

But this rough-and-ready demand analysis is erroneous in that it does not take account of any other factors which may have also been changing over the period. Two important factors we know will have changed and affected the figures:

1 The value of money has been falling, i.e., the effect of inflation. This can be corrected for fairly easily by deflating the prices according to changes in the index of retail prices to show the trend in real terms, as presented in Figure 7.3, by the conversion of all the prices to 1999 money value using the Retail Prices Index. This then indicates a fall in real price over the period from £8/kg to £3/kg, thus bringing our rough estimate of price elasticity down to around -2.7.
2 Rising incomes: the effect of this factor can only be determined by some detailed market analysis.

Several studies of demand for salmon, producing estimates of price elasticity, have appeared in the academic literature, as listed by Asche *et al.* (1998). There are considerable variations in the values estimated, arising from differences in geographical markets and products analysed, price data obtained at different levels in the distribution chain, data from different dates and measuring short- or long-run elasticities, and differing methodologies of analysis, but most of the results confirm the demand for fresh salmon as own-price elastic, with the elasticities mostly in the range −1 to −3. However, analysis by DeVoretz and Salvanes (1993) showed own-price elasticities for Norwegian salmon trending downward in both Europe and the USA from around −5 in 1983 to values mostly between −1 and −2 in the latter part of the 1980s, and Clay and Revell (1995) obtained values around −1 for steaks, fillets and 'All High Quality Salmon' using retail price data. On the other hand, the more recent analyses of Asche *et al.* (1997, 1998) produced values of −3.728 and −0.634 for fresh salmon and −2.569 and −1.453 for frozen salmon. Thus the indication is that the demand for salmon remains fairly responsive to the market price so, while prices will fall significantly in response to rising supplies, the drop in price is likely to be less than proportionate to the increase in supplies.

7.2.3 Other aspects of demand

Demand is a dynamic concept; the quantity demanded adjusts not only to changes in the price of the product itself, but to other changes in the marketplace, and to changes in buyers' circumstances. The main factors that will influence the quantity demanded of a good or service, apart from its own price, are:

- prices of other goods: substitutes or complements;
- income;
- income distribution;
- population size, distribution and age structure;
- tastes and preferences.

The demand for any good is determined by all of these variables acting simultaneously but, as noted already in relation to price elasticity, in order to analyse how each of these factors bears upon demand, we must simplify things by imagining that all of the variables remain constant except for one. By varying only one factor at a time, we can then focus on its relationship to demand.

7.2.3.1 Prices of other goods

Substitutes

Consumers buy a wide range of products for a wide range of reasons. We know that if the price changes for a good, this will lead to a change in the quantity demanded. Because there are many similar goods that a consumer can choose in order to satisfy their demand, this price change will also affect the amount demanded of 'substitute' goods. Substitutes can be defined as one of two or more goods that can replace each other in consumption, that is, each provides similar basic satisfaction of wants and needs (Amos, 2000). An increase in the price of one good causes an increase in demand for the substitute. This is because consumers, when faced with a price increase, will search for alternatives that are relatively cheaper and will transfer their demand to these substitute products. The impact of the price increase, therefore, is that the quantity demanded of the original, now slightly more expensive, good will decrease (according to the 'law of demand') while the quantity demanded of the alternative, relatively cheaper, good will increase.

With a product such as farmed salmon, substitute products will include not only other fish products, but also other food products that provide a source of protein (i.e., poultry, beef, pork). If the price of salmon increases, consumers will search for an alternative source of protein, which will decrease the amount of salmon demanded and increase the amount of the substitute product demanded.

Complements

Complementary goods are those that are often consumed together and are therefore generally purchased as a group. Examples are fish and chips, or fish and tartare sauce. If the price of salmon increases, consumers will reduce their purchases of salmon and, as a result, the demand for complementary goods will also fall.

Cross-price elasticity of demand

As with changes in the price of the product itself, changes in the demand for a product resulting from changes in the price of a competitive or complementary product can also be measured in terms of elasticity, in this case the *cross-price elasticity of demand.* The relevant formula is given below.

$$\varepsilon_{PC} = \frac{(Q_{1_B} - Q_{0_B})/Q_{0_B}}{(P_{1_A} - P_{0_A})/P_{0_A}} \tag{2}$$

where the subscripts A and B refer to the quantities (Q) and prices (P) for goods A and B respectively. The two points in time are represented by time 0 and time 1.

If the two goods, A and B, are substitute goods, then the elasticity measurement will be positive, since an increase (decrease) in the price of good A will lead to a decrease (increase) in the demand for this good, and an increase (decrease) in the demand for the substitute good. Therefore, both the price of good A and the quantity demanded of good B will move in the same direction, making the resulting numerical measure positive.

If the two goods, A and B, are complements, however, then the cross-price elasticity of demand will be negative. For complementary goods, an increase (decrease) in the price of good A will lead to a decrease (increase) in its demand for this good, and a decrease (increase) in the demand for any goods which are consumed with it (e.g., good B).

Cross-price elasticities for salmon

It was noted by Asche *et al.* (1997) that demand analyses of the EU salmon market have indicated varying degrees of substitutability among fresh and frozen salmon and fresh salmon and other high-value fish species. In their own analysis in that paper they found a high cross-price elasticity between fresh salmon and frozen salmon (2.880) and a moderate level of cross-price elasticity between fresh salmon and crustaceans (0.653), indicating substitute relationships between these products. A subsequent analysis (Asche *et al.*, 1998) examined the relationships between prices of fresh Atlantic salmon, frozen Atlantic salmon and frozen Pacific salmon. Again, positive cross-price elasticities showed all three goods to be substitutes. These results have considerable significance in relation to any policy measures that may be taken, either by producers' organisations or governments, to try to manage the market through controlling farmed Atlantic salmon production or supplies, in that the availability of supplies of a substitute such as frozen Pacific salmon is likely to limit the extent to which the market price can be controlled.

7.2.3.2 Income

As people's incomes increase, their demand for goods and services will change. If a household receives a 10% increase in its income, it will increase the quantity of goods and services it buys, but it will not increase its expenditure on *all* commodities equally. Very little extra bread will be bought, perhaps 21 loaves per month instead of 20 (a 5% increase). With the same increase in income, it may be that a great deal more fresh fish might be purchased, say five portions per month rather than four (a 25% increase). For some products, demand may even drop: consumers will buy only five tins of baked beans rather than their previous ten (a 50% decrease).

How a change in income will affect the demand for any individual product is determined by the type of the good. There are three 'types' of goods: normal, luxury, and inferior. A normal good is any good for which the demand increases with an increase in income. Most goods tend to be normal when reacting to income changes. When people have more income, they tend to buy more normal goods and services. A luxury good is a special case of a normal good. The demand for these goods grows with increases in income, but in this case by a relatively large amount, more than proportionate to the rise in income.

Alternatively, an increase in income may cause the opposite reaction in the demand for a good. There are many goods on the market for which demand drops when incomes increase. These goods are called inferior goods—a term developed to show that they are viewed as suitable for a particular income level, but that consumers wish to replace them as soon as they can afford to do so. Many food products may fall into the inferior goods category such as own-brand baked beans, potatoes, tinned tuna and mince. The feature these products have in common is that they are relatively inexpensive and tend to be demanded in large quantities by people on low incomes. There are also more expensive and typically more preferred alternatives (i.e., Heinz baked beans, fresh pasta, fresh tuna and steak) that people switch to if their incomes increase.

It is important to remember that the categorisation of a good as normal or inferior is highly dependent on the individual or consumer group being examined, and their level of income. A good which is inferior at one income level to one group may in fact be a normal good to a different group of consumers at the same income level. An example of this could be a cheap fish such as mackerel, which may be viewed as a normal good to health-conscious consumers who are purchasing it primarily for its high omega3 fatty acid content, but an inferior good to consumers in the lower income bracket, who are buying it primarily because it is cheap rather than for any intrinsic value they see in it.

Income elasticity of demand

As with changes in price, the effect of changes in income on the demand for a product can also be represented by a measure of elasticity, in this case the *income elasticity of demand*. The formula used to estimate this elasticity for any commodity is:

$$\varepsilon_Y = \frac{(Q_1 - Q_0)/Q_0}{(Y_1 - Y_0)/Y_0} \tag{3}$$

where ε_Y is the income elasticity of demand, Q_i is the quantity demanded at time i (in the equation two points in time are represented, time 0 and time 1), and Y_i is the income at time i.

In the examples given earlier, when income rose by 10%, purchases of bread rose by 5% (21 loaves were purchased rather than the original 20). This translates to an income elasticity of demand for bread of 0.5. For fish, demand rose by 20% due to the 10% increase in income, making the income elasticity of demand 2.0. The income elasticity of demand for beans however is negative at −5.0. From these measures we can see that while both fish and bread are what we would call normal goods, the demand for bread is much less sensitive to changes in income than is the demand for fresh fish. This is as we expect because there are fewer substitutes for bread and because bread only accounts for a small proportion of a consumer's total food budget. Own-brand baked beans, however, have a negative income elasticity of demand, from which we can determine that this produce is an inferior good. The demand for own-brand baked beans fell (by a relatively large proportion) when income increased.

The formula given above for calculating income elasticity of demand uses a physical measure of the change in demand caused by a change in income. It is often the case that the more useful way of measuring the impact of a change in income on the demand for a good is to measure the change in *expenditure* rather than the change in physical units purchased. This measure is more appropriate when the income change causes consumers not to change the quantities of a product they purchase (e.g., bottles of wine), but rather to change its quality (to more expensive, better-quality wine). In this case, the quantity has not changed, but the expenditure on wine has.

Income elasticity of demand for salmon

Most studies have found salmon to be a luxury good, in that demand appears to show a high positive response to changing incomes. In their study of the EU salmon market, Asche *et al.* (1998) estimated expenditure elasticities of 1.384 for fresh

Atlantic salmon and 2.724 for frozen Atlantic salmon. However, the elasticity for frozen Pacific salmon was –0.270, indicating that this product has an *inferior* status in this market.

7.2.3.3 Income distribution

Changes in the demand for a good may occur when income is redistributed from the rich to the poor (or vice versa). Any redistribution will affect the demand of both income groups: those who have experienced an increase in their income are likely to demand more of a normal good, while those with a decrease in income demand less. Whether the net effect is positive or not (i.e., whether total demand goes up or down) will depend on the particular demand characteristics of the good (i.e., normal, luxury or inferior), the relative changes for each income group, and which group of consumers is the main purchaser of the product in question. For instance, if the product in question is smoked salmon, and the redistribution of income is from the rich to the poor, it is likely that the total demand will fall, because smoked salmon is a luxury product primarily consumed by high-income consumers. While the low-income consumers have had an increase in income, unless this increase is substantial it is unlikely that their demand for smoked salmon will increase sufficiently to compensate for the decrease caused by the falling incomes of the high-income group.

7.2.3.4 Population size and distribution by age and region

Changes in the total number of people willing and able to buy the product will have an impact on demand. Trends in the population size will give an indication of how total demand will be affected, but it is also important to look at demand per capita. Per capita demand will differ according to age group, gender, size of family unit, religion, region and social traditions. For example, older consumers in the UK are more likely to buy fresh fish, and as the number of people in the 45–54 age group grew by 15% between 1991 and 1996, it could be expected that the demand for fresh fish would increase (Mintel, 1997).

7.2.3.5 Tastes and preferences

Consumers' tastes and preferences for a product determine their willingness to buy it: before you have a demand for a product, you must be willing to purchase it, therefore you must have a preference for it. In general, if consumers have a greater preference for a good, then they will buy more of it. While this particular category is not as well defined or as clearly measured as changes in incomes, prices and population, buyers' preferences, tastes, attitudes, likes and dislikes all have a major impact on demand. Advertising, through television and radio commercials, newspaper and magazine advertisements, highway billboards, internet ads, and corporate sponsorship of sporting events, is largely designed to influence buyers' preferences. Producers of food products increasingly seek to influence consumer preferences by adapting their marketing efforts in order to exploit the latest trends and differentiate

Table 7.1. Demand* for salmon in main world markets, 1990–98 (tonnes).

	1990	1991	1992	1993	1994	1995	1996	1997	1998
France	71,651	79,723	80,407	73,687	76,629	82,744	86,596	81,125	78,197
Japan	418,779	393,654	373,116	477,738	491,055	467,338	503,024	428,485	395,621
UK	57,386	65,966	65,582	67,895	87,253	82,965	99,770	112,618	146,355
USA	219,861	263,712	210,403	277,191	302,051	408,766	309,284	227,316	271,724
Total of Selected Countries	767,677	803,055	729,508	896,511	956,988	1,041,813	998,674	849,544	891,897

* Measured by apparent consumption which is defined as {production (wild and farmed) + imports − exports}
Source: FAO (2000).

their products from competing or similar goods, and thus capture the public's attention and stay up-to-date with the ebb and flow of preferences.

7.2.4 Review of demand for salmon[1] in the main world markets 1990–1998

The consumption of salmon grew significantly during the 1990s as supplies increased and prices dropped. The four major world markets for salmon are France, Japan, the United States and the United Kingdom. A summary of the growth in demand for salmon in these markets is given in Table 7.1.

The Japanese are by far the largest consumers of salmon in the world, primarily consuming Pacific salmon, although there has been some market penetration of Atlantic salmon in recent years, mainly supplied by the Norwegians. Consumption in Japan rose substantially from the mid-1980s, although it appears to have peaked in 1996—perhaps due to a more open market, and therefore increased competition from alternative proteins, but also because it was affected by a devalued yen, making salmon a relatively more expensive product in Japan as the vast majority of it is imported from other countries.

In the United States, consumption has also risen, with the consumption of Atlantic salmon tripling during the 1990s. This was primarily due to lower prices, increased promotion of farmed Atlantic salmon in the retail sector, and year-round availability of fresh farmed salmon (ISFA). Similar factors have influenced the market in the UK and France, the two largest European markets. Lower prices served to increase the overall consumption of salmon as it became more affordable for a larger proportion of the population, and because of the substitution effect. The lower prices would have diverted demand away from competing protein sources and towards salmon. Increased promotion of salmon increased consumption as consumers' awareness grew that salmon offered the types of taste and health features they demanded, and perhaps also by influencing their preferences.

[1] Includes both Pacific and Atlantic salmon, farmed and wild.

7.3 SUPPLY

An understanding of the factors that influence the supply of a product from other sources is important for any business, as that supply represents competition in the market. This section covers the factors influencing supply, as well as how changes in the market impact the supply of a product. An overview of the supply of salmon from the major producing nations is presented to give the reader a broad understanding of the main trends in supply and what has driven these changes.

7.3.1 What is supply?

The supply of goods is the other half of the market exchange process. Individuals or companies who have ownership and control over resources (labour, capital, land and entrepreneurship) will use them to produce the goods and services that satisfy the wants and needs of the market. Ownership and control of these resources are the ultimate sources of supply. But there is more to the specific economic process of supply than just having resources. There are three notable aspects to the concept of supply:

1. Supply occurs when the owner of the resources or goods is both willing and able to sell goods to the market.
2. Supply occurs over a range of prices and quantities.
3. Supply occurs over a given time period.

Whether a good is supplied to the market depends on both the willingness and the ability of the seller to sell the good. To supply a good, you must both be *able* to sell it, and have the *willingness* to sell it. With a farmed fish the ability and willingness essentially depend (a) on the technical feasibility to produce it and (b) the financial incentive provided by the cost of production being less than the expected market price, thus offering a profit potential.

That the first point alone is not enough is shown by the example of the cultivation of lobsters, e.g., European lobster (*Homarus gammarus*). It is technically possible to produce farmed lobster. Some hatcheries are already producing juvenile lobsters for restocking purposes, but the cannibalistic tendencies of lobsters mean that they would have to be individually confined during growout to marketable size and, as this involves a fairly lengthy period, as yet the costs have seemed likely to exceed the revenue obtainable, so there does not appear to be a profit potential. Production and supply of farmed lobster has therefore not occurred, but if the price of lobster increased to a level in excess of expected production costs, then production and supply of farmed lobsters would develop.

Similar to the demand curve, we can map out the supply of a product on a graph, as in Figure 7.4. This supply curve shows the relationship that exists between the price of a product and the quantity supplied (usually for a whole industry). It relates only to a given period of time and assumes all other market forces remain unchanged. From this figure, we can determine how the *quantity supplied* to the market is related to price. However, if any other market force changes for this

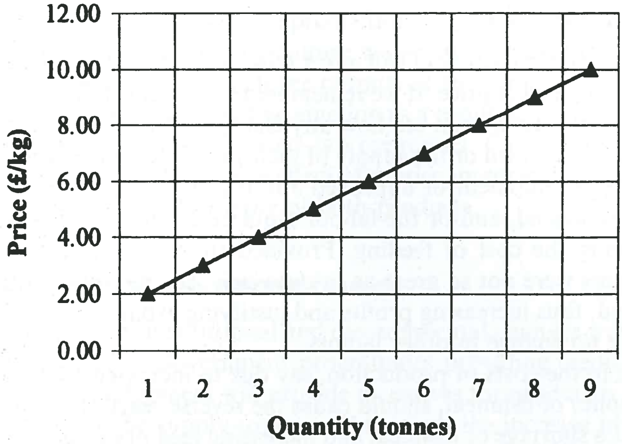


Figure 7.4. Monthly supply of salmon (hypothetical data).

product, or for the producer, the supply curve will change and we will need to examine a new supply curve.

7.3.2 What affects supply?

The main factors that will influence how much of a product is supplied to the market are:

- market price for the product;
- costs of production;
- profitability of alternative production;
- institutional and environmental changes;
- changes in production and marketing technology;
- random shocks.

7.3.2.1 Market price for the product

When the price of a good rises the quantity supplied will also rise. This can be seen on the supply curve shown in Figure 7.4. For example, when the price for salmon is £5.00/kg, the quantity supplied to the market will be four tonnes per month, assuming no other changes occur. The relationship between price and supply is defined by the supply curve, which is upward sloping. This positive relationship between price and supply is termed the 'law of supply' which says that, all other things remaining equal, a larger (smaller) quantity of a good will be supplied to the market as the price goes up (down). The increase in price makes production more profitable, which encourages both existing and new producers to devote more resources to production. The higher price justifies production even from rather less appropriate or efficient resources, and/or more costly resources.

7.3.2.2 Costs of production

Changes in the costs of production will affect how much of a good a producer is able to supply at a given market price. If we remember that the cost of inputs is simply the price paid for them, then we can see how any change in the market for these inputs (i.e., in the demand for them or the supply of them) will affect the cost of production. For example, the development of improved automatic feeders for fish farms meant that less feed was wasted, and/or the labour required for feeding was reduced, thus effectively reducing the cost of feeding. Provided the extra capital and operating costs of the feeders were not so great as to outweigh this, the total costs of production were reduced, thus increasing profits and justifying expansion of production, as always assuming no change in other factors.

An increase in the costs of production, say due to increased feed costs resulting from scarce supplies of fishmeal, should cause the reverse reaction. It may, however, be observed that a shortage of fishmeal and increasing feed prices associated with the effects of 'El Niño' in the South Pacific in 1997/98 did not produce a reduction in world production of farmed salmon. There are a number of reasons for this:

- *Ceteris Paribus*: the effect can only be directly seen in the level of supply if this is the only change occurring. Many other factors may be working in the opposite direction.
- *The time factor*: prices of inputs fluctuate over time, so producers may not respond to input price changes until they are convinced that they are continuing in the longer term.
- *A fixed investment ratchet effect*: if a significant proportion of production costs are in the form of investment in capital items such as sea-pens and buildings, the costs of which cannot readily be recouped if production is reduced or abandoned, then once that investment has been made the effective costs (or marginal costs) of maintaining production are significantly below the full costs including the initial capital investment. Thus it may take a large reduction in profitability to result in any significant reduction in production and supplies.

7.3.2.3 Profitability of alternative production

The supply of a product will depend in part on the prices, and costs, of all the other possible products that are within the firm's production possibilities. If the price for large trout increases but the price of salmon remains the same, then the supply of salmon could fall as some salmon farmers could switch all or some of their cage volume into growing sea-reared trout. Both species compete for the farm's resources, and an increase in the production of one species, led by a rise in its price or a reduction in production costs, will necessitate a reduction in the production of the other species (at least in the short term when cage volume is in fixed supply). In this situation, sea-reared trout and salmon are termed competing products. As technology for production of alternative marine species develops, there may be many more alternative products competing for fish farm resources.

Some products exist for which the production process is inseparable from that of some other good. Examples in aquaculture would include abalone farming, where both the gonad (meat) and the shell are outputs of the farming process. If abalone farmers are attracted into increased production as a result of a high price for abalone meat, then more shells will be produced as a byproduct. Closely-linked products like these are termed joint products. The effect of a price increase in one of the products will lead to an increase in the supply of both products.

7.3.2.4 Institutional and environmental changes

The impact on supply of institutional and environmental changes will depend on the nature of these changes. Government programmes providing credit, capital grants and infrastructure development will provide incentives for producers to supply more to the market, or for the supply to increase through the increase in the number of firms entering the industry. These types of programmes were very much in evidence in the UK during the early years of salmon farming, with a combination of national and EU funding supporting the establishment of new farms in the remote, economically-disadvantaged areas in the north and north-west of Scotland.

Government regulations may also impact the supply of salmon in that they may limit the areas in which farming can occur, the size of farms and the operation of those farms, thereby affecting their production capabilities. In the past in Norway, the production level of individual farms was restricted by the government in an effort to ensure that production was dispersed among coastal areas where employment opportunities were needed.

The effects that a fish farm can have on its immediate environment and further afield will constrain to a greater or lesser extent the potential supply of farmed fish, either in terms of a direct effect on the efficiency of fish production, or in terms of the costs incurred to minimise the environmental impacts, whether self-imposed or as a result of legislative controls.

7.3.2.5 Changes in production and marketing technology

In salmon farming, similar to the situation in agriculture, there is a constant search for improvements to the production process in order to improve efficiency. Many of these improvements are purely reducing specific elements of cost, but many reduce costs by means of increasing growth or yield, thereby increasing the output achieved from given resources. With the latter type of technological development there may be extra costs, but the additional production results in lower costs per tonne. The introduction of high-energy feeds is an example of such a technological advance. While these feeds were substantially more expensive than the previous types of feeds, their effect was to improve the feed conversion ratio and increase the growth rate and therefore reduce the time needed to get the salmon to market size. So the reduction in feed used per tonne of production, plus the increased production achievable with the same set of fixed resources (labour, sea-pens, boats, etc.) resulted in reduced total costs per kilogram of salmon produced.

The effect of an advance in technology is to shift the supply curve of a good to the right, allowing more to be produced for a given market price. It should be kept in mind, however, that in the longer term this may not necessarily be advantageous to the industry because of the effect the additional supply has on the market price, reflecting the nature of demand for the product, as illustrated earlier in Figures 7.2a and 7.2b. Even though most studies have indicated a fairly elastic demand for salmon (i.e., as in Figure 7.2b), there are indications that the elasticity is declining, and if the new technology is associated with significant additional costs that are justified only by means of it also providing considerable extra production, the price fall in the market resulting from the increase in supply might outweigh the unit cost reduction and the expected profit improvement could prove illusory.

While this situation is beneficial to consumers who now pay a lower price for the product, there may be no ultimate benefit to the producers. Unfortunately, the spread of such technological advances is difficult to halt in a competitive environment, for the producers who first adopt the new technology may benefit for a time because they will be able to increase their production while the price of the product is still high. Prices will only fall significantly once the bulk of the industry have adopted the new techniques, and the supply has increased sufficiently to affect the market.

New developments in processing, preserving and storing fish may also affect the supply of the product or products, because developments in these areas can often achieve a diversification in terms of spreading supplies into new markets—i.e., they may avoid the simple adding of increasing production to existing markets. The introduction of controlled atmosphere packaging (CAP), increasing the shelf life of fresh fish, both enabled the supplying of more distant markets and the supplying of different types of market outlet, with less rapid product turnover. The development of new processed product forms, whether pre-prepared meals or items to form parts of a meal, takes the supply into different market segments which may compete only to a limited degree with the traditional fresh salmon supplies.

7.3.2.6 Random shocks

The final group of factors that will affect the quantity of a good which is supplied to the market are those changes which are random. These include such events as bad weather, disease outbreaks or labour strikes. While it is impossible to predict the occurrence of such events, they can sometimes have a significant impact on the market, as shown by the outbreak of Infectious Salmon Anaemia in Scotland in 1998/99.

7.3.3 Review of the supply of farmed salmon by the main world producers

The production of farmed salmon has grown tremendously in the 1990s, with Atlantic salmon being the predominant species whose production has grown

Table 7.2. World farmed salmon production: main producing nations, 1990–98 (in tonnes).

	1990	1991	1992	1993	1994	1995	1996	1997	1998
Norway									
Atlantic salmon	145,990	154,900	130,509	163,891	202,465	261,522	297,557	332,580	360,536
UK									
Atlantic salmon	32,004	40,657	36,302	48,791	64,266	70,322	83,344	99,422	110,917
Chile	23,092	33,970	46,547	55,189	69,078	98,658	144,656	170,821	184,128
Atlantic salmon	9,478	14,957	23,715	29,180	34,175	54,250	77,327	96,675	107,066
Pacific salmon	13,614	19,013	22,832	26,009	34,903	44,408	67,329	74,146	77,062
Canada	21,167	29,009	28,026	33,858	32,815	42,510	45,556	56,775	58,341
Atlantic salmon	9,475	13,248	16,735	22,431	25,250	33,669	36,407	51,013	49,475
Pacific salmon	11,692	15,761	11,291	11,427	7,565	8,841	9,149	5,762	8,866
USA	3,559	7,124	10,322	10,927	10,944	14,106	13,939	18,028	14,523
Atlantic salmon	3,185	6,661	10,028	10,750	10,906	14,075	13,906	18,005	14,507
Pacific salmon	374	463	294	177	38	31	33	23	16
Total world salmon production									
(farmed)	277,860	329,918	316,265	375,129	441,744	537,044	643,168	740,757	788,418
Atlantic salmon	225,492	266,032	253,329	312,868	372,414	465,240	551,838	646,513	687,906
Pacific salmon	52,368	63,886	62,936	62,261	69,330	71,804	91,330	94,244	100,512
Farmed Atlantic salmon as a % of total world production of farmed salmon									
	81.15	80.64	80.10	83.40	84.31	86.63	85.80	87.28	87.25

Source: FAO (2000).

fastest. Norway, the UK, Chile, Canada and the US are the primary producers in world terms, with Norway leading the industry in terms of production volumes. A summary of the growth in supply is given in Table 7.2. The growth in the industry can be attributed to increasing productivity due to improvements in technology and husbandry practices (see Table 7.8), combined with a demand for the product which is responsive both to reductions in the product price and to increasing incomes. Thus, although the large increases in the supply of farmed Atlantic salmon have at times caused significant falls in price that have squeezed profit margins and caused some producers to give up production, sharp price falls have always been followed by some subsequent recovery in prices and more efficient producers have still found it profitable to expand, resulting in a continuing upward trend in production.

7.3.4 Measuring the impact on supply of changing market conditions

7.3.4.1 Price elasticity of supply

The price elasticity of supply measures the responsiveness of production, to changes in the price of the product. It is defined by the following formula:

$$\varepsilon_P^S = \frac{(Q_1^S - Q_0^S)/Q_0^S}{(P_1^S - P_0^S)/P_0^S} \tag{4}$$

where ε_P^S represents 'price elasticity of supply', Q_i^S represents quantity supplied at time i (in the equation two points in time are represented, time 0 and time 1), and P_i^S represents the market price for the product at time i.

Due to the relationship between the market price and the quantity supplied by producers, we expect that the price elasticity of supply will be a positive number: as prices go up, producers will supply more and as prices go down, producers will supply less. The supply of a product is said to be elastic when the quantity supplied is very responsive to changes in the market price ($\varepsilon_P^S > 1$), as illustrated in Figure 7.5a. In contrast, where supply is relatively unresponsive to price changes in the market it is described as inelastic ($\varepsilon_P^S < 1$), as shown in Figure 7.5b.

The production of a good does not occur instantly; it takes time for a firm to change output levels in response to price changes on the market. In some cases, the responsiveness of supply to increases in price will differ to the responsiveness to decreases in the price. The factors that influence the price elasticity of supply are:

- the time period under review and the length of the production cycle, and
- the cost structure of production.

The responsiveness of a producer to price increases is dependent on the time period chosen and the length of the production process for the commodity being examined. Normally supply is much less elastic in the short run, because this is defined as a period too short for producers to be able to add to the productive resources of their businesses. With salmon farming having a production cycle of 18 months to three years, it is only over a period in excess of that that the full elasticity of supply in response to a change in price is likely to be seen, because it will take that long for measures aimed at increasing production to come to fruition in terms of additional fish harvested[2]. However, it may be noted that, while supply will tend to be inelastic for any shorter period than that, it is possible that supplies may be more elastic in the very short term than in the medium term, in that salmon can be harvested at a range of size grades, from 1–2 kg to over 5 kg, so the level of supplies to the market can be significantly altered in the short term by adjusting harvesting plans and the sizes of fish marketed (harvesting early at lighter weights in response to favourable prices, or postponing harvesting in response to unattractive prices, assuming some optimism for prices to improve later).

[2] Note: the period may be somewhat shorter if there are juvenile fish (smolts or parr) that are currently culled as surplus to market demand, but which could be on-grown if required.

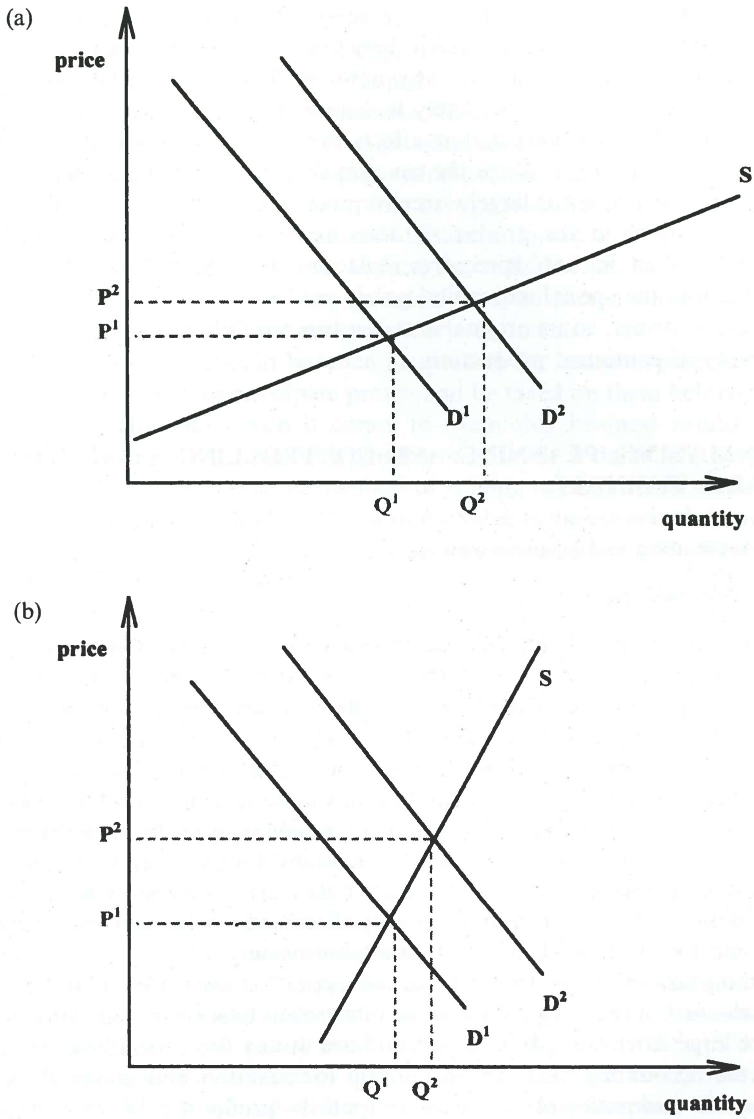


Figure 7.5. (a) The impact of a shift in the demand curve on goods with relatively elastic supply; (b) The impact of a shift in the demand curve on goods with relatively inelastic supply.

The cost structure of production affects the elasticity of supply in terms of the extent to which production is based heavily on investment in specialised capital items that are difficult to resell, or based mainly on direct inputs and/or general purpose capital items, whose value can fairly readily be recouped by resale. A significant part of the costs of salmon production lie in sea-pens, buildings in remote areas, and other specialised equipment for which there are not good resale markets. The need for such capital, in addition to the large amount of working capital required owing to the long production cycle, is likely to constrain the supply response to positive price signals from the market, but affects even more the elasticity of supply in response to falling prices. Once the investment cost in the specialised capital has been incurred, because it is largely irrecoverable other than by producing salmon, it no longer features in the producer's assessment of the price required to justify continued production, until it requires replacement. If the producer decides to give up production, the specialised capital goods are likely to be sold at a knock-down cost to a new owner, so its original cost is again not fully accounted in establishing the viability of continued production.

7.4 ANALYSING, PLANNING AND CONTROLLING A SALMON FARM BUSINESS

7.4.1 Accounting and business analysis

7.4.1.1 Measuring profit

Analysis of the financial performance of a salmon farm, as with any business, starts from the financial accounts, and the basic measure looked for is the profit. In everyday language, profit is seen as the difference between the receipts from sales and expenditure on costs. That would seem at first to be quite a clear and straightforward definition. However, when the profit is to be determined for a specific period, such as the accounting year, the definition has to be specified in a little more detail, and an issue arises that results in alternative measures of profit, depending whether you are concerned with accounting for taxation and company reporting purposes, or for business analysis and management purposes. The issue is the valuation of stocks. It is an important issue in salmon farming that needs to be clarified before we go further into the analysis of salmon farming businesses.

Salmon farming has a long production cycle: 2–3 years for the full cycle from ova to sale, or 1–2 years from the time smolts are put to sea. Consequently, normally there are large stocks of fish on a salmon farm at any time, including the start and end of the accounting year. In accounting for taxation and company reporting purposes, the convention of 'prudence' is applied—profits should not be anticipated prior to their actual realisation in the form of sales. It follows from this that the standard accounting procedure is that stocks are valued at their *cost of production* (or net realisable value[3] if that is lower). Notionally this is quite clear—all expenditure on each group of fish is recorded, and the total of those costs, including the original purchase of the fish or ova, is their value at cost of production. That is reasonably straightforward for direct inputs such as feed and chemical treatments (though even for these it can become complicated if there is much

[3] See following paragraph for definition.

movement of stocks, and particularly mixing of stocks). But what of the other costs incurred for wages, salaries, fuel, electricity, repairs, buildings and equipment, etc? How can these be allocated to specific groups of fish? Methods can be devised, all of which are more or less arbitrary. For example, the costs may be allocated according to the proportion of the total volume of cages occupied by the group of fish, but how do you deal with empty capacity, or again with movement and mixing of stocks? In any case, accounting standards lay down that non-production overheads should not be included in the valuation of stocks, and the definition of what constitutes such overheads is open to varying practice. In fact, the values of stocks in salmon farm accounting statements commonly only include a fairly restricted allocation of costs other than the direct costs of feed and veterinary treatments.

This is certainly as it should be when accounting for taxation purposes, where you certainly do not wish to anticipate profits and be taxed on them before they are actually realised. However, when it comes to examining business results from a management viewpoint—i.e., assessing whether a business is financially secure and operating profitably—the alternative method of valuing stocks at their *net realisable value* gives a more realistic picture. Net realisable value is the estimated receipts that could be obtained from the sale of the stock at the earliest practicable time of sale, less all the estimated costs to be incurred to bring the stock to that sale. These costs include harvesting, marketing and haulage, and the estimated sale value includes allowance for likely mortalities before sale and the likely proportions of fish in different size and quality categories when harvested.

In tax accounts, where stocks have been valued at cost of production, the opening value is added into the Cost of Sales and the closing value is deducted from that: i.e., the costs charged in the Profit and Loss (P&L) account for the year are purely those for the fish that have been sold in that year, and the costs relating to the fish in the sea at the year end are simply cancelled out by the cost of production valuation being added back. However, for management purposes as much up-to-date information is needed as possible, so all the costs incurred in the year are charged and the valuations, in terms of net realisable value, are used to adjust the sales in order to give a measure of what value the business has created during the year in terms of the fish produced, whether they have been sold or not: i.e., the *output* of the business for the year is measured. If the business makes purchases of part-grown fish or fish for direct resale,[4] the cost of these is deducted in the calculation of output (instead of being included with other costs) because that fish value has not been produced within this business. Thus Output is defined as:

Output = fish sales + closing valuations − opening valuations − fish purchases[2]

This is then a measure that can be used to compare performance between fish farms by relating it to the basic resources used by the fish farm, e.g.:

[4] NB. If comparisons of output are to be made across salmon farms which include smolt production, then smolt purchases should be included as part-grown fish but, if only salmon on-growing is being considered, smolt purchases may be treated as a cost rather than being deducted in the calculation of output.

- output per m^3 of cage capacity;
- output per £1000 feed input, or per tonne of feed;
- output per employee;
- output per 1000 smolts stocked.

and thus also set *benchmarks* as to what is reasonable or good performance. The unadjusted Fish Sales figure would not make a meaningful measure of performance to compare between different fish farms, because it does not necessarily reflect the production on the fish farm:

a if there has been a significant change in fish stocks between the start and end of the year, or

b if there have been significant purchases of fish beyond the normal intake of smolts or ova.

The effects of valuing fish at fairly low levels in terms of cost of production, as in tax accounts, are as follows.

- Any fish farm in the process of starting up or in major expansion, will be likely to show a net loss, because of the undervaluation of the increase in the stocks of fish at the year end.
- The fish stocks are a major part of the assets of a salmon farm, so valuing these at a level significantly below what could probably be realised from their sale will make the capital position of the business appear less secure than it really is.
- If a business makes earlier sales of fish than normal, thus boosting its sales for the year and realising profits on fish that would otherwise have been in the closing fish stocks, a business can appear to show a profit, when it is really running into financial difficulties.

Thus, if one is analysing the financial performance of a salmon business for which both the tax accounts and data on the numbers and weights of the opening and closing stocks of fish are available, then adjustment of the valuations to net realisable value should be made to give a clearer view of how the business is performing. To illustrate the third point made above, Table 7.3 shows a P&L account presented (a) in tax account format and (b) after adjustment of the valuations and conversion to an output presentation. The tax account shows a net profit because it reflects the realisation of profits available in the opening stocks of fish, which are valued at less than market value. In the business analysis account the profit on the opening stocks has already been accounted to the previous year, by valuing them at net realisable value. The net loss shown is thus giving a more up-to-date view of the trading performance of this business in the current year, which is revealed to be less than satisfactory.

7.4.1.2 Assessing profit

In a case as shown in Table 7.3, where profit is negative, it is clearly unsatisfactory but, where the profit is positive, how can one assess whether it is satisfactory or not? It can be assessed in two ways:

Table 7.3. P&L Accounts for (a) tax assessment and (b) business analysis.

(a) Tax Account	£ '000	(b) Business Analysis Account	£ '000
Sales	2200	Sales	2200
Cost of Sales:		+ Closing Valuation	900
Opening Valuation	840	− Opening Valuation	1080
+ Production Expenditure	1500	− Fish Purchases*	0
− Closing Valuation	700	Output	2020
	1640	Production Costs**	1500
GROSS PROFIT	560	GROSS PROFIT	520
Overheads	540	Overheads 5	540
NET PROFIT (LOSS)	20	NET PROFIT (LOSS)	(20)

* Smolt purchases included in Production Costs.
** NB. If the valuations included stocks of inputs (e.g., feed) the production expenditure would be subject to adjustment, according to any change in those stocks, to derive production costs.

Opening stocks of fish: 600 tonnes
Closing stocks of fish: 500 tonnes

Valued at £1.40 cost of production — Valued at £1.80 net realisable value

1 In pure business terms, is it providing an adequate return on capital?
2 As a salmon farm, is it achieving a margin comparable with other salmon farms?

There are two measures that can be used for return on capital.

Return on Equity (ROE) is a measure of the return that shareholders in the company are obtaining from their investment, calculated as:

$$\textbf{ROE} = \text{net profit after tax} \times 100/\text{equity}$$

The equity (commonly titled Shareholders' Funds, or Capital and Reserves) is shown in the company balance sheet, and is the estimated money value that would accrue to the shareholders if the business was wound up and all assets sold. It should be the equity at the start of the year in which the profit has been earned that should be used in the calculation, as the equity at the end of the year will include any retained profit. To measure the return that shareholders are making on that capital, the profit after payment of corporation tax is used, because that is what remains for the shareholders. That return is then directly comparable with what could alternatively have been earned by investing the capital elsewhere, e.g., in a safe investment such as a deposit account, which will normally yield somewhere between 5 and 8%, depending on the level of inflation at the time. So in a fish farm business, which is subject to significant risks, one is looking for a return significantly better than that—say 15% or more.

It should be noted that, if the return is calculated from tax accounts, it will tend to be an overestimate, because the equity is likely to be underestimated, as the stock valuations do not fully reflect all the costs which have been invested in the fish (i.e., some overheads are excluded). On the other hand, if net realisable values are used for the fish valuations, the return on capital will be slightly underestimated, because that valuation includes the profit element.

Return on Assets (ROA) is a measure of the total return on all the capital employed in the business, calculated as:

ROA = operating profit (i.e., before interest charges and tax) × 100/total assets

This measure uses operating profit because (a) interest charges represent the return on whatever capital has been borrowed and so are part of the return on the total capital employed, and (b) because tax is also a part of the return on total capital, i.e., the part which is claimed by the government. The value of Total Assets is found from the balance sheet, by adding together the totals of Fixed Assets and Current Assets. Ideally it should be an average over the accounting year, but normally has to be crudely estimated as the average of the values in the opening and closing balance sheets, and often is calculated simply on the values in the closing balance sheet. Again it may be noted that, if calculated from the values in a tax account, the return on capital will be slightly overestimated as a result of the fish valuations being at cost of production.

The primary criterion of a satisfactory ROA is that it should be significantly above the interest rate being paid on borrowed capital to allow for risk, so again 15% plus is a good target. However, it can also be compared with that achieved by other businesses, and in particular other salmon farms, which may at times indicate that a return falling below that target is due to difficult trading conditions in the industry rather than being a problem of that particular business.

Margin on Sales is another measure that can be used to assess profitability, which is normally defined as:

Margin on sales = operating profit × 100/sales

The typical Margin on Sales varies between different industries and at different times, so the value can really only be judged by comparing other salmon farming businesses at the time. Anything in excess of 10% is normally regarded as satisfactory.

Marine Harvest McConnel: a case study

The rates of return and margins on sales being achieved by public companies in the UK can be calculated from their public accounts, available from Companies House. Examination of the accounts of the largest UK salmon farm, Marine Harvest McConnel, over the last decade makes an interesting case study, as shown in Table 7.4.

In 1990 and 1991, when Marine Harvest Ltd was a subsidiary of Unilever, it was making large losses. It was purchased in 1992 by Mari Farms UK Ltd, which was a subsidiary of a company incorporated in the USA. The original name of Marine Harvest Ltd was then taken over by the company, and its American parent company changed its name to Marine Harvest International Inc.

Although the next set of accounts presented results for a 15.5 month period ending 30 September 1993, the profit has been analysed as the return on assets for a

Table 7.4. Profit and return on assets for Marine Harvest McConnel, 1990–1999.

Year ending	Operating profit/(loss) £'000	Total assets[1] £'000	Return on assets %	Sales £'000	Margin on sales %
31 Dec. 1990	(25,892)[2]	48,745[3]	negative	26,993	negative
31 Dec. 1991	(9,856)[2]	44,601	negative	27,001	negative
15 Jun. 1992–30 Sep. 1993	7,344	31,493[3]	23.3	39,252	18.7
30 Sept. 1994	6,427	33,906	19.0	41,647	15.4
30 Dec. 1995	11,546	66,234[3]	13.9[3]	483,694	13.8
29 Dec. 1996	9,778	67,450[3]	14.5	72,663	13.5
27 Dec. 1997	(352)	67,637	negative	69,860	negative
28 Dec 1997–27 March 1999	(22,729)[5]	49,842[3]	negative	85,193	negative

Notes:
[1] Average of opening and closing values where available.
[2] Profit before tax, but after interest charges, which were not presented as a separate item in these accounts.
[3] Closing value only.
[4] Adjusted to annual return based on 15 months trading reported.
[5] Includes a £17 million write-off of the fixed asset values.

year, as the Marine Harvest assets were only actually purchased in October 1992. The details of how the profitability was turned around to give a very satisfactory return on capital of over 23% and margin on sales of 18.7% cannot really be fully determined from the information provided in the public accounts. However, the following points can be made.

The balance sheet at 30 September 1993 shows the tangible fixed assets valued at £4.9 million, compared to £16.7 million at 31 December 1991. How much this arose from some of the fixed assets of the original company being divested before the ultimate sale to the new owners, and how much due to writing down of the asset values, is unclear, but the result is (a) a reduction in the total asset value of the company and consequently (b) a much lower level of depreciation being charged in the P&L account. However, that only accounts for around £2.7 million of the change in profit.

The main change in the P&L account was an increase in turnover from £27 million in 1991 to over £39 million in 1992/93, with an increase of only £1.5 million in the cost of sales. Several factors were involved in this, but likely to be most important were that (a) salmon prices recovered significantly in 1992/93 from a low level in 1991; (b) the average survival rate of salmon was increasing due to improved disease control practices, including the introduction of vaccines against furunculosis (see Table 7.8); and (c) growth rates and feed conversion rates were improving with the introduction of higher energy diets.

It is interesting to see how a major multinational like Unilever can make what appear to be very poor financial decisions in relation to a part of their business—supporting the company through a number of years of major losses only to sell out just before the recovery. However, in the overall context of the conglomerate company group it may have been well justified, in that the problems of salmon production were perhaps diverting too much management effort away from their main core business.

Marine Harvest continued to make satisfactory profits in 1993/94, but it was again sold in November 1994, being bought by the Booker Group and merged with its existing salmon farming subsidiary (McConnel Salmon) as Booker Aquaculture Ltd, trading under the name Marine Harvest McConnel. The absolute profit increased further in 1995 and 1996, but on a much larger total asset value and turnover on the returns were lower, though still reasonably satisfactory. In 1997 the company reverted to a loss-making situation, owing to a combination of rising costs and a falling market price for salmon. Booker placed the company on the market and it was eventually sold to Nutreco in 1999. The accounts for the 15 months ending 27 March 1999 show the operating loss rising to almost £6 million (at least partly due to the effects of the outbreak of Infectious Salmon Anaemia in 1998), to which is added a £17 million write-off of fixed asset values. Clearly Nutreco drove a hard bargain and have secured a company with fixed assets at a book value of £1.6 million, which little over a year earlier were valued at over £21 million. This provides a period in which depreciation costs will be minimal, giving added profit potential. Future profit levels will be watched with interest.

The return on assets and margin on sales shown for Marine Harvest McConnel, although representing around 30% of total Scottish production in recent years, is not altogether representative of the industry as a whole. Results given in an analysis of a sample of over 20 companies' accounts from 1985 to 1994 by MacRae (1996) suggest that, while the trend of profitability shown in the first part of Table 7.2 was common across the industry, average performance did not show quite such extreme variation. Although a majority of the companies were experiencing losses during 1990/91, they were not as great in relation to turnover and capital invested as occurred with Marine Harvest at that time, but also the average ROA and margin on sales were not as high in 1994, being of the order of 15% and 10% respectively, which are probably more reasonable industry targets. The returns shown by Marine Harvest McConnel in 1995 and 1996 were more in line with these, though with the margin on sales still probably higher than would be typical for the industry as a whole.

7.4.1.3 Assessing business security

What is meant by business security? The answer is: how easily can a business survive a period of difficult trading conditions, or the occurrence of a serious production problem, and/or a loss of confidence in the business by its creditors? To assess this the capital position of the business is examined, i.e., essentially:

1. How much of its capital requirements are funded by borrowing?
2. How much of that borrowing could be subject to recall in the short term, and are there sufficient readily saleable assets to be able to repay it if required?

The simplest measure, which answers question 1, and is most easily understood and interpreted is

$$\textbf{\% owned} = \text{equity} \times 100/\text{total assets}$$

With businesses subject to significant risks, such as fish farming, providers of loan finance are more confident about lending to a business where at least half the capital is provided by the owners/shareholders, i.e., 50% owned. Where the proportion of the borrowed capital goes to higher levels, the providers of finance become concerned that, if the business were to run into serious difficulties, there is an increasing risk that they might not be able to get all the capital repaid which they have loaned to it. Certainly most sources of loan capital will be unwilling to provide capital to a business which is less than 30% owned. As with other measures, care has to be taken if it is calculated from the tax accounts, as the undervaluation of stocks will affect both the equity and total assets and, as that underestimation will be greater as a proportion of the equity, the percentage owned will also tend to be underestimated.

Gearing is another term used to describe the extent of dependence on borrowed capital. There are a number of different measures that may be described by this term, so one needs to look at the definition if a measure of gearing is quoted. The simplest one, commonly used in America, is easily understood:

$$\textbf{Debt/equity ratio} = \text{total borrowed capital/equity}$$

If all borrowing, including short-term creditors, is included as debt, then this is really a straight alternative to percentage owned, and a ratio of 1:1 is equivalent to 50% owned.

A business with a debt/equity ratio greater than 1 can be described as highly geared. High gearing can be favourable for profit levels in times when trading conditions are good, but it is a high-risk strategy which may place a business in jeopardy if the trading performance of the business, and/or the level of interest rates, becomes unfavourable at some point, as illustrated by the example in Table 7.5, showing two businesses with similar levels of equity capital but different levels of gearing. The high-geared company achieves much the better profit in good trading conditions, but if trading conditions turn difficult it makes a large loss, which would threaten its survival if sustained over anything more than a short period, whereas the low-geared company still makes a small profit and so can survive the difficult trading conditions over an extended period.

A point to be noted is that it is not appropriate to assess the security of a company which is a subsidiary within a company group, as with Marine Harvest McConnel, because much of the liabilities may be to other companies under the same group ownership and these are not subject to any outside decision on repayment. For example, when under Unilever ownership in 1991, the balance sheet for Marine Harvest Ltd showed the equity (capital and reserves) as negative to the level of over £31 million, i.e., taken at face value the business appeared insolvent by that amount, but a little examination of the details showed that over £64 million of its debts were to other companies in the Unilever Group. The security

Table 7.5. Gearing and profitability.

	Low-geared company £'000	High-geared company £'000
Equity	1000	1000
Borrowed capital	500	2000
% owned	67	33
Good trading conditions		
ROA (%)	15	15
Profit before interest	225	450
Interest @ 10%	50	200
Net profit	175	250
Difficult trading conditions		
ROA (%)	5	5
Profit before interest	75	150
Interest @ 12%	60	240
Net profit/(loss)	15	(90)

aspect for a subsidiary company can only be meaningfully assessed in relation to the group as a whole from its consolidated accounts.

The measure normally used to answer question 2 is

Current ratio = current assets/current liabilities

Current assets are those assets that could be realised in the short term without damaging the longer-term production capability of the business. On salmon farms, current assets are essentially the stocks of fish, plus debtors (sums owed to the business by others), plus any stocks of feed or other inputs. Current liabilities are the amounts that the company owes to others, which are—or could be—required to be repaid in the short term, and they consist of creditors, bank overdrafts, and loans to be repaid within a year.

Current assets and current liabilities are shown in the company balance sheet, usually with the current liabilities being deducted from the current assets to show the net current assets or net current liabilities. If it is the latter—i.e., current liabilities exceed current assets, which means the current ratio is less than 1—then there is potentially a serious problem in that if all the current liabilities demanded to be repaid fairly immediately, the company would have to sell some of its fixed assets (land, buildings, machinery, equipment, vehicles) in order to do that. Many textbooks suggest that a business is in a risky position if the current ratio is less than 2, but in practice many businesses operate with current ratios well below this without any problems. It is really only of great significance if the creditors start to lose confidence in the financial viability of the business. In any case, because the fish stocks represent a large part of the total capital investment in a salmon farming business, most salmon farm companies have a fairly strong current ratio.

7.4.2 Physical performance and costs of production

Beyond the broad analysis of financial status and performance of a salmon farm business, which can be done directly from the financial accounts, those responsible for the management of the business have to concern themselves with the detailed analysis of technical performance as well. We have already discussed the calculation of output as a measure of financial performance, which is derived so as to allow meaningful comparisons between different businesses, or fish farms within a business. The same sort of procedure needs to be carried out to give a meaningful measure of the production achieved by the fish farm in physical terms, i.e., expressed in kilograms or tonnes:

Production for the year = fish biomass sold + closing fish biomass
− opening fish biomass − fish biomass purchased

As with output this is then a measure that can be used to compare performance between fish farms, by relating it to the basic resources used by the fish farm, e.g.,

- production per m^3 of cage capacity;
- production per man;
- production per £1000 feed input, or per tonne feed input.

The latter is, of course, more normally measured as its inverse, i.e.,

Feed conversion ratio = tonnes feed used/tonne fish produced

It has to be remembered—if one is calculating this for a whole farm from feed purchase records rather than feed use records (which is a worthwhile check against the FCRs derived for individual groups of fish from the feed use records)—that it is necessary to adjust the purchases for any change in the feedstocks in store at the start and end of the year, in order to derive the correct measure of feed used.

The cost category totals, which are presented in the trading P&L account of the salmon business, can also be related to the tonnage produced (as calculated above), to give a breakdown of the costs of production per tonne, which can be compared between salmon farms or against such overall industry standards as are available. The comparative production cost data most readily available are that collected and published by the Norwegian Fisheries Department (Fiskeridirektoratet) from a sample of the Norwegian industry, which are presented in Tables 7.6 and 7.7.

These data obviously have to be interpreted with care if comparisons are to be made with results for a Scottish company. In particular, in Table 7.7 it has to be appreciated that the labour costs and production per man indicated are essentially for the growing activity only, because the typical system in Norway is for the fish to be harvested from the cages into a wellboat by a contractor for transport to the slaughter, grading and packing station. In Scotland, in contrast, the harvesting and slaughter will normally be carried out by the staff of the company, and some companies also operate their own grading and packing facilities.

Table 7.6. Average smolt (and fry) production costs in Norway, 1997 and 1998.

No. of hatcheries	1997 *89* NOK (£[1])	1998 *68* NOK (£[2])
Ova and fry	1.10 (0.09)	1.08 (0.09)
Feed	0.98 (0.08)	1.16 (0.09)
Insurance	0.16 (0.01)	0.19 (0.02)
Electricity	0.32 (0.03)	0.34 (0.03)
Vaccination	0.65 (0.06)	0.79 (0.06)
Sundry	1.75 (0.15)	1.44 (0.12)
Wages	1.32 (0.11)	1.55 (0.12)
Interest payments	0.17 (0.01)	0.27 (0.02)
Compensations and bad debts	−0.27 (−0.02)	−0.09 (−0.01)
Owner's estd. wage	0.01 (0.00)	0.01 (0.00)
Estd. interest on equity	0.13 (0.01)	0.13 (0.01)
Estd. depreciation	0.52 (0.04)	0.56 (0.04)
Total costs per smolt/fry sold	**6.85 (0.59)**	**7.44 (0.60)**
Revenue per smolt/fry	**7.67 (0.66)**	**7.58 (0.61)**
No. smolts/fry sold	628,793/211,397	667,879/190,942
Labour: full time equivalents	3.8	3.8
Smolts/fry produced per man	221,103	226,006

Notes:
[1] Converted at 11.585 NOK = £1
[2] Converted at 12.502 NOK = £1
Source: Fiskeridirektoratet (1999).

The clearest point to be observed from the production cost data is the prime importance of feed costs, which amount to over 45% of the total.

Figure 7.6, showing the longer term picture, reveals the particularly strong downward trend in costs from 1992 to 1995 arising from great improvements in productivity. It is notable, however, that the average cost per kilogram increased in 1998 for the first time in the last ten years.

Survey data on costs of production in the Scottish salmon industry have not been publicly available for the period since 1992/93 (Sutherland *et al.*, 1994), but the survey of physical production data carried out by the Fisheries Research Services does provide some performance measures which are useful for comparative purposes, as presented in Table 7.8. As with the data from Norway, quite dramatic improvements in productivity are indicated.

For the future it seems unlikely that productivity can continue to improve as rapidly as in the first half of the past decade (Tveterås and Bjørndal 1998). Firstly, there is obviously a limit to improvements in the survival rate, which was the most significant source of improvement in the first half of the decade—the average survival rate of around 90% achieved with the smolts put to sea in recent years (apart from the 1996 cohort) cnanot be greatly improved upon. Secondly, the Norwegian survey results show that the feed cost per tonne of salmon produced, after falling steadily for several years to 1996, increased somewhat in the next two

Table 7.7. Average production costs for salmon (and trout) in Norway, 1997–1999.

	1997	1998	1999
No. of accounts	*256*	*207*	*209*
	NOK (£[1])	NOK (£[2])	NOK (£[3])
Smolts	2.69 (0.23)	2.23 (0.18)	2.53 (0.19)
Feed	9.11 (0.79)	9.71 (0.78)	8.62 (0.65)
Insurance	0.24 (0.02)	0.25 (0.02)	0.28 (0.02)
Sundry	2.59 (0.22)	2.61 (0.21)	2.85 (0.21)
Wages and salaries	1.62 (0.14)	1.61 (0.12)	1.49 (0.11)
Net financial expenses	0.74 (0.06)	0.77 (0.06)	0.87 (0.07)
Estd. depreciation	0.57 (0.05)	0.65 (0.05)	0.66 (0.05)
Slaughter costs	2.42 (0.21)	2.19 (0.18)	2.56 (0.19)
Total costs per kg	**19.98 (1.72)**	**20.03 (1.60)**	**19.88 (1.49)**
Revenue per kg	**19.86 (1.71)**	**20.96 (1.68)**	**23.23 (1.74)**
% Salmon in total sales	92	88	89
Feed conversion rate	1.22	1.25	1.21
Production tonnes per farm	1049	1466	1592
Labour: full-time equivalents	5.5	5.9	6.4
Production per man-year (tonnes)	190	248	249

Notes:
[1] Converted at 11.585 NOK = £1
[2] Converted at 12.502 NOK = £1
[3] Converted at 13.327 NOK = £1
Source: Fiskeridirektoratet (2000).

years, largely due to a rise in feed prices. This was mainly caused by a short-term shortage of fishmeal associated with the effect of 'El Niño' on the Peruvian anchovy fishery but, as salmon production and other forms of fish farming dependent on diets with high fishmeal content expand, there is likely to be increasing pressure on fishmeal supplies, which will be reflected in feed prices despite some progress being likely in reducing the levels of fishmeal in fish diets.

The main potential source of future productivity gains lies in genetic improvement. However, consumer reactions against the use of genetic manipulation in food production seem to be likely to limit that to a steady development by traditional selection procedures rather than a great leap forward.

7.4.3 Some key issues in planning salmon farming systems

7.4.3.1 Economies of scale

Salmon farming is an activity which is subject to significant economies of scale arising from several sources:

1 **Equipment and building costs** decline sharply with increasing size of unit. Figure 7.7 shows how, with increasing diameter, even at a fixed depth, the volume of a circular sea cage increases much more than the circumference.

Table 7.8. Measures of performance in the Scottish salmon industry.

Year	Survival rate (fish harvested as % smolts put to sea)[1]	Average weight per fish harvested (kg)	Labour productivity (tonnes per person)	Production per m^3 capacity[2] (kg)
1990	63.4	2.5	22	na
1991	57.9	2.7	32	na
1992	61.6	2.7	29	5.4
1993	66.9	3.1	40	7.4
1994	78.9	3.4	51	9.5
1995	90.7	3.5	52	9.5
1996	91.5	3.5	60	9.8
1997	87.8	3.7	77	9.3
1998	78.1	3.2	85	9.5
1999	89.6	3.9	97	9.3

Notes:
[1] Total from smolt input 2 years before
[2] This measure of annual production per m^3 of capacity must not be confused with the stocking rate, which is also measured in kg per m^3.
Sources: SOAEFD (1991–1998), SERAD (1999–2000).

Since the main cost of the cage is the floating collar, which is determined by the circumference, the cost per unit of volume enclosed declines markedly with increasing cage size, even though the collar has to be made to a stronger specification as the size increases.

The cost of the net for a sea cage or of a tank constructed on land are both determined mainly by the area of the base and walls. The relationship between this and the volume, which is shown in Figure 7.8, again indicates that the cost per unit of volume declines markedly with increasing size. Similar relationships exist for much of the equipment used on fish farms (e.g., boats) and for buildings.

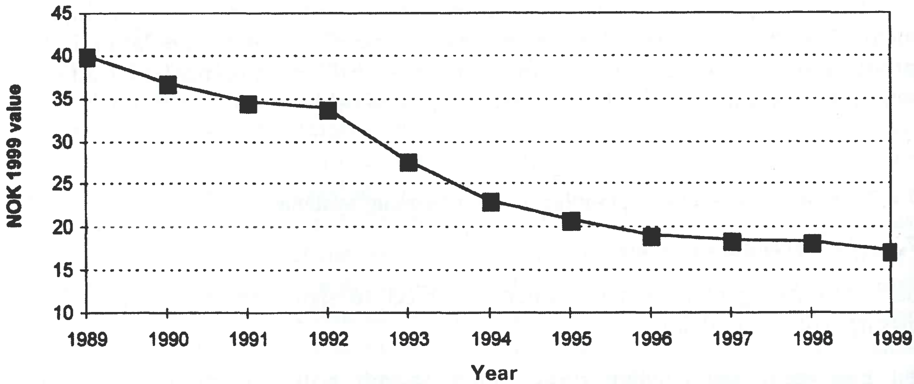


Figure 7.6. Trend in production costs of salmon in Norway. *Note*: 'Production costs', as used here, excludes the slaughter costs indicated in Table 7.7. *Source*: Fiskeridirektoratet (2000).

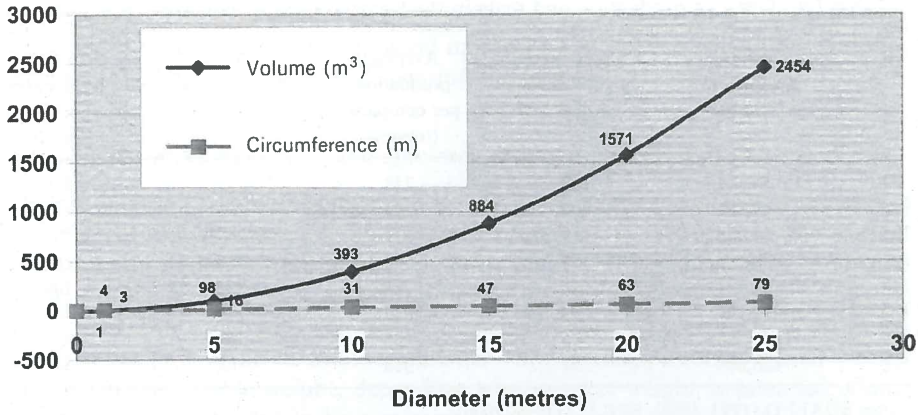


Figure 7.7. Volume and circumference of 5 metre deep sea cage in relation to diameter.

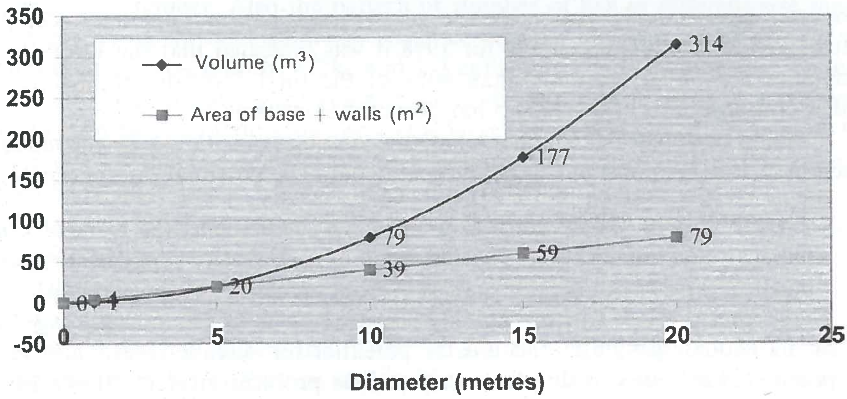


Figure 7.8. Volume and area of base + walls in relation to diameter (depth 1 m).

2 The **bargaining power** which comes with scale can enable reduced input prices to be negotiated, particularly for feed and equipment, and may also aid sale prices by being able to meet large contracts and possibly provide supplies year round.
3 Larger scale allows **greater specialisation** and thus potentially greater expertise, e.g., employing veterinary, engineering and accounting specialists.
4 **Spreading of overhead costs**, e.g., office, transport, management, across a greater total production reduces the cost per unit of production.

The trend in the industry in Scotland towards increasing concentration in larger businesses, with larger sites, as indicated in the statistics in Table 7.9, appears to support the benefits of scale in salmon production.

The increase in scale is really greater than is indicated by the statistics, in that a significant number of fish farm businesses that are still registered as separate

Table 7.9. Trend of production and scale in the Scottish salmon industry, 1992–1999.

Year	Total production (tonnes)	Companies in production	Average production per company (tonnes)	Sites in production	Average production per site (tonnes)
1992	36,101	140	258	279	129
1993	48,691	132	369	283	172
1994	64,066	119	538	262	245
1995	70,060	108	649	268	261
1996	83,121	106	784	278	299
1997	99,197	98	1012	275	361
1998	110,784	95	1166	289	383
1999	126,684	94	1348	264	480

Source: SOAEFD (1993–1998), SERAD (1999–2000).

companies have actually been sold to larger organisations, and operate under their control. In the production survey for 1998 it was indicated that the seven largest companies accounted for more than 60% of the total Scottish production, and further concentration of ownership has occurred since then.

It should be noted that countervailing diseconomies of scale can be encountered, which may at some point outweigh the economies. The potential diseconomies are:

1 The possibility of losing motivation and diligence amongst the workforce in a large, scattered organisation. The likelihood of serious effects on performance as a result of a poorly motivated staff is certainly great in salmon farming.
2 The greater risk arising from holding larger numbers of fish in single cages and on individual sites, e.g., the greater potential for disease spread and larger potential fish losses arising from any serious problem incident. However, for the largest businesses, that risk of larger losses in the event of a problem is balanced by having production spread across several separate farms.

Results obtained in the sample survey of production costs for 1991/92 and 1992/93 in the Scottish Industry (Sutherland *et al.*, 1994) did not show any clear indication of economies of scale. In 1999, suggestions were made in Norway, associated with the first results from a new benchmarking club to compare on-farm performance between production units, that 'the top achievers tend to be family-run businesses with sufficient production sites and output volume to offer reasonable economies of scale, without being so large that site managers are no longer able to stay in control' (Ley, 1999).

One of the technological developments that has contributed to the gains in labour productivity in salmon farming has been the production of reliable, fully-automated, computer-controlled feeding systems. But here again scale comes into play, because large production sites are needed to bring the capital cost of this equipment down to a reasonable level per tonne of salmon produced. Then the saving in labour costs per tonne can fully justify the investment, but with such a system comes the potential for diseconomies to creep in if the staff are not sufficiently trained and motivated to keep up good monitoring of the fish when they no longer have to actually be on the spot dispensing the feed to them.

7.4.3.2 The production cycle and efficiency of use of holding capacity

The production of salmon is governed to a large extent by the effects of the seasons and the natural life cycle of the fish, which evolved in response to the seasons. Traditionally, following the natural pattern, smolts (S1s or S2s) have been ready and put to sea in April/May. Growth is rapid through the warmth and long daylight of summer, but slows with the shorter days and lower sea temperatures in winter, and it takes part or all of another summer—and perhaps another winter—before they reach marketable weight, depending what market weight is intended. Consequently, there has tended to be a seasonal pattern in salmon supplies.

Overall supplies tend to peak in the late autumn, following the period of faster growth in the summer. Also the pattern of supplies of fish in different size ranges results in varying seasonal differences in price between the sizes. Most salmon will reach the smaller size grades (1–2 kg and 2–3 kg) within a year, or just over, so these sizes tend to be plentiful in early summer but in short supply in winter. On average it takes 18 months or more to grow fish to the larger sizes (>5 kg) and virtually all fish are harvested within two years. Thus large sizes attract a positive price differential in August/September but a negative price differential in February/March, whereas small sizes are relatively most expensive in November–January and cheapest in May–July (Guttormsen, 1998).

Apart from the problem of producing fish of similar sizes to everyone else at a particular time in the year, and thus tending to obtain lower prices, there are difficulties in making efficient use of the fish farm's holding capacity as a result of putting smolts to sea at the one season of the year, due to the length of growing period, and the practices required to minimise transmission of diseases and pests (not mixing different year classes on a site, not mixing different groups of fish into a cage, and having a fallow period before restocking a site). If the fish on a site are harvested before late winter, then the site will be empty for an extended period before it can be restocked with S1 smolts in spring. Also, the stocking density is very light when the smolts are first put to sea on an empty site, particularly if the fish are harvested as a batch at one point in time, although this has merits in terms of minimising handling of the fish.

The issue of how to make efficient use of cage capacity has become more problematic as growth rates have improved in the past few years. In the past, when it took nearly two years for most fish to reach the larger size grades (>5 kg), a two-year cycle was the norm, but now, with high-energy diets an average weight of over 5 kg may be achieved within 18 months, or 16 months if large smolts are used. Stocking different cages with different sizes of smolts and splitting the stock from a single cage into two cages at least once during the grow-out period, including grading them into faster- and slower-growing groups, does reduce the problem to some extent and enables the harvesting on a particular site to be spread over several months. This can

Table 7.10. Trend in categories of smolts put to sea in Scotland, 1993–1999 ('000s).

Year	S½s	S1s	S1½s	S2s	Total
1993	—	19,843	—	698	20,541
1994	1,865	19,701	113	274	21,953
1995	2,442	23,081	589	674	26,786
1996	5,527	26,157	180	974	32,906
1997	8,936	33,274	182	374	42,766
1998	12,796	32,649	190	235	45,870
1999	11,585	29,119	335	68	41,107

Source: SOAEFD (1994–1998), SERAD (1999–2000).

be extended further by restricted feeding of selected groups but, as that is aimed at restricting the growth rate of the fish, it will not actually improve the efficiency in terms of the production per cubic metre of cage capacity. Thus, as shown in Table 7.8, while other performance measures in the Scottish industry have continued to improve (except for the survival rate, due to the effects of ISA), the annual production per cubic metre of capacity has remained fairly static since 1994 at a little less than 10 kg per cubic metre.[5]

A potential means of improving on that is provided by the technology which has developed in recent years for producing 'out of season' smolts. This is achieved by control of light patterns for the broodstock in order to vary the spawning time (or by importing ova from the southern hemisphere), and by controlling the temperature and light patterns for the fry/parr to speed growth and induce smoltification. Thus smolts can now be obtained at most times throughout the year, but the majority of out-of-season smolts are S½s which are put to sea in September-November.

Appendix 7.1 shows a plan of a system using S½s for a notional salmon farm to give an 18-month cycle including a 6–8 week fallow period, which offers the potential to raise the production per cubic metre of cage capacity to at least 12 kg. Note, however, that to maintain a constant level of sales from year to year, it is necessary to have three sites operating the 18-month cycle, alternating between stocking S1 smolts and S½s.

Table 7.10, giving the statistics for the categories of smolts put to sea in Scotland in recent years, shows that the adoption of S½s by the industry in Scotland was limited initially, beginning with less than 10% of the smolts put to sea in 1994. Inevitably there were some question marks over whether their survival and growth would match that of S1s and, as might be expected, there undoubtedly were problems in some cases. However, the steady increase in their use, amounting to

[5] It may be noted that the Norwegian cost survey reports give figures of production per m^3 which are quite different, e.g., 36.4 in 1977, 33.1 in 1998 and 32.3 in 1999 (Fiskeridirektoratet, 2000; figures of over 90 kg per m^3 were being presented in the equivalent report in 1992, covering 1988–1990, but in subsequent issues were adjusted down by a factor of 4 times, i.e., to just over 20, after these values were queried in correspondence with the authors). Such production figures could only be achieved with stocking rates considerably higher than that.

around 28% of the totals put to sea in 1998 and 1999, suggests that the technology is now becoming widely established in the industry.

The other approach that can be conceived for maximising the efficiency of use of cage capacity is to go all out for a one-year cycle. The problem is that to allow for a fallow period, this means a growing period of only around 10 months. A reasonable market size can only be reached in such a short period by starting with a large smolt, e.g., 100 g plus. Artificial lighting within the cages may also be used to extend daylength in order to maximise feeding and growth through the winter period. Even then, the *average* size of fish that can be marketed from such a short grow-out period is unlikely to reach 3 kg. Consequently the production costs, other than the cage costs, will be higher but the annual production per cubic metre of cage capacity will be virtually equal to the final stocking density, perhaps 18 kg or more.

7.4.3.3 Monitoring, budgeting and planning

Most salmon farms now operate sophisticated computer programs for recording and forecasting fish numbers and weights cage by cage, as well as costs and sales. With the risks and uncertainties to which salmon farming is subject, regular monitoring of actual performance against previous projections is highly important in order to identify problems early, so as to be able to modify plans to deal with any problems and to take best advantage of any favourable circumstances arising. In this process the examination of the effects of alternative scenarios and variations in the plans can be time well spent to help decide the best way forward.

This type of planning is based on 'trial and error', testing of modifications from a basic system which is already in place. Sometimes it is worth standing back from the present system and examining from a clean sheet the resources of the business and the alternative potential ways in which they might be used to generate profits. That may include activities other than salmon production but, even within salmon production, for large companies with several sites varying in size, and perhaps including smolt production facilities and/or grading/packing/processing facilities, there are likely to be a very large number of alternative ways in which these resources could be used. Trying to examine all of these by simple budgeting, even with the help of the computer budgeting program, is rather inefficient, and examining only a few selected options tends to stay within a set line of thinking. An alternative comprehensive type of analysis that can be carried out is to use linear programming (LP), which applies a mathematical optimisation procedure to select the system that gives the highest expected total margin, based on data for the margins from alternative activities, the resources used by those activities and the amounts of those resources which are available. An example of its use in normal fish farm planning is provided by Varviagos and Horne (1987), and in a research context by Reith and Tveterås (2000).

This technique, which is carried out using a computer program, is part of what is called Operations Analysis, deriving from its original use for determining the most efficient use of shipping resources when it was first devised during the Second World

War. It has since found application in many different spheres wherever there is a problem of optimisation subject to a set of constraints; for example, in the formulation of compound feeds such as fish diets (see Chapter 4) it is used to determine the least cost combination of alternative ingredients which will provide the specified nutrient content in the diet.

An important principle utilised in this procedure when it is used in selecting between alternative production activities is the distinction between fixed and variable costs and this is relevant to any approach to deciding production plans for a business.

Fixed costs are those costs which a business incurs that do not change significantly with adjustments in the production policy of the business, e.g., office and accounting costs, managerial salaries, equipment and building depreciation.

Variable costs are those that vary directly in proportion to the specific activities which are carried out by the business; i.e., they are the costs of inputs which are required to be provided in order to produce each additional unit of the particular activity. The clear examples are feed costs, ova or smolt purchases, haulage and packing of fish. Some other costs may be classified differently according to the planning situation. If the alternative activities being considered do not have radically different labour requirements and do not require different types of specialist staff, regular labour costs will usually be treated as a fixed cost, i.e., the labour force is seen as a fixed resource of the business. Varying demands of different activities for labour at different times in the year are taken into account in terms of the estimated labour hours required, which are measured against those available from the workforce employed. However, if part of the labour requirement can be provided more flexibly by way of casual/contract labour, employed only as required, then this is treated as a variable cost.

The advantage of this distinction is that the fixed costs can be set aside in the first instance, the contribution of each potential activity to business profit is estimated as its gross margin per unit produced, which is the expected receipts per unit of the activity less the estimated variable costs per unit, and the planning problem is then simplified to that of maximising the total gross margin of the business (or net revenue as it is termed in the LP literature) which can be produced from the resources available. This equates to maximising profit in that the deduction of the fixed costs from the gross margin gives the profit.

The procedure requires the estimation of a lot of data in the first instance, mostly on a seasonal basis (e.g monthly), to construct the input matrix in which the resource requirements per unit of each activity have to be defined, as well as the activity's gross margin per unit and the available resources of the business. The resource requirements will normally include demands on holding capacity volume (as defined by stocking rates for different sizes of fish and seasons), water flow requirements in the case of a flow-through tank system, labour requirements and constraints on market availability, but any factor which may limit the maximum level of any one or more activities should be included. The production process can be broken down into its various parts (ova, fry, parr, smolts (fresh water), smolts (seawater), ongrowing, grading, packing, processing) as much as is necessary to define the differing resource requirements. Essentially the procedure is attempting to model mathematically the production possibilities of the business.

In the first instance the model is often a very crude estimate of reality and there are some theoretical limitations one has to be aware of, but once a basic matrix has been produced the flexibility and speed of modern computers make it very easy to test and modify the model, refining and improving its representation of reality and analysing the outcome of different assumptions regarding the production performance and the market situation. Although the assumption of a fixed set of equipment and buildings is adopted as an initial simplifying assumption, this can be re-examined by rerunning the program with the addition of further equipment (or with reduced resources if sale of some of the buildings and equipment may be an interesting possibility) and the profit potential compared to assess whether the investment is worthwhile.

7.5 CONCLUSION

At the end of the day the analysis and planning of any business comes down to a matter of sound judgement, and that is particularly true of salmon farming, with the risks and uncertainties involved. But that is not to say that sophisticated techniques such as demand analysis, investment appraisal, linear programming or even detailed budgeting are irrelevant. The point is to appreciate that 'one begins with a judgement and one ends with a judgement. The purpose of the figures is to come in the middle, in order that the judgement with which one ends is more soundly based than the one with which one began' (Anon., 1994).

Appendix 7.1. Plan for salmon production based on 18-month cycle, using S1 and $S\frac{1}{2}$ smolts alternately on three sites.

Facilities: 3 sites, each licensed for up to 6–70 m plastic circle netpens (or 10–50 m × 15 m square steel pens) with maximum net depths 10 m.

Planned Growth: Based on temperature profile ranging from 6.5°C in January/February to 13.5°C in August. Fish fed for maximum growth, using up to 30% oil feed. Mortalities assumed at 0.7% per month, 10% overall.

Stocking rates: Smolts stocked at around 10 per m^3, split before reaching 15 kg per m^3, max 18 per m^3 at harvest.

Sales: The sales from each batch are estimated at 50% of the total fish numbers at the time of sale and the mean weight, firstly of the largest fish and secondly of the slower growing half of the batch.

	Site 1	Site 2	Site 3	SALES tonnes
March	147,500 50 g S1 smolts			
April	stocked in 4 pens			
May				
June				
July				
August				
September		154,900 50 g $S\frac{1}{2}$ smolts		
October		stocked in 4 pens		
November	139,500 fish at 1.47 kg			
December	spread into 6 pens			
January				
February				
March			147,500 50 g $S\frac{1}{2}$ smolts	
April			stocked in 4 pens	
May	**66,850 fish harvested @ 3.15 kg**	146,500 fish at 1.10 kg		**210.6**
June	Remaining fish in 4 pens	spread into 6 pens		
July	**65,900 fish harvested @ 3.16 kg**			**208.2**
August	Site fallow			
September	154,900 50 g $S\frac{1}{2}$ smolts			
October	stocked in 4 pens			
November		**70,200 fish harvested @ 3.00 kg**	**139,500 fish at 1.47 kg**	**210.6**
December		Remaining fish in 4 pens	spread into 6 pens	
January		**69,200 fish harvested @ 3.21 kg**		**222.1**
February		Site fallow		
March		147,500 50 g S1 smolts		
April		stocked in 4 pens		
May	146,500 fish at 1.10 kg		**66,850 fish harvested @ 3.15 kg**	**210.6**
June	spread into 6 pens		Remaining fish in 4 pens	
July			**65,900 fish harvested @ 3.16 kg**	**208.2**
August			Site fallow	
September				

Total Production, Tonnes per annum		**851.6**
Annual Production, kg per cubic metre of holding capacity:	**(a) Using 14 pens (minimum feasible)**	**15.6**
	(b) Using 18 pens (more likely in practice)	**12.1**
Average Weight per Fish. Kg		**3.1**

8

Risk assessment and management for salmon farmers

This chapter developed from a project carried out under the European Commission FORCE programme 'Continuing Vocational Training in the European Aquaculture Industry' which involved partners from industry and universities in Greece, Ireland and Scotland.

8.1 INTRODUCTION

Any activity combining water, livestock, machinery, electricity, chemicals, new technologies, weather and the possibility of human error can be considered to entail a high degree of risk: most forms of aquaculture combine some or all of the above factors. The consequences of failure of part of the culture system can be catastrophic: blocked inflow pipes, damaged nets, misused chemicals or other relatively simple system failures can lead to the sudden and total loss of extremely valuable stock. It is obviously essential that the farmer understands all of the potential hazards on or around the farm in order to manage and minimise or eliminate them. By so doing, the welfare of the stock is promoted and environmental impact minimised.

Financial aspects of salmon farm operation are dealt with elsewhere in this book. However, a farm run to minimise biological and technical hazards is likely to perform better from the financial point of view and produce a higher-quality product than one where carelessness is endemic. Health and safety aspects of farm operation are governed by regulations and legislation.

This chapter aims to provide a practical guide to the identification, evaluation and reduction or elimination of risks on salmon farms. It also provides guidance on the correct actions to be taken in the event that a disaster affecting the farm does occur. It covers the major sources of risk for different types of farm, dealing with the general features commonly associated with each hazard. Many case studies are used to illustrate (all too clearly) genuine examples of the various types of problem. These are drawn from real occurrences on salmon (and a few trout) farms, and clearly demonstrate the consequences of failure to appreciate and control hazards around farms. Some of the case studies illustrate relatively simple aspects of equipment failure while others (notably Case Study WQ7 relating to the Braer oil spill off Shetland) are used to guide farmers on procedures once an incident has occurred.

Examples are listed under categories such as water quality (WQ) and equipment failure (EQF). However, most disasters have a range of contributory causes.

8.2 THE ENVIRONMENT FOR AQUACULTURE

The risks facing the fish farmer come from either of two directions:

- outside the farm (external factors);
- inside the farm (internal factors).

8.2.1 External factors

With few exceptions, aquaculture takes place in an open environment, placing the farmed animals, farm staff and farming equipment at risk from factors that are, at least partially, beyond the control of the operator. Such external factors include:

- severe weather: high winds, waves, storms, floods, drought;
- water quality: dissolved oxygen levels, pH, salinity, turbidity;
- chemical contamination: pollutants in the water supply system (e.g., sheep dip, agricultural chemicals);
- physical problems associated with water supply: water shortage; extreme high or low temperature;
- biological contamination: pathogens, parasites; toxins associated with algal blooms;
- predators and scavengers;
- human interference: theft; vandalism; unreliable suppliers; changes in finance arrangements (interest rates, market, etc.); pressure from individuals or groups with conflicting views.

Although these factors come from outside the farm, most of them can be influenced or controlled to some extent by the operator.

8.2.2 Internal factors

In addition to the factors originating outside the farm there are problems produced internally which should be within the control of the operator. Many of these follow a similar pattern to those originating outside the farms. These include:

- chemical contamination: chemicals badly stored or used on or around the farm;

- water quality: nitrogen supersaturation, ammonia, oxygen depletion, elevated levels of suspended solids;
- physical problems associated with the water supply: water supply interrupted;
- biological contamination: pathogens;
- operational problems, resulting from: mismanagement; poor maintenance; insufficient investment; inadequate training; new initiatives within the farm; failure to take new initiatives within the farm.

8.2.3 Knowing your risk

Some people might say that aquaculture is one continuous risk: it is certainly a high-risk occupation. It has also been queried whether aquaculture is more risky than agriculture. Both are based on biological processes, which are likely to have less predictable outcomes than physical ones. However, there are at least two major differences:

- stock held underwater is more difficult to observe than animals or plants cultured on land;
- aquaculture techniques and practices are still relatively new and likely to produce unpredictable results from time to time as new equipment, diets, new species and strains are introduced, and as new diseases affect the stock.

The best way of controlling risks is to know what they are and from which direction they are likely to come.

Effective risk control is the product of experience and data accumulation. Every site and system varies; therefore measurement of specific risks must be from accumulating experience and data (data = record of experience) for specific sites and systems.

The risks facing any farm will change as the farm develops. At the beginning of the operation, the farmer will be looking for the unexpected from the environment; the 'once in 100 year flood' (which always seems to occur twice in the first year), the tidal flow which is so fast that cages are distorted, the stock which simply do not perform under the conditions specific to a new farm. Once these have been sorted out, the predominant hazards are likely to be associated with familiarity (or even complacency), and must be combated by effective monitoring, record keeping and decision-making. Examples of risks arising from complacency include buying in cheaper, unvaccinated stock (why pay for vaccination when you have not had an outbreak of the relevant disease for several years?) or not replacing cage nets regularly ('the net still looks fine, only a few tears which can easily be mended, let's leave it for another year'...).

8.2.4 Siting of farms

Farm sites are chosen for a number of reasons. These may include land availability, access to transport systems, proximity to markets and, most importantly, the likelihood of safe operation with minimal risk. Points to consider in respect of risk minimisation include:

For freshwater

- Is there adequate water quantity and is it of suitable quality (see Section 8.2.5)?
- Are there other water users either upstream or, in the case of still waters, using the same water body?
- Are there other land users in the catchment area that might impact on water quality?
- What is the probability of the site flooding?
- What is the proximity and concentrations of predators (e.g., heronries)?
- Is the site close to built up urban areas (human predators)?
- How close is the operator's house—improving the observation of the farm?
- In the case of still waters: is it sheltered from wind and wave action?
- Are there other fish farms on the same water course or nearby (birds and horizontal transfer of disease)?
- Has the site got good access (especially for staff during an emergency situation)?

For seawater

- Is the water quality suitable (see below)?
- What other water users share the same resource (e.g., commercial, fishing, pleasure boats)?
- What is the proximity and concentrations of predators (e.g., seal colonies)?
- Is the site sheltered from wind, waves and current?
- Are there other fish farms nearby?
- How easily is the site monitored (observed) by the operator or staff?
- Does the site have good access (again, especially in the event staff are called in to deal with an emergency)?

Risks attached to a particular site will vary in degree according to the use made of the site. For example, a sea cage site exposed to the direction from which severe storms are likely to come could be used in summer with very little risk of damage but is unsuited to winter use when the risk of severe weather is unacceptably high. Conversely, other sites may be suitable for winter use but not advisable for the summer because of the toxic effects of algal blooms. Such sites are termed 'marginal', particularly in respect of 'year round use' and types of farming practice which can reduce risks associated with these sites include:

- using stronger equipment, e.g., plastic or metal cages rather than wooden ones;
- planned reduction of the density of the cultured stock at times when water supply rates are reduced and water temperatures are high;
- incorporation of partial or total water recirculation within the farming system.

These examples refer to the amount of 'redundancy' or 'backup' incorporated into equipment or a farm management plan. Redundancy refers to the 'additional margin of safety' created by design and careful planning.

8.2.5 Inputs to farms

Risks to the health of fish on the farm can be minimised by ensuring that inputs to the farm are always of the highest quality. The term 'input' essentially covers anything coming into the farm, including the:

- water;
- stock;
- equipment used in farming, transport and harvest;
- food supply;
- drugs and chemicals;
- staff: skills, experience, motivation, responsibility.

8.2.5.1 Water

In Europe, Directive E3/79/923 designates the quality of a body of water and affects commercial activities within it. Other Directives to be considered include the Urban Waste Water and Nitrate Directives.

The most important features of the water supply are quantity and quality. Some intensive farms take in very little water from the environment, recycling existing water through filters and treatment systems. However, most farms rely on a throughput of water from outside, through the farm and then back into the natural watercourse or body of water. Because of this, changes in the characteristics of the inflow water can have a major, perhaps disastrous effect on the stock on the farm.

8.2.5.2 Water quantity

For farms drawing their supply from a source of running water, the quantity of water available *all year, every year* is often the most important factor in determining the weight of stock that can be held on the farm at any time. This is mainly because water brings in the oxygen and takes away the wastes from the fish. Fish farmers are increasingly recognising that holding fish at densities below those dictated by oxygen availability is beneficial to health and survival (by improving the safety margins during unpredicted or irregular periods of high oxygen consumption; during high temperatures or following feeding for example).

The quantity of water available from a source of running water will be determined in several ways.

- From a knowledge of the *minimum flow* in the stream or river, taken from information collected over as many years as possible. The golden rule is that the *minimum* flow, not the average or maximum, controls the amount of fish that can be produced. This may be a severe limiting factor on the siting of a farm as minimum flows often tend to occur in summer, accompanied by high water temperatures. The combination of these two factors leads to an overall reduction in the amount of oxygen available to the stock on the farm, often at a time when the biomass (number × weight) of fish held is high. An example of how this may restrict the options available to a farmer is in the production of out-of-season smolts. For S1 smolts, the maximum biomass of fish will be held in March/April when waters are likely to be unlimiting and cool. A switch to producing smolts in August/September means that the maximum biomass is held during the summer. A farmer following this course of action would have to substantially reduce the overall numbers of smolts produced by the farm.

- From discussions, followed by a binding agreement with authority(s) controlling abstraction from a watercourse (e.g., in England and Wales, the Environment Agency or in Scotland, the Scottish Environmental Protection Agency, SEPA, Hydro Boards, etc.).

Ideally a prospective fish farmer should have available records for the site under consideration going back over at least three years (preferably more). These should demonstrate that there is *always* enough water of suitable quality for the species to be farmed or that backup and supplementary systems (such as aeration devices) are adequate to cope with the extreme predicted lows of water flows).

8.2.5.3 Water quality

As with water quantity, it is not good enough having suitable conditions '99% of the time': the 1% of the time where quality (e.g., low oxygen concentration, industrial pollution) falls below acceptable limits is enough to create a catastrophic loss. What should be done to determine whether water quality is suitable and to identify possible sources of trouble for the future?

Know your water source. The farmer should have available full records of the chemical composition of the water supply and, where possible, biological information (fish species and invertebrates present) to back this up. The fish and invertebrates provide a better long-term monitor than on-the-spot chemical readings. A water sample giving a favourable chemical analysis accompanied by biological samples indicating a scarcity of fish and/or insects might indicate that the water was subject to periodic flushes of pollutants. It would certainly merit further investigation. 'Data loggers', that continuously record various water parameters (such as oxygen, pH, temperature), are affordable and an extremely efficient way of accumulating and maintaining such information.

Know the requirements of the stock to be farmed. Each species will have its own requirements in terms of aspects of water quality such as oxygen concentrations, levels of trace elements or pollutants. For each species there is likely to be an optimum concentration range (or a maximum or minimum concentration) in which the growth, behaviour and health of the fish can be described as normal. There is also likely to be a range of concentrations that, while not directly lethal, is associated with reduced performance and increased susceptibility to pathogens. At the extreme, there will be concentrations that kill the fish directly: low concentrations for oxygen, high concentrations for pollutants, heavy metals (e.g., from mine waste). The same can also be said for acidity/alkalinity (pH). (Salmon, for example, are more tolerant of higher salinities than trout; which may fail to osmoregulate under a combination of high temperatures and high salinity.)

Know where trouble is likely to come from and when it is likely to come. Many problems are seasonal although, as with forestry planting, felling or road construction which are likely to send large quantities of silt into the water, they can be one-off events. Effluents such as silage run-off or domestic sewage are rich in organic matter and ammonia and therefore exert a high biochemical oxygen demand (BOD) as they are oxidised by bacteria. This results in oxygen depletion in the water which is counteracted eventually by turbulence in waterfalls and riffles and by the oxygen produced by the photosynthesis of aquatic plants in the daytime. Possible sources of reduced water quality in freshwater and some of the likely components or effects of effluent from these sources include:

- farms: silage, dairy effluent, pesticides such as sheep dips;
- industrial, agricultural and domestic sewage outfalls;
- mining operations, past or present: abandoned mines may be sources of heavy metal contamination and it may be difficult to trace an owner or other person with the responsibility for cleaning up an effluent, even if such an operation were feasible;
- distilleries and thermal power stations: there may be an increase in water temperature because the water returning to the stream has been used to cool stills or generators;
- quarrying: silt can lead to suffocation of eggs and gill damage;
- forestry planting or felling: silt, leaves and other debris;
- construction of roads or buildings: silt;
- algal blooms in lochs: reduced oxygen levels, toxins;
- weed-cutting upstream: weeds left in the water decay, exerting a high BOD (weeds that float downstream may block intakes);
- other fish farms.

The above sources of pollution are likely to be obvious to the fish farmer, to the polluter (in many cases) and also to the authorities assigned to monitor and regulate discharges. A further possible source of trouble comes from what could be described as 'benign neighbours'. These are not obvious polluters but are seemingly safe buildings where no industrial or agricultural processes take place. Nevertheless these neighbours may have the means of destroying or contaminating the stock. These polluters include the neighbours who tip waste liquids (oil from a car service, waste paint, empty chlorinated swimming pool water) into the storm drains and which find their way, untreated, to the water supply.

In seawater it is usually less easy to identify sources of likely water contamination. The following factors should be considered:

- proximity to the mouths of rivers: pollutants often come to the sea from freshwater;

- proximity to shipping lanes: the effects of oil from wrecked tankers in Alaska, Galicia and Shetland have been devastating for local fish and shellfish farming;
- industry close to the shore near the farm site: for example, production from a clam hatchery was wiped out as a result of antifouling paints leaching into the water while being applied to ocean-going ships in a nearby ship yard;
- any history of algal bloom problems which might result in the production of toxins damaging to farms or the reduction of oxygen in the water;
- other fish farms or even other sites operated by your own farm;
- sewage outfalls.

Water quality is a vital element in the success of any aquaculture operation. In the case of plankton blooms, the toxins in the water can cause sudden and dramatic losses. With most physical and chemical changes to water quality however, the cause of the problem is often less obvious and may not always be readily identifiable or easily corrected. Water-quality problems will generally develop over a long period of time and a single water analysis or irregularly spread samples may not give an adequate indication of potential problems. Poor general water quality will often allow outbreaks of disease, in some cases to the extent that the disease problem masks the primary problem, the water quality itself (see Case Study WQ1). Water-quality problems in freshwater sources can often be confirmed by an examination of the invertebrate fauna of the supply. Aquatic invertebrates are long-term residents and the numbers and species range are closely related to water quality. A single pollution event may pass through the water system too quickly to be measured by instruments assessing water quality but an absence or reduced diversity of invertebrates should indicate that there has been a problem.

8.3 CASE STUDIES

The following case studies illustrate different ways in which water-quality problems manifest themselves. For the most part, juvenile stocks are more sensitive than older ones and, as a rule, when more than one source of water is available (or where the resource is used more than once), the best quality is reserved primarily for juvenile production.

8.3.1 Case Study WQ1: Gill damage at a hatchery on a spate river system

The farm This is a salmon smolt unit on a spate river system. It was established to produce smolts for the company's sea site operation. The system was initially gravity-fed with a small filtration unit for the incubation system.

The loss From inception, the company experienced varying levels of gill damage with first-feeding parr. Repeated treatments with salt, Chloramine T and formalin were necessary to minimise the effects of excessive mucus and growth of myxobacteria. After a spate, losses could escalate quickly. The situation was complicated because a creamery operated beside the river, upstream of the farm. It was considered that effluent from this business might be partially responsible for the continuing gill problems. Water-quality analysis revealed high levels of iron, aluminium and suspended solids, and at times the water could be very alkaline. It was decided to invest a substantial sum in water quality control when, in its fourth year of production, the farm experienced a total loss of its first feeding parr.

Response This is often slow in water quality situations because of the difficulty of isolating any specific water-quality parameter as being responsible. In addition, the company in this case had experienced at least one good year of production with few losses attributable to gill damage. However, recognising that there was a genuine and variable water quality problem the company chose to:

- develop a nearby spring for use with the juveniles;
- install a 20 µm drum filter system on the main water supply;
- monitor water quality on a more frequent and extensive basis.

Pressure was also brought to bear on the creamery, which eventually faced some action by the pollution control authority over unlawful discharge and which has since upgraded its water treatment procedure.

Result In the first year following these actions, the company achieved its best-ever production with negligible mortality at every stage. Some problems arose in a subsequent year, which may have been linked to the natural alkalinity of the water. However, the company is still in business and the gill damage problems have receded.

8.3.2 Case Study WQ2: Repeated losses from gill damage

The farm This was a very old trout and salmon hatchery on an established salmon fishery. Stock were traditionally raised for release until the commercial market for salmon smolts developed. The company invested in equipment and brought in a recognised strain of farmed salmon eggs to hatch and rear to the smolt stage.

The loss In spite of a relatively good record in rearing native trout and salmon, the first year's production of imported stock was disastrous. More than 30% of the fish were lost through gill damage. Results were similar in the second year and in the third year there was an almost total loss. Small stocks of native trout and salmon at the same hatchery were affected to a lesser extent.

Response It was apparent that the commercial strains of salmon were unlikely to do well at this site, at least not in the first feeding juvenile stages. The native salmon and trout appeared to have a natural resistance to the problem. Water-quality analysis could not identify any obvious factors to which the problem might be attributed. It was also apparent from experience with other imported stocks, that once the fish weighed 5 g or more, they were relatively immune to any damage. The company had the option to put their ova out to another farm with a different and proven water supply, although the quantity of water at the independent site was only sufficient to rear the required numbers of fish to about 7 g.

Result A contract was arranged, and the independent farmer now rears the fish for the company which had experienced the gill damage problems, transferring the stock when they reach weights in excess of 5 g. Although the hatchery has since closed down, the arrangement worked well for a number of years with no recurrence of the original gill damage losses. Experimental trials have subsequently confirmed that the ongrowing site is still unsuitable for small salmon juveniles although the reason is still not clear.

8.3.3 Case Study WQ3: pH fluctuation and total loss at a freshwater unit

The farm This was a new operation built on a river system with no record of salmon cultivation. The location was a remote island with no industry other than sheep farming and fishing.

The loss The farm operated a simple flow-through gravity fed system. Water quality had been checked periodically and found to be satisfactory. Following a rainy spell in midwinter the stock suddenly began to die. Within days virtually everything had been lost. Up until then the fish had performed well; they were about 20 g in weight at the time of the loss.

The response The fish had suffered extreme gill damage, many were bleeding from the gill tissue. Water samples taken 12 hours after the beginning of the incident (when the river was in spate) revealed a pH of 4.8 and the loss was diagnosed as resulting from the sudden onset of acid conditions. The effect of acid water on the local fauna (heather, peat, etc.) and sudden run-off of the rain (which may itself have been acid) were theories advanced to account for the situation. The farmer and his insurer recognised the need to monitor and guard against a recurrence of this situation, whatever its source. A commercial buffering plant was installed and a pH monitor fitted, linked to an alarm.

Result In the two years following the original incident, pH was recorded as low as 3.7. The buffering system has maintained the water in the rearing tanks at above 5.4, even in the most extreme acid situations. Most important of all, no stock has been lost due to low pH since the original incident.

Comment If more thorough monitoring of water quality had been carried out on the site before the hatchery was established, the problem might have been detected prior to the occurrence of this incident.

8.3.4 Case Study WQ4: Contamination of a borehole and subsequent loss of stock

The farm The unit originally started up as a trout farm. With the commercial development of salmon farming the operators expanded and moved into salmon smolt production. The original river water supply was limited in quantity and variable in quality, so much of the expansion relied on the development of several boreholes on the site. These tapped into the extensive water table in the area.

The loss Following two or three years of drought in this region, the water table level dropped considerably. However, the boreholes remained operational as originally they had been drilled quite deep. Whilst the manager was away on his annual break, a problem occurred with one of the boreholes which began to produce reddish-brown water. Unfortunately, this was not detected immediately by the relief staff. They reacted slowly and the first feeding salmon fry were exposed to dirty water conditions for 24 hours before the contaminated borehole was detected and shut down. Gill damage and subsequent infection by myxobacteria eventually resulted in some 60% of the stock dying (300,000 fish).

Response Water-quality analysis revealed the contaminated borehole to contain extremely high levels of iron. None of the other boreholes were affected. Little research has been carried out on the toxicity of iron, but there is some indication that the metal interferes with the respiratory process in addition to imparting physical damage to the surface of the gill.

In general, boreholes are considered to be closed systems, stable and protected from pollution or contamination. However, it is often the case, especially when water tables fall, that quality deteriorates and contamination through leaching arises. As with all water systems, quality must be monitored.

Result The company now regularly monitors the water at the source with all their boreholes and carries out frequent analysis. The quality is never taken for granted and staff have a greater awareness of the speed at which a problem such as this can develop into a large loss.

8.3.5 Case Study WQ5: Gradual contamination of water supply from a rotting iron screen in a filter unit

The farm A well-established, purpose-built salmon hatchery with both spring-fed stream water and borehole supplies.

The loss The company was in its fifth year of production when it experienced severe losses among its juvenile parr stocks (post first feeding stage): 400,000 fish died.

Response The water supply at the time was the spring-fed stream which passed through a large sand filter tower prior to use. It was apparent that the water supply might have become contaminated, causing gill damage in the fish stocks, and that high levels of iron might also be involved. In fact, over the preceding two years, losses at first feeding had increased slightly; this had culminated in the severe loss described above. The filtration tower was dismantled and it was discovered that the iron screens at the bottom of the filter (full of gravel and sand) had collapsed at some time due to rust and that the substrate was badly contaminated by this rust. The screens and filter substrate were subsequently replaced.

Result The problem has not occurred again and the company has improved its water-quality monitoring procedures to avoid a similar situation arising undetected.

8.3.6 Case Study WQ6: Pump ashore marine farm water-quality problems

The farm A pump ashore seawater farm built for the purpose of ongrowing salmon in large 12 m and 25 m diameter steel tanks.

The loss Within three years the operators had experienced numerous problems relating to water quality. Coastal water can become turbulent and if, as in this example, an intake for a pump ashore unit is poorly designed, debris, suspended solids and surface pollutants will be drawn into the supply line. This particular company repeatedly experienced high post-smolt delivery losses with, typically, severe gill pathology being diagnosed. In addition, the stock performed poorly and there were many fish health problems and associated high stress levels that could be attributed to adverse water quality.

Response The original intakes went about 60 m off the shore and were placed above the substrate, 2 m below the level of low water spring tides. If prevailing wind and sea conditions coincided with low tide, water quality deteriorated rapidly. At times, screens and pumps became clogged and water flow rates decreased when seaweed was sucked against and through the intake screens. The decision was finally taken to extend the existing intake pipes by 40 m, taking them down to around 5 m below low water spring tides. Intake screens were redesigned and two additional backup intakes installed.

Result The extension work cost £100,000 and was only partially successful. Oxygen alarms and improvements to the aeration system helped but, in spite of better production results, the slump in salmon prices eventually forced the closure of this unit.

Comment Intake designs are vital to the success of pump ashore units and prior consideration of all likely prevailing coastal conditions must be made before deciding on a suitable design. Examples exist where operators have been able to draw on high-quality sea water by system designs which include:

- sinking boreholes, especially in chalk areas where seawater may permeate inland through the substrata for some distance;

- laying out field drains below the sea bed and using the sea bed itself as a natural filter;
- extensive filtration of pumped water using drum units capable of handling high-volume flows.

There are also a great many sites that have been chosen specifically for the quality of water naturally available. Investment in site selection should not be underrated for this type of operation.

8.3.7 Case Study WQ7: MV Braer oil spill, Shetland, 1993

The effect of the wreck of the oil tanker, MV Braer, on the salmon farming industry of the Shetland Islands was far greater than would have been predicted in advance. The economic impact extended beyond the farms whose cages were in the path of the oil to those over 100 km from the pollution whose market disappeared almost at once and for the immediate time span of the spill incident. The success of the industry in dealing with the disaster owed much to its organisation into a strong trade association.

However, the incident provides many lessons for individual farmers and has therefore been included as a case study here. This study adopts a different format from the others as it has been written in diary form, recording the events relating to the salmon farmers as they unfolded at the time. The diary was kept by Martin Holmes of the North Atlantic Fisheries College, Scalloway, a central figure in the response team. In the diary the key events are recorded, together with the questions they posed for the farmers and the subsequent actions taken.

Time 11:10, Tuesday 5 January 1993
Event MV Braer grounds on rocks at Garths' Ness, Shetland in a Force 9 gale.
Cargo 85,000 tonnes Gulfaks crude oil plus 500 tonnes of bunkers.

Time 11:37, Tuesday 5 January 1993
Event Oil starts to leak from stricken vessel.
Scenario Major oil spill disaster of unknown consequences.

Time Tuesday 5th January/Wednesday 6th January
Event Formation of a team to coordinate the actions of the salmon farmers and the response of the industry in the offices of the Shetland Salmon Farmers Association. This team comprised the officials and staff of the Association and public relations and technical experts brought in to help. The team continues to work together over the next few weeks.

Time Morning, Thursday 7 January 1993
Event Fish farm located 12 miles north of spill site reports surface oil in cages.
Question To feed fish or not?

Response Do not feed if surface oil is present—ingestion of oil could cause internal damage and tainting of flesh.

Time Morning, Friday 8 January 1993

Event 16 farm sites on west coast of Shetland affected by surface oil. Weather slackens (Force 6) and allows use of dispersants by aerial spraying.

Questions How to feed if oil present?
Should oiled nets, etc., be cleaned?
Effect(s) of dispersants on fish?
Possibility of towing cages out of harm's way?
Use of booms to stop oil entering cages?

Response Do not feed if surface oil is present; if equipment is available, can try feeding subsurface using water injection pumps.
Time consuming and pointless to clean nets/floating structures as further oil contamination likely, also increases stress levels on already stressed stock Request aerial dispersant spraying does not encroach within two miles of fish farms because the effects of dispersant on the fish are unknown.
Weather, movement orders (disease) and lack of suitable sites precludes moving cages.
If booms are available, use to reduce oil inflow to cages. Note: in this incident insufficient absorbent boom was available in the first stages of the spill to be of use to a single site let alone 16. Deflection booms were incapable of withstanding prevailing weather, broke up and caused damage to nets.

Time Late afternoon, Friday 8 January 1993

Event Voluntary exclusion zone imposed by Shetland fishing industry to stop harvest and sale of salmon, whitefish and shellfish from sites/areas within zone. Later this was enforced by the Scottish Office under the 1985 Food and Environmental Protection Act (FEPA).

Question What about the fish farms that were intending to harvest now and in the future weeks, and the potential low income?

Response Speak to and maintain contact with own insurers; liaise with local salmon farmers' association. Compensation should be available from the International Oil Pollution Compensation Fund (IOPCF) to a total of £55 million, for all those affected, not just the fish farmers; keep accurate and detailed records of what is done and when, e.g., additional labour and equipment, numbers of fish intended to be harvested, mortalities, presence of oil, whether samples of oily water are taken and where from, photographs, etc.

Time Morning, Monday 11 January 1993

Event Full-scale programme in place to monitor oil and hydrocarbon levels in the water and at fish farm sites inside and outside exclusion zone.

Should ensure that any fish caught or harvested outside the zone are of the same quality as before the spill occurred.

Time Tuesday 12 January 1993
Event First report of increased mortalities from an affected farm site.
Question Does this mean all farms can expect high mortality losses?
Response Unknown: mortalities need testing to confirm cause of death. Note: cause of death could not be confirmed in this incident.

Time Wednesday 13 January 1993
Event Samples of salmon from within the zone show signs of a high hydrocarbon taint; weather slackens and allows divers into cages.
Questions Can salmon ever be sold?
Will salmon depurate themselves in time?
What about the obvious cash flow implications?
Response As fish have been contaminated, unlikely that they will be allowed to be sold for human consumption.
Cash flow problems should be eased by IOPCF.
Salmon depurate themselves given clean water—impossible to say when water hydrocarbon levels will fall to background.

Time Thursday 14 January 1993
Event Supermarkets request hydrocarbon testing on all Shetland salmon harvests outside zone.
Question With large numbers of fish involved, how can this be done and at what cost?
Response Agree to testing based on a percentage of each harvest from each farm site, using independent laboratories if the local one is not available; additional costs to farmer/association should be met by IOPCF.

Time Friday 15 January–Tuesday 26 January 1993
Event Continuation of the same problems. Weather remains bad: 20 out of the first 21 days of January produce gale conditions of Force 8 and above.
Response Keep smiling and keep going!

Time Wednesday 27 January 1993
Event White fish caught outside exclusion zone show signs of hydrocarbon taint.
Question What does this mean?
Response Fish probably moved out of original zone. FEPA exclusion zone extended but no new farm sites covered by extension.

Time March 1993
Event IOPCF agree price to allow the slaughter of the total 1991 generation of fish inside the exclusion zone.
Question What do you do with 2000 tonnes of fish?

Response Fish killed and ensiled for feed on Norwegian mink farms; they still cannot go for human consumption.

Time 23 April 1993
Event Exclusion zone lifted for white fish following the disappearance of taint and contamination from the samples. The exclusion zone remains in place for salmon and shellfish.
Response Continue with claims for compensation for stock.

Time August 1993
Event Sediment surveys reveal some 29,000 tonnes of oil bound to sediments in two areas, one west of Shetland and one to the southeast. A month-by-month slaughter is agreed for the 1992 generation of fish inside the exclusion zone with appropriate compensation from the IOPCF.
Question Is this a sensible solution?
Response Probably not as none of the 1992 fish will ever be allowed to go for human consumption having been grown in contaminated nets. The situation is still unclear for the 1993 intake: these fish will definitely not obtain any of the quality marks even though, by May, water hydrocarbon content was back to background levels inside the zone.

Time October 1993
Event The IOPCF agree in principle to the total destruction of 1992 stock within the zone.
Response Same as for the 1991 stock.

Time October 1993
Event Scottish Office Agriculture and Fisheries Department partially lift the ban for 1993 stock following a series of clear results—harvesting can now proceed. The IOPCF accept that price damage has occurred to Shetland salmon but disagree with estimates of £20 million, putting it closer to £400,000.
Response Farmers set about organising harvests and breathe a sigh of relief as cash flow is eased slightly. Continue with price damage claim.

Time March 1994
Event Destruction of 1992 stock completed.

Time May 1994
Event Donaldson report on M.V. Braer (*Safer Ships, Cleaner Seas*) published with recommendations.
Response Report greeted warmly.

Time 1 October 1994
Event Exclusion zone lifted for crabs and lobsters, remains for scallops, queens (*Chlamys opercularis*), mussels and Nephrops.

Time February 1995
Event FEPA zone for scallops lifted. Compensation claims proceeding

through civil courts after IOPCF cannot meet all claims in full. For the fish farmers, a test case is to proceed; if successful, the others will follow.

Time Spring 1995
Event The IOPCF pull the plug on further payments from the compensation fund.
Response Shouts of 'foul'. Meetings held to discuss what to do next.

Time Autumn 1995
Event Salmon farmers decide to pursue claims through the courts using the Scottish legal system initially and then, if this action fails, perhaps the American courts.

Time January 1996
Event Claim lodged with court to meet 3-year deadline from spill date.
Response It is now a waiting game as the claim progresses through the long-winded legal process.

Time 30 August 1996
Event Nothing new to report. The exclusion zone still remains in place for mussels and *Nephrops* and will remain so for some time as monitoring goes on. The legal process continues.
Response Life goes on.

Time November 1999
Event None. FEPA ban continues for mussels and *Nephrops*. Despite ban, works licence applications for mussels farms within the zone are made and agreed in the hope that ban will soon be lifted. Test court case against IOPCF going through appeal process.

Time January 2000
Event FEPA zone lifted for all species. Test case against IOPCF dropped by SSFA on the grounds that it was unlikely to succeed and payout, if successful, would have been insufficient. Shetland Islands Council also drops its claim to allow small claimants (in Shetland) to get their money from the small amount of funds left.

Time 5 January 2001
Event Eight years on the Braer is a distant memory.

Action required If threatened by an oil spill from any source, the following steps are recommended as the minimum required.

1 Keep an accurate record of everything that happens and your response to these events.
2 Keep accurate records of all additional costs for labour, equipment, testing, etc.
3 Liaise with your insurers and keep them informed of the situation; if they

recommend a course of action, comply as best you can, keeping a note of what you do and what happens.

4 Liaise with your local association and harbour authorities who may be monitoring the spread of the problem.
5 If the weather allows and booms are available, use them to absorb or deflect the approaching oil, but only in consultation with insurers, etc.
6 Take samples of water at regular intervals in screwtop, airtight (preferably dark) glass bottles. Never cheat: hydrocarbons (and other pollutants) have very distinctive fingerprints—anyone filling a bottle with seawater and sump oil will quickly be found out.
7 Keep or send mortalities for testing to ascertain cause of death through expert *post mortem* examination.
8 Do not feed if surface oil is present in cages; subsurface feeding is a possibility that seems to work.
9 Do not clean and/or remove nets or floating structures until the incident is over; this saves time and keeps fish stress levels down.
10 Do not speak to the media without prior consultation with association/insurers.

A problem that is of increasing concern to salmon farmers in Scotland, Ireland, Tasmania and New Zealand is that of losses attributable to jellyfish. The following and last case study for this section on water quality, illustrates some of the observations relating to the management of this problem. (The problem is also similar in many ways to the management of algal blooms involving – monitoring, measuring and mitigation activities).

8.3.8 Case Study WQ8: Jellyfish losses on a New Zealand salmon (Chinook) cage farm

The farm A well-established salmon farm with 'live in' staff and very experienced management.

The loss A massive bloom of jellyfish swept unnoticed into the bay with the incoming tide, and on the outgoing tide swept up against leading cages on a group. The fish nets were totally clogged by the jellyfish. Divers reported that in the cages, it was like 'swimming in jelly'. This loss was the second such loss in two years. The verdict for cause of death was 'suffocation'.

Comment Most jellyfish losses involve the supposedly 'innocuous' *Aurelia* (moon jellyfish). Previously it was assumed that most losses resulted only from 'suffocation' as with this case study from New Zealand, either from when nets became clogged and water exchange diminished or simply from the sheer numbers of jellyfish in the cages. In some instances, however, this has proved quite toxic (to salmon). This is certainly the case in Tasmania, with a number of recent losses on record following contact between Atlantic salmon and the jellyfish. One spectacular loss arose from the accidental introduction into a cage of massive numbers of 'jellies' during a net change. More research into this aspect of jellyfish kills is being carried out.

The life cycle of the moon jelly has four distinct stages: larval, polyp, ephyrae and the medusa stage. The medusa (adult stage) is clearly identified from the pink, clover-shaped ring of sex organs in the bell. The females release eggs and confine them in the oral cavity until fertilised by the male. These become motile planula which eventually settle to form polyps. The polyps can reproduce asexually, forming large colonies, and will survive for many years, ultimately maturing into a strobilla from which 'ephrya' bud off, generally as the water temperatures increase. The ephrya are only about 2 mm in diameter, but grow quickly as they develop feeding structures. The adult medusa (upto 40 cm diameter) are capable of movement and have (limited) senses of smell and taste. They live for between two and six months. It is these motile stages (ephrya to medusa) that pose the greatest problem to fish farmers.

Response For sites experiencing jellyfish problems recommendations to farmers include:

1 If the net change involves pulling a clean net around the old net, divers check below nets before the nets are changed. Ideally (as is standard practice at many farms now) sew the nets together and swim the fish through.
2 Where clogging and oxygen depletion have proved problems in the past it is recommended that aeration systems be fitted (as used commonly in Norway and Canada for dealing with plankton blooms). Air will maintain oxygen levels and should blow any 'jellies' already in the cage to the surface where they can be removed. Airlifts also draw clean water from below cages (assuming this area is free of jellyfish) to displace contaminated surface waters which is the principle applied in the use of air-lifts for dealing with plankton blooms.
3 Towing cages to 'push' jellies up against a net side and bring clean water into the fish may also help (used mostly in the case of single cages such as plastic circles). Outboards have been used with limited success to achieve similar results, but because of the recent discovery that *Aurelia* can prove toxic (in unknown circumstances or specific to as yet unidentified but different family groups), this practice is no longer recommended. It has been suggested that when stressed through severe agitation, the jellyfish toxicity can become significantly worse. Furthermore the use of outboards can 'chop jellies into pieces' where (a) smaller pieces are able to enter the cage net yet retain their stinging capability; and (b) the pieces are capable of regeneration increasing the problem.

Result Following the (repeat) loss of salmon in respect of the case study, the Insurer deemed it appropriate to suggest to the owners that they consider installing a system based on the second recommendation above. Whilst there was no guarantee that the aeration system would prevent all such future losses, it was clear that inaction would allow further such losses to occur, with possibly even more catastrophic consequences. Once a system such as this is in place and utilised, it can be modified and developed as experience and staff initiative see fit. Ultimately it was thought it could become as integral a part of the operation as are the airlift systems on deep-water sites in Canada, Norway, Ireland, etc. (where plankton blooms are frequent events, at times arising very suddenly). At the time of this publication no further losses of this nature had occurred.

8.4 THE STOCK

The best possible starting point for any rearing process is a strong disease-free stock with a proven ability to thrive in the conditions on the farm where they will be growing. Reductions in growth rates and survival from poor or unsuitable stock will lead to reduced income and cash flow. The later in the production cycle that mortalities occur, the heavier will be the financial burden.

In order to minimise the risk of bringing disease on to the farm and to ensure a good rate of growth and survival, stock should be:

- disease-free: all stock entering a farm should be certified by an independent authority to guarantee freedom from pathogenic diseases. Certification authorities will vary from country to country;
- from a reliable source: check how eggs/smolts from this source have performed on other farms and your own farm in the past;
- of a recognised stock or strain: although this is not yet an exact science, a great deal is now known of the performance of different strains of fish in culture;
- delivered to the farm in a way that minimises transport-related stress;
- vaccinated if appropriate;
- counted accurately: this is one of the few times during the production cycle when the farmer can obtain accurate counts of stock. Knowledge of correct numbers helps prevent problems resulting from overstocking (which may lead to underfeeding), or understocking (which may lead to overfeeding);
- isolated from stock already present on the farm; this will probably involve using separate sites for cage farms; and
- must (in Europe) conform to the legal requirements of EC Directive 91/67 on stock movements.

Most stock losses other than those relating to equipment failure or pollution are generally associated with outbreaks of disease associated with pathogens, parasites and nutritional deficiencies.

Disease losses can be the most significant risk for some types of aquaculture operations. The Taiwanese shrimp industry is a good example of how severe the effects of disease on an industry can be. As a result of disease, production fell from 100,000 tonnes in 1987 to 30,000 in 1993. It should be remembered that the disease did not strike at random: environmental conditions on the farms had been deteriorating over a number of years.

Disease losses manifest themselves in a variety of ways; losses are not always a direct result of the disease implicated. Some of the examples (DL4 and DL5) illustrate how the treatment itself can cause losses.

Case studies DL1 and DL2 are of a general nature. The first illustrates how disease control can be achieved through improvements in the management of farms, in particular using separate year class sites and regular fallow periods. The second illustrates how an introduced species might be susceptible to an indigenous pest and also how the most natural of resources (in this case freshwater) can sometimes prove the most effective treatment.

8.4.1 Case Study DL1: Furunculosis

This example is based on a problem that initially affected the Scottish salmon industry and has subsequently affected the industry in Norway and elsewhere. It illustrates how a relatively controllable disease can, in time, become devastating and how a united approach by an industry is necessary to bring it under control.

The problem Furunculosis is caused by the bacterium *Aeromonas salmonicida*. Initially salmon farmers found the bacteria to be susceptible to a wide range of antibiotics. However, as production increased, greater quantities of antibiotics were required to prevent furunculosis outbreaks. Traditionally (in the 1970s and up to the mid-1980s), two or more year classes were grown on the same sites and by different farms operating in the same body of water (a sheltered sea loch for example). Smolts introduced to sites encountered existing carrier populations and, subsequently, the disease itself. The bacteria acquired resistance from repeated exposure to antibiotics; this resistance was passed on when the bacteria reproduced. Eventually the farmer's limited armoury of antibiotics was exhausted as multiple-resistant strains of *Aeromonas* wreaked havoc throughout the industry. At one time, the only control was to harvest all fish on a site, sometimes prematurely. Some farmers experienced total losses. Freshwater units acquiring the disease could not sell their stock and also had to kill their fish, often without compensation.

Response The Scottish industry has been able to reduce significantly the impact of furunculosis (and other diseases) by adopting a unified approach to the problem. Not least of all the actions taken is the implementing of Area Management Schemes that involve:

- the screening of stock intakes (to ensure they are disease free);
- synchronised fallowing (i.e., leaving sites empty of fish);
- single year class stocking;
- mutual health and water-quality management approaches;
- improved sharing of knowledge between farms and coordination of activities such as treatment of disease.

Fallowing in particular is vital to break the disease cycle and prevent resistance to therapeutic agents from developing. However, it is only effective if all farms sharing the same water resource fallow at the same time. Improved husbandry techniques, reduced stocking densities, an increased range of antibiotics and, particularly, greatly improved vaccines have also been vital in controlling furunculosis.

Survival rates to harvest of salmon smolts transferred to seawater in Scotland increased from 58% for the fish harvested in 1991 to 90% for the 1995 harvest (SOAEFD figures).

8.4.2 Case Study DL2: Amoebic gill disease of Atlantic salmon in Tasmania

Atlantic salmon were introduced into Tasmania for commercial farming in 1984. The industry grew to produce over 7000 tonnes per annum (1997), from sea cages, and continues to expand (estimated to be about 11,000 tonnes in 2000/01).

The problem Amoebic gill disease was diagnosed in the first year of commercial sea farm production. The agent is a protozoa that attacks the surface of gills, causing respiratory distress and which, if left untreated, can cause mortalities of 2% or more per day. The problem is less common in Europe (although it has been responsible for losses in Ireland), and appears to be a good example of an indigenous disease finding an opportunist host in the introduced species of salmon (*Rickettsia* in Chile is a similar type of problem). The Atlantic salmon has no natural resistance to the problem and the damage is therefore exacerbated by the fish's naivety. Losses in Tasmania were, initially, catastrophic.

Response An epidemiological analysis of the problem suggested that:

- the disease is worse when fish are in full-strength seawater;
- it is also worse when temperatures are high (15°C or above);
- it does not occur in freshwater and is less likely to occur in low salinity, brackish sites.

It was found that immersing the salmon in freshwater baths (for about two hours) was effective in removing the amoeba. The treatment is natural and the process has been made easier with the introduction of fish pumps and other fish-handling equipment. By carrying the process out prophylactically (as water temperatures rise or at the time when a problem has historically arisen on a site), losses have been kept to a minimum and the problem is generally well controlled. In some cases, farmers have been able to select brackish water sites in which the amoebae do not naturally occur.

This case study points to the dangers of transferring any species outside its native range. There may also be problems where introduced fish of a native species bring with them pathogens or parasites, infecting the native fish (example *Gyrodactylus salaris* brought from Sweden to Norway).

8.4.3 Case Study DL3: Furunculosis outbreak in a spring-fed unit

The farm A small, spring-fed salmon hatchery producing 80,000 smolts each year from tanks in an outside compound.

The loss The farm ran well for about three years. The spring water supply emerged from a hillside very close to the unit and was piped to the farm. With the water supply thus protected, the farm was in an ideal position to maintain a disease-free status. River systems with endemic fish populations can often make it difficult for freshwater operators to exclude disease. However, in its third year of production, furunculosis was diagnosed in the fish. The farmer lost his market for the smolts; although the disease was treatable, few ongrowers wish to buy salmon smolts which have been diagnosed as being furunculosis-positive.

Response The farmer in this case was devastated. He had been reasonably careful about hygiene and all stock brought onto the farm as eggs had 'disease free' certification. However, the hatchery was in an area of intensive sea farming amongst which furunculosis problems were common. The farmer and his staff had on occasion visited the sea sites. In addition, not far from the hatchery was a municipal dump in which some farmers buried carcasses of fish that had died from furunculosis and seagulls sometimes managed to get at these dead fish. The implications therefore with regard to the source of infection suggested it came from either (a) accidental transfer on staff boots or vehicles; or (b) bird faeces.

Comment Sensible control measures include monitoring staff movements, avoiding cross-contamination through movements between sites, and covering water tanks and supply channels where possible.

8.4.4 Case Study DL4: Sea lice treatment loss

The farm A salmon sea cage in the North of Scotland. Salmon were being ongrown in large circular cages typical of many other farms in the area. The farmer is a very experienced operator.

The loss Sea lice are one of the most prevalent problems still affecting salmon farmers in Europe. If the lice are left untreated they cause considerable damage to the epithelium of the fish which, in turn, leads to large losses of stock. However, sometimes the treatment itself can prove problematic; this example shows how. In this case, the farmer had carried out many treatments before using the same method, and had experienced no problems. On this occasion, however, he experienced a 40% kill of salmon in two of the three cages treated. The third cage treated experienced a kill of about 15% of the fish. In a good treatment, losses should be negligible.

Response There are a number of options being developed for the treatment of sea lice including recent, licenced 'in vitro' administrations, but at that time the most effective treatment available which complied with the appropriate legislative controls in Scotland was an organophosphate bath, based on the product sold under the name 'Aquagard'. For reasons which have not been identified, the reaction of salmon to the treatment can vary. The following variables are likely to be different in every treatment carried out:

- water temperature;
- water quality;
- metabolic rate of the fish;
- size and condition of the fish;
- general health of the fish.

These can give rise to adverse reactions. In this example (and in other similar 'bath treatment' incidents), the fish became lethargic and settled to the bottom of the cage net. Sometimes a panic reaction will also occur with fish actively swimming into the net floor. The net pulls in on itself under the weight of fish, which eventually suffocate. A farmer's natural reaction is to drop the net in order to give the fish more room. Unfortunately, this can make the problem worse, allowing the net close in on itself further.

The most consistent approach developed to attempt to eliminate such reactions from bath-type treatments involves a number of factors. These include:

- preparing the stock by starving for 24–48 hours in advance of bath treatment: this will reduce metabolic rate and therefore oxygen demand;
- enclosing the cage in a complete lightweight tarpaulin, oxygenating throughout the treatment and for a short time afterwards;
- ensuring that oxygenation is effective: concentrations should be monitored throughout the treatment;
- keeping the nets shallow throughout the treatment (2–3 m) and for several hours afterwards or until the stock has clearly recovered (so that stock can be easily observed and to reduce cage volume for minimising the amount of treating agent being used). It is important to observe the stock *at all times* not only during, but also *immediately after* the treatment.

If the fish begin to settle or dive into the net, water exchange in the cage must be increased as much as possible. Tarpaulins should be removed immediately. Fish pumps or boat engines (*outside the cage*) can be used to create currents through and around the cage. Ropes under the nets and buoys tied to lines attached to the net floor can be used as a precaution to stop the net bagging under the weight of the stock.

Keeping detailed records of difficult disease treatments allows farmers, over time, to develop the procedure that is most appropriate to their circumstances. It is also essential that all staff involved in treatments have received appropriate training and have been assessed for their understanding of the procedures and their ability to carry them out.

8.4.5 Case Study DL5: Operator error during a disease treatment

The farm A small freshwater farm producing salmon smolts. The operator and his staff are very experienced. The site had been established for a number of years at the time of this incident.

The loss Staff carried out a routine formalin-malachite green treatment to remove *Costia* from the fishes' gills. Five tanks were treated on a 'flush' basis (continuous water flow rather than a static bath), a method that had worked successfully in the past. The tanks were left unattended whilst staff assisted with a smolt transfer. When they returned a few hours later they found that nearly all the fish in one tank had died and that there were also high mortalities in two of the other tanks. The overall production loss for the fry came to about 30% for a treatment which normally causes no mortalities.

Response When the staff returned they immediately realised that the treatment had not flushed through the tanks properly and that some stock had been exposed to the flush treatment for longer than they should have been. The green tinge of the malachite is used as an indicator for this very reason. The water flow rate was increased immediately and the tanks flushed as quickly as possible. At low flows it is possible to create dead water areas in the tanks and this appears to have been the case in this particular incident.

Comment With any sort of disease treatment stock should *never* be left unattended. In this case, the tanks had always been attended in the past so water flows would have been adjusted to prevent the 'dead areas' occurring, and the staff would have ensured that the treatment was flushed thoroughly.

There are numerous examples of operators beginning similar treatments, sometimes shutting the water down completely, then going off to make a phone call or deal with something else and forgetting about the treatment altogether. It is very easy to be distracted in such circumstances and the best policy is to ensure that the treatment takes priority over other activities until completed. Familiarity with apparently routine tasks can bring about complacency. It is best that staff have a written routine to follow with checkpoints clearly indicated for any activity such as this.

8.5 EQUIPMENT AND SERVICES

As all fish farmers know, good equipment costs money; it may be possible to save a great deal of money, initially, by buying second hand or inferior grade. Similarly, savings may be made by installing equipment without professional advice and assistance.

However, such savings may be false economies, increasing insurance premiums and placing the stock at risk. The following examples illustrate the mistakes that can be made.

- Buying ordinary, non-specialist pipes and other plumbing for hatcheries. Hatchery-grade equipment is made from inert materials (such as plastics) that do not release toxic chemicals into the water. Minute concentrations of heavy metals such as cadmium, zinc or copper are lethal to fish and shellfish eggs and larvae.

- Buying second-hand wooden cage frames. It might seem prudent to buy these from a bankrupt farm or a farm which is investing in metal or plastic cages. However, the softwoods normally used are prone to attack by the shipworm *Teredo* (actually a mollusc), which burrows into the wood, leaving only a pin-sized hole on the surface but resulting in a structure similar to Swiss cheese on the inside. *Teredo*-infested timbers break up readily in storms, resulting in stock loss.
- Buying second-hand metal, plastic or rubber cages. Problems are not confined to wooden cages: all of the structures providing support and flotation are likely to deteriorate with age, particularly at the points of maximum stress or tension such as hinges, joints, mooring or net attachment points.
- Installing 'home made' anchors and moorings. Farmers prepared to spend money on new fish cages must also be prepared to invest in professionally-built and installed moorings.

Other common failings associated with equipment arise from the following.

- Poor maintenance or from extending the life of items such as cage nets beyond what has been recommended. Peter Crook (*Fish Farmer*, 1996) put very clearly the point that in aquaculture—a very young industry—the 'if it ain't broke don't fix it' attitude should not prevail as equipment cannot be regarded as being standardised to the extent that its working life can be predicted. Regular maintenance and replacement schedules should be an important feature of the farm operation.
- Poor understanding of the operation of equipment, including that used in monitoring. A manufacturer of seal scarers quotes an example of a farmer with cages in shallow water who had followed instructions to hang the scarer two metres below the cages by attaching it to two metres of cable more than the depth of the cage. The result was that the scarer became buried in the mud beneath the cage, the output was effectively smothered and the equipment was thus useless.
- Equipment designed to reduce risks around the farm is misused. Another example is the reliance on a faulty oxygen meter to monitor oxygen concentrations during a treatment for sea lice. Because the meter is there and in use, staff may rely on it and pay less attention to any signs in the behaviour of the fish that might indicate distress (see Case Study DL4).
- Equipment not suited to the site where it is to be installed. See Case Study EQF7 for an example of a disaster resulting from the installation of a steel-framed cage on an extremely exposed site.

Equipment failure can sometimes cause spectacular and sudden loss in land-based or floating units. However as is illustrated by Case Study WI3, equipment failure involved in the loss may be less direct; the loss as illustrated in this case study was merely exacerbated by a failed alarm system. EQF3-EQF5 demonstrate how equipment failures on land-based units can also directly contribute to loss.

EQF6-EQF10 are taken from offshore units (floating marine installations) and illustrate the two main areas of equipment-related loss still occurring at sea: cage and net failure. The latter situation in particular is still a prevalent cause of loss on marine cage farms and warrants elaboration. The following text was adapted from one of the authors (Kennedy) entry in the Sunderland Marine, Aquaculture Risk Management newsletter (year 2000).

Net failures (examples include case studies EQF1 and EQF2), are one of the more frequent equipment failures that cage farmers experience and generally are amongst the most costly. Net design and technology does not appear to have changed a great deal in the past few years although there are differences in how nets are handled as well as the renewed application of nets to particularly large cages (such as the Ocean Spar type cages and large 120–160 m circumference plastic circles).

8.5.1 Causes of net failure

1. Boat propeller nicking the net. When boats are pulling away from a cage, 'throttling up' can create a vortex and pull loose netting up onto the propeller.
2. Tearing during retrieval or deployment. On cage stanchions or boat fittings.
3. Catching on the sea bed, reef, anchor or debris as the result of a careless tow, shifted moorings or by locating cages on a site that has not been thoroughly inspected.
4. Net becoming unattached to the cage and allowing fish to escape (weak attachment or due to the cage collar or stanchion breaking during rough weather).
5. Predator (and malicious human) damage.
6. Poor storage, lack of maintenance and old age contributing to failure when stressed by storm, tide or handling of nets.
7. Poor or inappropriate design contributing to failure also during periods of stress.

Areas of loss described in 1–4 can generally be countered by the application of commonsense (and training), and by ensuring staff adhere to proven procedures. Many companies have drawn up 'operational manuals' and post appropriate summaries in work places, on boats, etc., reviewing these from time to time during routine meetings (where foremen and leading hands involved in activities under review are also present). All net handling procedures should be logged with appropriate comments relating to procedure or damage/repairs entered. Losses due to (5) are becoming infrequent, as predators will rarely damage a good, strong net. Malicious damage can arise, especially in respect of animal activists or disgruntled employees where a net is deliberately cut. Prevention of the latter is down to security and vigilance and the design or condition of the net is usually of little relevance.

The losses described under (6) and (7), on the other hand, are very dependent on the integrity of the net (and may also be influenced by handling procedures as appears to have been the case with the case history presented at the end of this section).

8.5.2 Factors affecting a net's integrity

Source of netting There are many producers worldwide, including Italy, Philippines, China, Taiwan and the USA. Once a reliable source of material is established, careful forward planning by the net manufacturer should ensure that the source of material remains constant. The farmer can influence this aspect by planning and submitting orders well in advance and by being clear in regard of the specifications for the order.

Material: nylon (polyamide) or polyester Most knotless nets are made from the former (lighter and cheaper), although some suggest that PES material is stronger and more resistant to fouling. They have similar UV resistance. Black material is considered better in this respect although one advantage of lighter-coloured material is that fish veer away from the net, reducing 'net on fish' damage. 'Nylon' is a common name for a polyamide of which there are hundreds of different types, which explains why 'nylon' nets from different suppliers (same denier and ply), may vary considerably in respect of breaking strain.

Knotless or knotted Almost always the former because of weight. Although considered stronger in relation to resisting 'running tears', knotted nets are heavier (have more material), are more costly (more material and expensive to build), and many operators believe that they increase the risk of 'net on fish' damage. They are also more subject to fouling and increase 'drag' in a current.

Weight and mesh size 'Weight' is one of the key factors looked at in respect of risk. This is a very site-specific requirement, with material of a higher breaking strain being heavier and more expensive, but essential in open sites with strong currents or exposed to stormy weather. They are also essential on larger cages where the stress of weights and handling on the net can be considerable. Twine size (e.g., 210/400 = 210 'denier' 400 'ply' or number of strands) is less informative than breaking strength which will vary between twines from different suppliers and whether expressed as 'wet', 'dry', 'point to point' or 'bar'. European standards use point to point (breaking strain on the diagonal where the ply is knotted or crosses), American standards favour 'bar' (taken on the square or halfway between knots). 'Bar' measured 'wet' probably best reflects a net's strength in use. For monitoring purposes, companies should work to a constant standard test measuring net deterioration against new or original breaking strain (e.g., minimum to be 75% of...). Mesh size is of relevance to stock size and net weight. For example, large mesh cages are appropriate for grower salmon or trout (but not smolts), less surface area (lower drag) and less fouling promoting better water exchange.

Net manufacture: supplier's reputation and conditions Generally, a net manufacturer who is prepared to visit the site and consult in situ will produce a finished product more suited to a specific situation. As with any equipment, manufacturers with a good reputation and who specialise in certain areas (e.g., make a lot of fish farm nets) are more likely to produce a better product and follow through with good after-sales support in the event of a problem arising. Look at conditions and standards regarding the contract. One Tasmanian net manufacturer (Netcraft Pty Ltd) outlined for us their standards, summarised below.

- Specification sheets supplied to the customer and upon acceptance of the order signed and returned to the assembler. Includes a drawing of the net.
- Stress test (breaking strain) of the netting provided.
- Manufacturer's warranty to be supplied with the net.
- After delivery the customer should inspect the net and sign a release to the assembler that the net has been built to an acceptable standard.
- Any alteration to the net after the net has been ordered or during the assembly should be in writing to protect the customer and supplier.

Design Design must suit purpose. For example, towing cages will put different stress on a net and require different fittings to nets intended only for holding stock. Activities involving net lifts should especially be considered in relation to design. Many salmon farmers incorporate 'rope lifting handles' into nets for tying back to stanchions during drying out. Design should always spread points of stress onto areas specifically reinforced to deal with this, and not directly onto the main net mesh. Common points of stress include cage panel corners (where net weights are attached), and water line attachment points. More successful designs have tended towards incorporating reinforcement panels (double netting) at these areas. In the case of lifting procedures this should only be applied to nets designed with this purpose in mind. For example this might involve fitting lifting handles onto the floor ropes with extensive reinforcing around the area. Single point attachment must be avoided.

Ropes and fittings Integral part of the design criteria. Where ropes are intended to carry stress of lifting and weights, specifications must be suitable. Increasing the number of wall ropes may add to the strength of a net but also increases the weight. Attachment points to collars should come off vertical ropes at the water line.

Antifoulants Reduce build-up of marine organisms and thereby reduce the need for net changes during a grow-out period. Can also enhance a net's life by reducing UV degradation and by reducing wear and tear experienced during cleaning. This is not always the case: we know of one product that came on the market which was shown to lower the breaking strain of the net mesh by 5–30%. Therefore care should be taken in using antifoulants, especially in respect of new (untrialled) products.

8.5.3 Deployment and maintenance of the net

The way in which a net is used and maintained by the operator has considerable relevance in ensuring that the integrity of the net remains at an acceptable standard. Even the best of nets will fail if they are not looked after and used correctly.

Use and cage collar compatible with design It is essential that a net is only deployed on the cage/collar that it has been built for. Failures often arise due to nets going onto incompatible collars. Ideally, cages and nets must be matched: new cages should be purchased with new nets unless cross compatibility is absolute. Nets 'too large' or 'too small' will not hang correctly and can become damaged, in the case of the former by snagging on the collar, and in the latter attachment points can break.

Handling of net (deployment and retrieval by staff) The most common cause of net damage is snagging or tearing during handling by staff. When staff are vigilant, even if a net is snagged and damaged, this should not contribute to stock losses. Snags are less common on deployment but divers should still check the net before stock is introduced. Retrieval should be followed by cleaning and full inspection, which in most cases will cover such events. If for some reason a net is retrieved for immediate redeployment elsewhere, it must be thoroughly checked first. Handling events, in situ repairs, net changes and inspections should always be logged and signed off by the foreman in charge.

Storage and shore handling of nets Problems arising from poor storage include vermin damage (rats nesting in rolled-up nets), UV damage from nets being stored in the open, nets being left rolled up in a dirty state, and heat from the decomposition of attached plant and animal matter causing damage (not to mention a bad smell). Even if damage is not obvious, life expectancy of a net will be improved through proper care and storage.

- Store in a dry, well-aired loft out of direct sunlight.
- Only store cleaned nets, and tend to dirty nets as a priority.
- Don't allow the nets to be 'dragged' across the shore or over structures.
- Run a vermin control programme (poison) in storage areas.

Cleaning, maintenance and testing Nets should be cleaned promptly, followed by a full inspection with repairs initiated before storage. In some fish farming regions, independent net makers offer annual refit and certification services with nets being cleaned, repaired, tested (and even stored) before return to the operators.

Age and history of nets, record keeping (operational log and test sheet) One of the more obvious criteria in relation to the risk of net failure is age. With regard to all other aspects affecting a net's integrity, there will be a gradual weakening of net strength from exposure to UV, handling, wear and tear, accumulation of stresses imposed during use and even during storage. In general farmers should look to replace nets after a period ranging from 3–6 years, probably four on average and closer to three for large cage and exposed offshore farms. The specific acceptable period of use does depend on site characteristics, the initial quality of the net and the standards of annual overhaul, as well as the outcome of inspection and testing reports.

When a company owns a number of nets the only reliable way to ensure information pertaining to a net's age and history is for that net to be tagged (at manufacture), with an associated log maintained. This should extend to operational reports as well as 'net loft' reports (on maintenance and testing). Recently some manufacturers have begun to offer hand-held computer data logging systems for in situ record keeping by farm staff. Such records, as well as assisting the Insurers during loss investigations, will provide a useful management tool in relation to logistical planning (net replacement, deployment and quality control).

8.5.4 Summary

Below is a list of 'do's and don'ts' to consider.

Do

Train staff Hold meetings (and other forums) to improve staff awareness about handling problems associated with nets. Identify set procedures and ensure staff (and contract divers) follow them. Highlight responsibilities and the need to maintain net records.

Review design and operational aspects in relation to net handling practices. Avoid single point lifts and monitor 'high risk procedures' closely.

Develop and maintain net records as an integral part of the farm database.

Don't's

Neglect your nets either when in use or when in storage. Ensure damage is repaired and reported by staff immediately; a net maker may be required to fix temporary repairs but at least if tended to quickly these should prevent stock losses.

Abuse the nets Inappropriate use, lack of care and maintenance and careless handling, apart from leading to stock losses, might be interpreted as 'negligent' by Insurers, affecting your ability to claim under the policy.

Leave replacement net orders to the last minute Ensure the net manufacture has plenty of time to fill the order and is able to build a good-quality net to your specifications.

Be tempted to keep old nets Have these destroyed or recycled into non-fish farming use once the spec falls below acceptable standards. Establish what those standards are and discuss these (working life, etc.) with your Insurer before a loss happens.

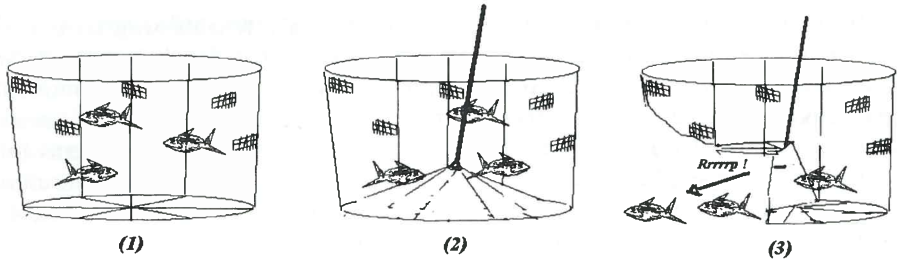


Figure 8.1. Failure off net being lifted by ropes.

8.5.5 Case Study EQF1: Net failure during handling

The farm In this example a tuna farm, but applies equally to a salmon or trout cage farm.

The loss A new approach being practised worldwide is the lifting of nets using a rope attached to a central point in the floor. Failure of the net during this procedure caused a significant loss on a farm in Australia. The sequence of events in respect of this particular loss is illustrated below. The net was being lifted to crowd fish for transfer into another cage. Close to the surface it split through the middle, completely across the floor (wall to wall), opening up the entire floor and allowing most fish to escape Figure 8.1.

Comment This process had been successfully used before, but clearly in this incident the net (three years old) was not up to it. During the lift one or more of the net floor ropes adjacent to the point where the lifting rope was attached (on the central 'donut') failed and the strain went directly onto the cage netting. This subsequently 'unzipped' along a cross rope (all the way to the net walls), as weight was transferred outwards from the point of attachment. It is probable that this was a failure waiting to happen and although it may have involved a 'weak' net, the lifting technique itself carries with it considerable risk of damage to a net not designed with this purpose in mind. It is a practice most farmers should not consider using, but if they do, they must have appropriate consideration for the risk, using only nets designed for the purpose and conducting the lift only under very careful supervision (e.g., using cameras or divers with sea to boat communications).

8.5.6 Case Study EQF2: Repeatedly torn nets on an exposed offshore site

The farm This is a true offshore salmon site in an extremely exposed location. It is frequently washed by a heavy Atlantic swell and the cages experience continuous and considerable movement. The cages are made from heavy-duty rubber and are well proven under such conditions.

The loss Each winter, between December and April, over a period of four years, nets tore and stock was lost. The cost to the insurers in this time exceeded £1,000,000. The cost to the farmer who had to carry the excess—and increasingly more expensive premiums—was also considerable.

Response This site is an incredibly difficult farm to operate. Yet despite the exposed conditions there were tremendous advantages in terms of stock performance. Fish growth and condition were consistently superb. The stock was able to be marketed at a premium because the company avoided all use of antibiotics or other therapeutic agents. The farm also provided a source of employment for locals in the remote site, many of whom were shareholders.

A solution was not reached overnight. A whole range of equipment aspects had to be tackled. Ultimately, however, losses were reduced to negligible levels by adopting the following strategy:

- A new design of heavy-duty net with shock absorber and chaff panels incorporated was deployed. All nets were upgraded and no net older than two years was used during the critical winter months.
- Heavy duty stanchions (redesigned to avoid chaffing nets) replaced the older stanchions.
- Numbers of fish in the cages were reduced considerably to about one-third of previous levels for the critical months. Marketable fish not harvested before the critical period were relocated to an inner, more sheltered, site.
- The infrastructure of the farm was improved with the purchase of a fish pump to allow quicker removal of stock and better control over stock movements.
- Maintenance schedules were upgraded.

The result was a dramatic improvement; since instigating the above strategies the company has operated without any loss resulting from torn nets.

8.5.7 Case Study EQF3: Fibreglass tank failure

The farm A salmon smolt unit producing about 120,000 fish every year.

The loss About eight months after the farm began production, one of the 5 m diameter fibreglass tanks split along the curve between the base and the side. At the time the tank contained about 12,000 parr at an average weight of 30 g; only a handful were recovered. The tank had been installed expertly and the seven other tanks in the building, all identical, were unaffected.

Response The loss happened while staff were in the building but it happened so suddenly that little could be done to prevent stock spilling onto the floor. The loss was below the level of the insurance excess and could not therefore be recovered against the stock insurer. However, the fibreglass tanks had been purchased from a reputable supplier and the cause of the loss was almost certainly a manufacturing fault. The farmer correctly notified the supplier immediately (and also his stock insurer who was prepared to assist with a compensation recovery).

Comment The damage was inspected by the supplier who agreed to replace the defective tank and compensate the farmer, in full, for the loss. Had the tank been purchased secondhand, without guarantees, or come from a less reputable supplier, or even been made by the farmer himself, there would probably have been no compensation.

This is a rare incident, genuinely not the fault of the farmer, although a total collapse and loss might still have been avoided if the tank had been partially buried with the bottom half metre supported by the surrounding substrate.

8.5.8 Case Study EQF4: Raceway collapse

The farm A trout production unit supplying stock for an associated put and take fishery. Most of the production came from 18 small 10 m × 1 m concrete raceways. In order to expand production, the farmer built a new 20 m × 5 m unit.

The loss With no warning, the outside wall of this raceway collapsed one morning, shortly after the fishery had opened for the day. Some 13,000 small trout were lost, most onto the adjacent ground and into the nearby river.

Response The farmer had built the raceway himself from breeze blocks. It had been in use for about four months and the blockwork had been expertly carried out. The design, however, was not adequate for the weight of water contained (approximately 100 tonnes) and it collapsed. Furthermore, because it was self-built there was no possibility of procuring compensation against a builder or supplier.

The operator was able to sustain the loss and rebuild the raceway. This time, however, the outer wall was backfilled to the extent that a path has been constructed along the length of the embankment. A recurrence of the incident looks to be unlikely although if more investment in the initial design had been made (or a reputable builder employed to do the job), the farmer would probably have saved himself the cost of this loss in the first instance.

Comment One of the lessons to be learned from this example is that scaling up from small or pilot-sized systems requires expert help. Simple calculations show the increase in the mass of the water involved in the above system.

A raceway measuring 10 m × 1 m × 1 m (depth of water) contains 10 m^3 water weighing 10 tonnes.

A raceway measuring 20 m × 5 m × 1 m (depth of water) contains 100 m^3 water weighing 100 tonnes.

For the same density, the larger of the two raceways will have ten times as many fish; any loss sustained due to failure of the raceway will therefore be ten times greater.

8.5.9 Case Study EQF5: Header tank collapse

The farm This case study concerns a well-established salmon smolt production unit with a gravity-fed water supply. In order to increase production the farmer built another unit which could hold 80,000 fish. To supply this unit he fitted a steel valve and pipeline to the existing glass fibre header tank. The water supply to the rest of the farm also came from this header tank. The new pipeline ran above the ground for five metres and was supported by wooden trestles.

The loss A few days before the salmon smolts were due to be transferred to sea, the steel valve and pipeline to the new unit tore out of the header tank. The tank collapsed and the water supply to the whole farm was cut off. The incident happened at night, and although alarms went off they were simply an audio system with no call-out facility. The farmer was not on the site at the time and did not discover the loss until he returned in the morning. Even if alarms and back-up systems had been available, the incident occurred so suddenly and was so catastrophic that it would have been difficult to save all the stock.

Response The tank was rebuilt and pipework reinstalled. This time, however, an engineer was called in to inspect the arrangement. He noted that the original failure came about as a result of movement of the pipe extension and advised that the pipe and valve be supported on a proper foundation (strapped into a concrete base), considerably more stable than the original wooden trestle arrangement. The alarm system was also upgraded with a telephone call-out link fitted.

Comment Although a very practical operator, this farmer should have called in expert advice when designing and installing the extension. With something as important as the water supply, it is essential that any modifications and systems are examined fully for weaknesses prior to their use. It is simply false economy to cut back on the expenditure on critical systems.

8.5.10 Case Study EQF6: Storm loss—steel cage failure brought on by mooring a barge alongside

The farm A sea cage salmon farm located at the landward end of a sea loch but exposed to the north/north west. The cages were constructed from steel and the unit was securely moored.

The loss Hurricane winds during February battered the group from its most exposed fetch. However, the group of cages might have escaped this storm without damage but for the fact that a large barge had been left moored alongside. During the storm, the barge actually landed on top of the group, destroying two cages and severely damaging moorings. Another four cages and their nets were also damaged. More than 8000 fish averaging 3 kg were lost.

Comment In this example the design of the cages was suitable for the site and they were almost brand new. Nets and moorings were also good. However, by leaving the barge tied alongside at a time when conditions were forecast to be bad, the farmer had created a situation which contributed significantly to the loss. In the turbulent seas the barge movement was far greater than that of the cages which were moored to the sea bed under tension. The movement and repeated battering of the barge onto the cages caused the loss.

Where barges and similar equipment are in use (e.g., netwashers on floating platforms, feeding barges), it is essential that independent moorings are maintained. The barges must be attached to these when not in use on the farm. Weather forecasts are not always perfect and, as a matter of routine, barges and boats should be removed to the independent moorings or pulled onto a slip, at the end of each working day.

8.5.11 Case Study EQF7: Storm loss—failure of a new design of steel cage

The farm This particular case study is based on a farm no longer in existence. It was established a number of years ago and lasted for less than one year. The operators decided to install 20 m × 20 m steel cages purchased through a reputable supplier. Although the cages were a new design, the supplier rated them for heavy duty and sold them on this basis.

The loss In the first winter during a very stormy period of weather, the cages broke up. The walkways snapped and, despite attempts to salvage stock, the farm finished up as a total write-off. It was never rebuilt and, although the insurers paid for the loss, the operators considered the operation to be beyond recovery and abandoned their investment.

Comment Guarantees against cage failure (extending to cover on the stock if lost through cage failure), are rarely given. Suppliers are in the business of selling and there are numerous examples of fish farmers purchasing a new design of cage in good faith, only to have it break up or sink in the first storm that comes along. Because they cannot deal with the cost of rectifying a design fault and supporting their product, some cage manufacturers may even end up going into liquidation. In such instances a farmer will have no hope of procuring a recovery except through their standard insurance arrangement.

Good advice is therefore to:

- buy tried and tested cage designs;
- buy from a supplier experienced in their material of construction (plastic, steel, etc.);
- obtain, wherever possible, both equipment and stock liability guarantees for at least the first year of a cage's use;
- ensure that the manufacturer offers good after-sales support (local suppliers have an advantage in this respect);

- make sure that the manufacturer installs the cages or supervises their installation by reputable, experienced contractors.

Failures of cages are not always so catastrophic: some types of cages are simply not suited to some sites. Examples include cages which distort under the effects of strong currents or others where hinges require constant maintenance even under normal operating conditions.

8.5.12 Case Study EQF8: Plastic cage failure on an exposed site during normal conditions

The farm An exposed 'offshore' site growing salmon in rubber cages. These had proved to be very successful, but expensive. The company wished to expand and was advised that plastic cages would be adequate. They chose two three-ring 80 m circumference plastic cages and installed these on the site.

The problem A very strong current runs through this site at speeds of up to two knots. Within a month of the cages being installed, and despite weather conditions throughout being calm, the cages had kinked and were in danger of breaking up.

Response The company acted quickly and the stock was salvaged without loss. Two new rubber cages were purchased and constructed around the plastic circles which were then dismantled and removed. No stock were lost and the plastic cage supplier agreed to refund the cost. It was a reputable company, but had underestimated the tidal influence on the site.

Comment Plastic circular cages are, in fact, generally excellent units, being low cost and low maintenance and yet very durable. Their integrity depends on the mooring design and the size of the circle. A lattice-type mooring design which avoids putting tension directly on the cage collar is the favoured system. With regard to circle size, smaller circles are the strongest with 50–70 m the most successful. As with all cages, it is essential that mooring systems, net attachment, anti-predator nets and weight systems have been discussed with and approved by the cage supplier, as poorly-designed ancillary systems can themselves contribute to cage damage.

8.5.13 Case Study EQF9: Problems on an exposed site resulting in its restricted use

The farm A sea cage operation located in the north of Scotland. This farm consisted initially of six plastic circles and was located at the head of a small loch. In the summer, water quality tended to be poor with higher temperatures and poor exchange hindering stock performance. A new site was established at the mouth of the loch, in an exposed location. Water exchange was excellent and stock performance visibly improved.

The loss In the first winter of operation the site experienced sustained storm conditions for around three days. The windward moorings dragged and the cage group came ashore. The nets were torn and most of the stock was lost. The moorings were improved and the farm continued into a second year. In the same period, mid-winter, stormy weather prevailed again. This time the moorings held, but debris was swept into the nets which ripped and a significant amount of the stock was lost.

The response The advantage of the outer site is that the better water exchange is beneficial to stock in summer, enhancing growth performance and reduced health problems. In the winter, however, with shorter days, reduced feeding and slower growth of stock, the advantage was only marginal. The risk of storm damage was clearly far greater.

The farmer therefore elected to run each site on a seasonal basis. Cages are located on the outer site and stocked with smolts for the summer. The cages, along with the fish, are brought in to the sheltered site for the winter. Moorings are maintained on both sites for convenience. Since adopting this strategy, the farmer has had no loss of equipment or stock due to storm conditions and production results remain excellent.

Comment Other companies adopting this strategy fare equally well, maximising their production in the summer on exposed sites with good water exchange, limiting their exposure in the winter by withdrawing to less favourable but more sheltered inshore sites. An additional benefit of operating such a system (particularly for the more sheltered site) is that one of the sites is left fallow, allowing the sea bed to recover from any organic input and breaking the life cycle of parasites.

8.6 OPERATING THE FARM

8.6.1 Alarm systems

These are most suitable for use in hatcheries and are essential in intensive recirculating systems. They can be used to alert the farmer to:

- **Changes in water level** These are likely to indicate blockages to inflow or outflow pipes which may occur through debris such as leaves or ice in the inflow, dead fish (outflow), or closure of valves.
- **PH** Decreases in pH usually accompany events such as rainfall or snowmelt. Increases in pH may be associated with the addition of seawater to freshwater units (sometimes used as an aid to smolt acclimation) and have the unwanted effect of increasing the toxicity of any ammonia present in the system.
- **Levels of dissolved oxygen in the water** The alarm can be set to function when the level drops towards the bottom of the range tolerated by the fish. When setting this level for this or any other factor, a safety margin should be calculated which allows time for an operator to reach the site and put in place emergency procedures.

- **Temperature** Where water is heated or cooled it is important to ensure that there are no failures causing sudden rises or falls of temperature.
- **Intruders** These can be humans, other mammals (rats, mink) or birds such as herons, cormorants or gulls. The detection part of the alarm system can be coupled to an audible scaring device.
- **Electricity supply interruptions** The alarm system should obviously be capable of functioning independently of the mains or normal electricity supply.

Alarm systems should be simple to install and operate. They should sound or produce signals where they are most likely to produce a response and be maintained regularly. Batteries should be changed or charged on a routine basis. Where rechargeable batteries are used, there should be two batteries or sets of batteries for each alarm system; one in use while the other is on charge. All farm workers should know exactly what to do if alerted by an alarm to a problem on the farm.

The golden rule with alarm systems is that the simpler they are, the more likely they are to operate reliably. If the system provides a record of the information this may help in taking precautions.

8.6.1.1 Actions to be taken if disaster strikes—or simply if changes from the norm are spotted

Obviously, the action to be taken depends on what has happened. However, some general points can be made:

- The person finding the problem should neither panic nor ignore it but should react according to their training and company instructions.
- Notify others who may be affected by the accident. This could include neighbouring farmers, insurers, pollution monitoring agencies.
- Take appropriate samples. Depending on the incident this could be samples of water, fish or feed. These samples should be taken with a view to being used as evidence, at worst in legal proceedings. They should be witnessed, stored or analysed with this in mind.
- Take photographs or video to give a clear record of the problem.
- Tighten security measures.
- The order in which these actions are taken will depend on the incident. For a localised incident within the farm, notifying outside agencies may be a relatively low priority: when the disaster is a result of pollution entering the farm from outside, notification of control agencies is a high priority.

8.6.2 Health and safety

Other equipment which must be of the highest standard relates to the safety of employees around the farm. In the UK employee safety is covered under the Health and Safety at Work Act 1974 of which COSHH regulations are an integral part. With regard to aquaculture this also covers the use of dichlorvos, antibiotics, fungicides, etc., to minimise the risk of accident to farm workers and ensure that equipment such as life jackets and survival suits are present and maintained if accidents do happen.

8.6.3 The food supply

The development of fish farm diets has removed much of the risk associated with the feeding of fish. These diets arrive on the farm in good condition; the farmer should need only to follow advice on feeding rates, practice and the appropriate size and grade of pellet to feed. Risks are introduced when feed is:

- stored badly, leading to the development of fungal toxins in the food and the breakdown of vital nutrients such as Vitamin C;
- left in opened bags or spilt around cages or ponds, encouraging the presence of predators or scavengers;
- not used in the correct rotation: newly delivered feed is used before old stock;
- badly distributed to the fish, inducing crowding and stress and causing growth differences to develop within a stock;
- of poor quality, including dusty feed (dust irritates and clogs gills) and feed that forms clumps owing to excessive oil on the surface of pellets. Much of this latter feed would be wasted, falling to the bed of the loch. Both these types should have been rejected. Some farmers keep a small, sealed and labelled sample from each batch of feed delivered to the farm in the deep freezer. If problems arise that might be food-related, this sample is available for analysis.

8.6.4 Drugs and chemicals

The purchase, storage, recording and use of drugs and chemicals is largely governed by regulations: fish farm managers must comply with these. If wrongly used, such substances are hazards to the health of the operators, the stock and to the environment. To avoid the risk of accidents associated with the use of hazardous substances the following guidelines must be observed.

- Always purchase the correct chemicals for the purpose intended. Chemicals associated with the food production industry are often of a higher grade than the standard equivalents and therefore more expensive.
- Make sure that you have a supply of the chemicals you are most likely to need in emergency but do not overbuy—keeping large quantities of dangerous chemicals on a farm causes its own problems.
- Store the chemicals safely, in the type of bunker or store approved by the Health and Safety Executive or other competent authority.
- Keep records of all purchases and use of chemicals.
- Use any hazardous substance as directed by the vet or as specified in the instructions supplied by the manufacturer.
- Make sure that all the staff using any hazardous substance are fully trained and aware of the consequences of misuse.

- Dispose of any drugs and chemicals past their use-by date in the manner laid down by the competent regulatory authority.

The farmer should be constantly on the look out for ways of minimising the use of hazardous chemicals on the farms. For example, many salmon farmers have reduced their use of such substances by improving their standards of husbandry.

- Reducing maximum stocking density: many salmon farmers have seen the benefits of improved growth and survival rates from reducing the density of salmon in cages to $10\,kg/m^3$ or below, having previously operated at twice or three times that level.
- Applying for and operating new sites so that year classes can be kept separate and new, disease-free fish are not infected from the older, longer-established fish.
- Leaving sites fallow for at least two months and preferably longer. This helps the seabed to recover and breaks the cycle for disease-causing organisms.
- Investigating alternative methods of controlling parasitic diseases (e.g., wrasse for sea lice on salmon farms).
- If chemicals or drugs have to be used they must be used correctly, ensuring effective treatments. In the long term this minimises the use of hazardous substances.
- Stocking with vaccinated fish. This will eliminate or greatly reduce the use of antibiotics on the farm.
- Regular net raising on cages, suction cleaning or pressure washing to reduce the use of anti-fouling paints.
- Pressure washing can create poor water quality conditions. Antifoulants have improved considerably and their uses are increasing all the time, especially on nets of $3500\,m^3$ plus. In such cases the benefits of antifouled nets outweigh possible disadvantages.
- Lists of antifoulants approved for use in aquaculture are kept by trade organisations.
- Instituting a programme of farm hygiene to reduce cross-contamination between cages or tanks.
- Routine use of 'dead socks' in cages. Mortalities can be collected and counted every day, reducing the use of divers (an added risk on the farm), removing a possible source of infection and enabling accurate daily counts of mortalities to be made.
- Record keeping and staff training (see below).

8.6.5 The human element

Most people appreciate that of all the factors making a successful fish farm, perhaps the most noticeable is a skilful workforce, taking an interest in the life of the farm. Several features go towards this.

- **Skills** The tasks carried out around any fish farm are varied and can be technically complex. The ability to carry out some of them well (e.g., fish feeding) comes from experience combined with an understanding of the consequences of bad practice, while others (first aid, boat handling, driving forklift trucks) are best learned by attending training courses, preferably designed with aquaculture in mind. In the UK, the development of vocational qualifications (such as the SVQ in Scotland), provides the means of assessing skills, recognising them with a qualification and finding out where there are deficiencies and more training is required. An unskilled worker will make mistakes or not be able to make decisions; this will lead to accidents around the farm, involving staff, stock or equipment.

- **Experience** The experience gained from frequent performance of tasks leads workers to recognise quickly when something is wrong (e.g., fish not feeding normally) which means that remedial action can be taken quickly, increasing the likelihood of disasters being averted.
- **Motivation** It has to be accepted as a fact of life that not all workers find fish farms such fascinating and rewarding places to work that they require no special motivation. Ideally, all workers realise that their observations and actions are vital to ensuring the health of the stock and the continued safe, efficient functioning of equipment. Ways of motivating staff include:
  —training, so that the consequences of actions and observations are fully understood;
  —sharing information, and reporting on actions taken as a consequence;
  —sharing responsibilities (see below).
  —providing financial incentives. Good, safe operation of farms, reduction in feed wastage, reduction in mortality, increase in harvest all should lead to increased revenue to the farm. Some farms operate a bonus scheme for workers based on improvements made. If all staff understand how their performance of their own daily work can contribute to the improvements, benefits are gained. Examples of activities that reduce risk on farms include increased observation of stock, reporting of any unusual behaviour of the fish or damage to equipment, increased care in handling equipment.
  —responsibility. Some farms give all workers special responsibility for tasks around the farm, sharing the tasks around the team. Besides the routine shared tasks such as fish feeding, net changing, etc., individuals might be given the task of a weekly check on all life rings on cages, checking all mooring points on cages, maintaining feed stores on cages, etc. All these tasks contribute to the overall effectiveness of the unit and any individual not doing his/her share is letting down the team and endangering the farm—and the team's bonus.
- **Making changes** There is a tendency in farms which are running perfectly well to make changes; these changes are often likely to increase the danger of things going wrong. Such changes include:
  —intensification: increasing the numbers of fish within the system; increasing feeding/growth rates.
  —increasing the size of the farm; operating new sites. One of the big problems

with expansion is that skilled staff are nearly always stretched much more thinly on the ground and that an increase in inexperienced husbandry people or trainees may lead to a disproportionate increase in losses as minor problems go unnoticed and develop into larger problems (see last point below).

—mechanisation: changing from manual operations to the use of machines (cranes, automatic feeders, pumps, graders).

—diversification: introducing new species to the farm or changing the specification to which the product is grown.

—changing feed type (brand, pellet size, fat content, pigment level).

—introducing new staff (at any level) to the farm.

- **Not making changes** Continuing in the same old ways may lead to complacency and a general lack of care around the farm. In addition to this, improvements in techniques and equipment are often beneficial to the running of the farm.

Small changes can have beneficial effects, counteracting the boredom that creeps in from continuing to carry out routine tasks year in and year out. Bigger changes need to be carefully thought through, ensuring that all staff have the skills and are given the training to cope.

8.6.6 Divers

The use of divers on farms introduces new risks and should therefore be reduced to the bare minimum. The operation of divers must conform to regulations relating to health and safety. Divers and their equipment should be disinfected when they come on to the farm and if they move between sites on the farm to avoid transfer of disease.

It is necessary to use professional or fully-trained amateur divers to check moorings and cage damage. It may *not* be necessary to use divers to collect mortalities from the bottom of cages: the use of dead socks or airlift systems should be investigated.

To use divers is becoming more and more common, with professional companies offering contract services. They are considered essential on Bridgestone-type cages and even Polar Cirkel type $3500\,m^3$ plus. Mortality recovery should be 2–3 × plus/week. This can be supplemented with underwater cameras, identify priority dive situations to maximise usefulness of divers. Always when contracting divers use professionals, check credentials and insist on disinfection.

8.6.7 Record keeping

The keeping of accurate, accessible records must be one of the best ways of ensuring that 'accidents' do not happen on fish and shellfish farms. Often what appears to have been an accident could have been avoided if accurate records had been kept and utilised as part of the management of the farm.

Records are also essential to the recovery of loss from insurers and must be complete before, during and after loss.

The following are some examples of problems that follow a predictable course and which are picked up quickly through the use of good records.

- **Mortalities relating to bacterial pathogens** (e.g., vibriosis, furunculosis). Such diseases are often characterised by a slow increase in the rate at which dead or dying fish are found in cages, for example one or two on day 1, four or five on day 2, 20–30 on day 3. Records kept for each tank or cage and checked daily by the health manager or site supervisor will give early indications of trouble and enable treatment to be given before losses are too great.
- **Catastrophic equipment failure** Records showing dates of inspection of cage hinges and moorings, for example, together with information from the inspection can help ensure that faults do not go undiscovered until storms cause cage break-up.
- **Predator damage** Signs of increased predator activity in the area (numbers of birds seen, fish in cages not feeding in the morning) should be reported. Any increase in signs of predators should trigger a check on defence and hygiene around the farm.

8.6.7.1 What records should the farmer keep?

Many farmers regard the effort of recording information as a tedious waste of time and restrict their records to the minimum required for legal and insurance reasons. At the other extreme are the farmers who make daily notes incorporating a wide range of information in such a haphazard fashion that the records serve no useful purpose. Records should:

- contain useful information (see below);
- be easily accessible;
- be organised;
- ideally, at least some of them should be recorded on a computer spreadsheet;
- be used!

Stock records

Keeping records detailing the performance of stock comes as second nature to an agricultural stockman: fish farmers should copy their example. Stock records, which may be kept as cage and tank records, should incorporate the following information:

- stock origin (source of eggs/smolts, and anything known of the strains from which they were bred);
- number stocked per cage;
- weekly or monthly mortalities;
- growth rates (taken from monthly sample weights);
- feed conversion rates;
- grilse percentage;
- operational details (grades, grilse harvests).

This information can be used to determine which strains perform best on a site in terms of growth, health and survival, and determine purchasing policy for future years.

Equipment records

In order to minimise the risk of equipment failure (cage or raft break up, leaking valves or taps on valves, etc.) records of equipment purchased and its maintenance should be kept. Regular checks on these records will help the farmer to determine which equipment is due for maintenance or replacement. It should also be possible, after a few years, to determine for example which cage types or sizes give the least trouble on the site. The maintenance record of moorings should also be recorded and the dates of future routine inspections noted.

Trade magazines and exhibitions should be used to glean information on new products that may perform better than existing equipment. Record keeping helps to identify persistent problems (e.g., hinge failure on cages).

Priority listings should be compiled for the maintenance of equipment, covering items such as:

- nets: use, storage, logs, etc.;
- cage collars: hinges, bolts, stanchions, etc.;
- moorings: checks, etc.

Weather records

It is important for the fish farmer to keep and use a few basic weather records. Over the years, these will give a good indication of how the stock on the farm will perform and likely problems. Two of the most important features of the weather to note are water temperature and storms.

The information can be linked to loss data and allow categorisation of risk levels according to the time of year. Many exposed sites reduce value at risk or remove equipment from sites during specific periods.

Water temperature records are important for the following reasons.

- Fish growth is temperature dependent. Prediction of growth rates based on temperature patterns means that the farmer can plan splitting, grading and harvesting operations and ensure that tanks or cages are not overstocked.
- The time of hatching and first feeding is largely dependent on temperature. The ability to predict the time of first feeding minimises losses through starvation at that stage.
- Much of aquaculture depends on the level of oxygen in the water. As temperatures rise, the fish has an increased demand for oxygen. Unfortunately, levels of oxygen dissolved in the water fall with rising temperature: these two features act together, leading towards disaster for the unprepared farmer.
- Activities, including grading, treatments and transfers, that stress fish and increase their oxygen demand should not be carried out at high temperatures.

If it is essential that the fish are stressed in this way, extra oxygen must be supplied to avoid the risk of mass stock mortality.

- The process of digestion itself uses up a great deal of oxygen. Monitoring temperatures will help the farmer to decide what time of day to feed and whether feeding should be discontinued completely.
- The appearance (or non-appearance) of algal blooms is temperature-related.

Information on exceptionally high winds and waves should also be recorded so that decisions can be made about checking moorings and cage hinges.

Storing the records

Records should be accessible and kept where they are needed. Most information should be kept in the farm office, where the manager can update it and inspect it readily. In addition, each cage or tank should have a waterproof record card attached giving simple information such as:

- cage, tank or raft number (assigned according to a plan kept on view in the farm office);
- stock origin;
- year class;
- details of feed (size, bags (or other quantity)/day, medicated);
- instructions not to feed prior to harvest or grading operations.

For sea sites or freshwater cages, a 'day book' should be kept either on the work boat or in the feed store on the cage group. This can be a very important information store. The site manager or other designated worker should use this book as a memory, transferring information to the main records kept in the farm office. The day book should be used to record:

- weather and environmental details such as water temperature;
- feeding: number of bags per cage, amount of feed transported to and stored on the cage groups;
- maintenance work carried out on the cages, such as net mending and checking safety equipment;
- mortalities: number of dead fish removed from each cage per visit;
- observations of fish behaviour, particularly when this differs from normal;
- indications of the presence of predators around the farm;
- treatments carried out;
- details of sample weighings;
- observations relating to wear and tear on cages, rafts, feeders, moorings;
- other observations, such as presence of lice or other parasites on the fish;
- algal monitoring: species, concentration.

This information should be transferred as a matter of routine to the main farm record book or computer, kept in the farm office. The use of spreadsheets for each cage enables information to be kept in an orderly fashion and changes (mortality, feeding rate, increased need for maintenance) easily observed.

Simple-to-operate computer spreadsheets, such as those that have been developed by the main feed suppliers, take all the strain (and inaccuracy) out of the calculation of feed conversion rates and mean that daily updates can be made.

The main records of the farm should contain all the information given above. In addition, they should contain information on:

- equipment purchases and maintenance: for example, it should be possible to check the history of each tank or cage;
- growth rates: calculated from information recorded daily;
- cumulative mortality rates;
- feed conversion rates: these should be calculated for each cage and the type of feed (pellet size, type (expanded, high energy, etc.) and maker recorded;
- transfers of fish around the farm and between sites;
- harvests: weights, numbers and destination;
- overall performance of stocks of different origin;
- record of visitors (name, company and purpose of visit).

Every farm office should have a master-list of important telephone numbers displayed in a convenient, accessible place. The obvious position is firmly attached to the wall near to the most frequently-used telephone. Examples of vital numbers are:

- farm manager or owner;
- vet;
- local pollution inspector;
- Environmental Health Officer;
- hospital;
- doctor's surgery;
- maintenance engineers for vital equipment;
- insurance company. Notifying the insurance company early is essential to loss recovery. The company can often assist with the procedure to minimise loss, and may even have their own contacts, vets, salvage, etc., which they may wish to send on the site.

In the UK all emergency services (police, fire brigade, coastguard ambulance) can be contacted by the 999 service. They are likely to arrive on the scene more quickly if given accurate directions. To aid this, the grid reference of each of the farm sites should be on the list of vital numbers.

Do not make the list too big—just have the life-or-death numbers!

8.6.8 Staff responsibilities

On all fish farms, no matter what the size, there must be a very clear plan showing where responsibilities for actions and reporting lie. Major disasters have occurred when observations on fish behaviour or signs of wear and tear on equipment have been ignored. Every member of staff should:

- have clear instructions on the work to be carried out each day/week;
- be on the lookout for any signs of trouble—this might be a change in behaviour of the fish at feeding time (possibly indicating an outbreak of disease or the presence of predators in the vicinity) or wear to equipment such as cages or ropes;
- be aware of the consequences of prompt action—or failure to take prompt action;
- have clear instructions on methods of reporting and recording information. It is very important that all workers know who to report to with urgent information. This should be true not only during 'normal' working hours but also at weekends and in the evening;
- have taken part in practice emergencies. Farm managers should spring simulated emergencies on their staff and then carry out an analysis of reactions. Such emergencies might include man-overboard drill, pump failure or a visit from safety inspectorate (nothing should need doing!);
- report any dying fish in a cage.
- check *every* alarm which sounds or otherwise indicates failures. Do not assume that such alarms are false alarms, even if the monitoring system is known to be unreliable. (Monitoring systems should not, of course, be unreliable!) In one case an alarm was ignored and unreported and 25,000 smolts died as a result of a blockage of the water supply system.

8.6.9 Case studies

The following case studies all relate to water intakes and problems where alarms have either not been installed or have not been effective.

There are two approaches to preventing loss from water interruption. The first is prevention and involves design, particularly of intake and supply systems. The second approach involves the ability of the farmer to react quickly once a problem does develop; this concerns alarms and backup systems. As a rule of thumb it is usual to make sure that every essential item has a backup (intakes, pumps, power, ensuring that alarms have an independent power supply and sometimes dual transmission capability, for example radio and telephone). Staff must be practised in handling emergency drills (pump replacement, know how divers, engineers, electricians, etc., should be contacted). Finally, backup systems and alarms are only as good as they are reliable and must be maintained and checked regularly, with checks recorded in a log-book.

It is very rare now for insurance companies to accept cover on land-based units where essential systems such as water supplies are not monitored by alarms. It is likely that insurers' requirements will extend to regular inspection of the systems.

8.6.9.1 Case Study WI1: Blocked intake in a smolt unit

The farm This case study concerns a salmon smolt unit in its first year of production, situated on a remote mountain catchment. At the time of the incident the unit was stocked with 200,000 salmon at 35 g. The farm consisted of several large tanks supplied by a single water intake. The latter consisted of an 18-in pipe set 7-ft down in a 14-ft natural rock pool.

The loss Shortly before the smolts were due to go out to sea the intake became clogged with an old carpet. The increased suction drew leaves, etc., onto the rest of the screen, reducing the flow of water to a trickle. All 200,000 smolts died of asphyxiation. The incident occurred at night when the site was unmanned; the system was not alarmed.

Response: Before the incident the farmer had assumed that the size of the supply line, the depth of the intake and the generally debris-free nature of the river made a blockage a remote possibility. Furthermore, he is a professional diver and checked/cleaned the intake routinely, two or three times a week. In all likelihood, if the incident had happened during the day the problem would have been detected by staff and a loss prevented. However, invariably such losses occur when sites are unmanned. The intake design was good but there were no backup alarm systems to provide cover when staff were absent.

If flow alarms had been fitted to each tank and if the alarm system had been linked to a telephone call-out system to alert staff, the problem would have been detected at an early stage and the chances are that most of the stock could have been saved. Oxygen could have been supplied directly to each tank until the intake screen was cleared.

Alarms are now fitted and tanks have been fitted with a stand-by aeration system linked to a blower unit.

8.6.9.2 Case Study WI2: Accidental closure of valve

The farm A small smolt unit located in a field and capable of producing some 30,000 fish each year for the company's ongrowing operations. The water supply was piped underground with the flow controlled by a large lever-type valve. This was fitted to the supply line close to the ground where it emerged adjacent to the four glassfibre tanks. The unit was checked twice daily, morning and evening.

The loss At night sheep in the field would often seek shelter around the tanks. One night a sheep chose the valve control lever to rub up against. This action closed the valve, shutting the water supply down and led to the loss of all fish. The system was not alarmed.

Response This was a small unit auxiliary to the main hatchery and the farmer had considered it to be a simple system not requiring alarms. The potential danger of livestock causing damage had not been considered. If alarms had been fitted the problem would have been detected and a loss prevented. If the site had been fenced off to keep stock out or the valve locked in the open position (some designs allow for this), the chances are the problem wouldn't have occurred at all.

The farmer still hasn't fitted alarms to this site but the unit has been fenced off securely and there have been no further problems.

8.6.9.3 Case Study WI3: Blocked intake and failed alarm system

The farm A large trout and salmon unit situated on a spate river system, consisting of ten glass fibre tanks supplied from a screened intake set below a weir on the river.

The loss In a tremendous storm with torrential rain and lightning, the river went quickly into spate. Shingle and debris blocked the intake, reducing the flow to the farm. The tanks were fitted with alarms and linked to a telephone call out of the system and should have alerted the owner. However, the lightning had knocked out the electricity and telephones, immobilising the alarm system.

Response The alarm system now has battery backup and the telephone call-out unit has been supplemented with a radio call-out unit to provide full cover. The river intake system was also modified with a second intake put in to provide additional security.

Comment Had the alarm system worked, oxygen could have been supplied to the fish, the screen cleaned and the loss mitigated. The farmer's error was not to foresee that the catastrophic type of situation which might cause such a loss could also disable his alarm system.

8.6.9.4 Case Study WI4: Blocked pipeline and failed alarm

The farm A small but efficient smolt unit supplied via a long 12 inch polythene pipe, fed from a screened intake in a loch above the site. At the time of this incident eight glass fibre tanks contained some 160,000 salmon fry.

The loss An eel worked its way past the screen at the intake and became lodged in the ball valve supplying one line of tanks. The flow was reduced and a good proportion of the fry died from asphyxiation. The incident occurred at night and, although the system was alarmed, the alarm was not triggered. The reason for this was that the sensor only measured pressure in the main supply line. The blockage was below this point, which meant that the water pressure in the system behind the blockage remained unaffected. Some water was getting to the tanks affected by the blocked valve but not enough to sustain the fish.

Response The farmer has now fitted alarms to each tank on the farm, which monitor the flow coming out of each inlet pipe. If the flow is reduced a float switch tilts, triggering the alarm. He also built a box with a lid around the screen at the intake supply line, to prevent eels from getting into the system again. There has been no recurrence of this loss.

8.7 THE RISK MANAGEMENT STRATEGY: LEARNING FROM LOSS

'Risk management' is all about being prepared: utilising previous experience and acquired knowledge from other sources, in order to develop a strategy to deal with future incidents. To benefit from previous experience:

- determine if any of your neighbours have a similar problem, e.g., oil spills (Alaska/Galicia/Shetland/Pembroke);
- start enquiries to determine if anyone has had similar experiences in the past. Take advantage of the information to learn from their experiences/mistakes/success. Information can be sought from associations, insurers and monitoring bodies.
- Keep detailed records of any incident and post analyisis, to help others in the future.

Use this post analysis period to improve existing risk-management strategies. If no such strategy exists, then take the immediate step of instigating a plan. This will be in three parts and deal with the following activities.

- prevention of loss before it arises;
- mitigation of loss during an incident;
- recovery from loss physically and financially

8.7.1 Prevention

A list of potential hazards should be drawn up based on an analysis of past problems specific to a site, and of potential problems. The latter can be determined from analysing the type of case studies listed in this book, from reading industry publications and from discussion with other farming groups. A 'what if' analysis applied to a specific site should identify the potential damage that might arise from the listed hazards. Concurrently it may be possible to identify affordable steps that can be implemented immediately to prevent or reduce the impact of identified hazards, on the stock.

Some examples of loss prevention steps have already been referred to in this text. These and others include: installation of a backup generator; installation of backup air blowers; instigation of a maintenance plan; setting up a health management plan; instigating staff training; participating in an 'area management' scheme; and developing site-specific stock management plans that minimise exposure to specific perils occurring at different times of the year.

8.7.2 Mitigation of loss

It is not possible to identify every hazard nor to predict accurately either the severity or the effect of various hazards on stock at different sites and different times. Inevitably, a problem will arise which will compromise stock. At this point all activities should be directed at protecting the stock from as much damage as possible and, by doing so, ameliorating the impact of the problem. In an emergency situation, *staff must act quickly and take the best possible course of action in the shortest possible time* if 'mitigation' is to be effective.

In respect of this goal, the 'risk management strategy' will be directed at setting up contingency plans for staff to follow in a specific situation. Where possible such plans will need to be tested, well before they need to be implemented, to ensure they achieve the aims of mitigating a loss and not exacerbating the situation. Certain equipment (such as spare moorings and nets), may need to be purchased and held on site, sources of additional equipment and skills (e.g., veterinary practices) must also be identified.

A mitigation plan is only effective if all staff are familiar with the procedures they need to follow. Inevitably major losses arise during holiday periods when managers are absent, so trainees and temporary staff must be well briefed in the plans and have written guidelines to refer to. A classic 'mitigation approach', for all aquaculture, is to remove stock from the site that is affected or being threatened by a hazard. For sea farms in particular this may involve towing cages to another location in order to temporarily hold the cages, for which pre-approval must be in place (legislative compliance). The location and route will also need to be vetted prior to use to ensure that it is free of hazard (especially in the case of algal blooms) and that the activity does not actually increase the risk of loss.

8.7.3 Recovery from loss

The way in which operators deal with the period following a significant loss can impact greatly on the future viability of a company. Even whilst dealing with the 'post analysis' activity aimed at preventing recurrence of a problem, it is important to take immediate steps to ensure that everything that can be done is done to get the business back to where it was before the loss. This will involve replacing lost equipment and lost stock. If a company has taken the step of insuring the same, and has involved their insurer in the problem as it has developed (in accordance with most policy rules), then financial settlement and replacement of lost equipment and lost stock will be more readily facilitated.

In the absence of insurance, alternative strategies must be assumed; these may include the ability to share or borrow facilities from another location and/or fund replacements from company reserves set aside for this purpose. Insurance is not always able to provide for stock replacement and this is particularly the case for geographically limited areas which may have a small industry (such as the New Zealand or Tasmanian salmon farming industries), where replacement stocks are simply not available and cannot be imported. In such cases a plan involving mutually-interested parties could be instigated to provide an industry pool of 'reserve stocks' (e.g., eggs, juvenile fry) on which members can draw in the event of a loss. Such plans are generally limited to early development stages of the fish and are better implemented in conjunction with rather than as a replacement for, insurance.

A recovery plan identifies the 'how', 'where from' and 'when' of replacement. The last—the timing of replacement—requires certain considerations. Restocking a unit or replacing equipment immediately following a loss can have tremendous positive benefits to staff (improving morale) and shareholders, as well as secure the future viability of the operation.

But if this is done so without proper analysis of the loss and before steps are implemented to prevent a recurrence, the risk of further and an often quickly-repeated loss may be increased! The repercussions of a repeat loss are even more devastating to the extent that insurance cover may be withdrawn, shareholders may remove their support and staff morale will be affected to the point that many may opt to leave.

Risk management is about planning for the expected and unexpected, it is about commonsense and good management. It allows farmers to build their business with a greater degree of certainty and provides staff, shareholders and other interested parties the confidence to support the farmer in achieving this goal.

9

Environmental considerations and legislative control of marine salmon farming

9.1 ENVIRONMENTAL IMPACTS AND EFFECTS

As with nearly all forms of aquaculture and agriculture, marine fish farming has impacts on the environment. Several of these have been well understood for many years, other impacts are only now being fully appreciated and some are still rather controversial and subject to ongoing scientific research.

A summary of the various impacts associated with the development of marine fish farming in Scotland is given in Table 9.1. The following sections provide a review of evidence of the nature and scale of the effects of marine salmon farms on the environment; and where scientific studies are ongoing, or are less definitive, there is a more general discussion of our present understanding of these more contemporary issues. The arrangement of these sections follows that of Table 9.1.

9.1.1 Feed and faeces

One of the major impacts from marine farms on the environment results from smothering and enrichment of the seabed around farm cages. This arises from the waste feed and fish faeces although the former, having a much more rapid sinking rate, is usually considered to be the greatest source of accumulation on the seabed despite recent successes in reducing the sinking rate of food pellets.

As one indication of the total amount, it is estimated that the organic wastes going into the sea from all existing Norwegian and Scottish salmon farms represents sewage discharges, after treatment, of the equivalent of a human population of 52 million, roughly the size of the United Kingdom (assuming a 90% reduction of phosphorus from the treatment plant, based on Pillay, 1992). Willoughby (1999) estimates that a fish farm producing 100 tonnes of salmon per year is equivalent in phosphorus releases to 764 people without municipal waste water treatment. Such

Table 9.1. Summary of potential environmental impacts associated with salmon farming.

Activity/ release	Cause of impact/ source of environmental disturbance	Potential environmental consequence/concern	Incidence of impact
Effluent/waste discharges	Faecal material Waste food falling through cages	Benthos: smothering and enrichment of benthos immediately below and adjacent to cages	Local
		Water quality: hypernutrification of water column	Local/ regional
	Chemical releases: disinfectants pesticides	Lethal effects to some organisms Sub-lethal effects on other organisms	Local Regional
	Antibiotics	Build up of resistance to antibiotics in the environment	Regional
Escapees	Release of genetically selected or non-indigenous strains of fish	Loss of genetic diversity in wild population	Regional
Disease and parasites	Sea lice	Increased infestation of sea lice on wild sea trout and salmon may lead to mortalities in wild stock especially in smolt (juvenile) stage	Local/ regional
	Other diseases and/ or parasites	Potential spread to wild stock or other farmed fish	Local/ regional
Physical presence	Aesthetic impact	Cages and landbases: detract from amenity value for both locals and visitors	Local/ regional
	Interaction with other users	May restrict freedom of other users: e.g., fisheries, shellfish farms, navigation, pipelines/cables, waste disposal, recreational uses, etc	Local
	Predator control	Seals may be shot if they are a persistent problem Birds may become entangled in netting	Local
Wider environmental concerns	Industrial fishing, energy consumption and greenhouse gas emissions associated with production of feed, etc	Climate change Environmental impacts of industrial fisheries supplying fish meal (e.g., sandeel fishery)	Global Regional

calculations, however, ignore the very localised impacts of these discharges and the comparatively huge inputs of nutrients from other land-based sources such as agriculture.

Where major accumulations are found, the natural sediment is smothered and aerobic bacterial activity on the surface of the accumulation can reduce oxygen levels. Beneath the sediment surface layer anaerobic bacteria can pose a different threat with production of hydrogen sulphide from sulphate in the waste. Other products of bacterial activity include methane, which in extreme conditions may be observed bubbling to the surface and, in this way, can increase the transport of hydrogen sulphide to surface waters.

The major effects on seabed sediments are well understood and have been rigorously studied. Where such large accumulations occur the naturally-occurring faunal community is smothered; the most obvious indicator of this type of pollution is the presence of the sulphur oxidising bacterium *Beggiatoa* (often referred to as sewage fungus) forming a surface mat over the wastes. Beyond this the wastes give rise to significant organic enrichment of the sediments and usually very high numbers of opportunist species (e.g., *Capitella* and *Scolelepis*, both polychaete worms) dominate. The total biomass of these communities is much greater than on equivalent seabed habitats not subjected to organic enrichment, but the biological diversity is hugely reduced. The range of effect on the seabed varies widely from site to site. Generally the area of the benthos affected may extend 20–50 m from the cages, although in extreme cases such effects have been observed up to 150 m from the cages. With the benefit of scientific modelling studies on the dispersion of solid wastes, the Scottish Environment Protection Agency's (SEPA) permitting procedures are able to take into account these potential effects for new farms and consents to discharge for a specified maximum consented biomass can be established accordingly (see Section 9.2.6). Where existing farming operations have demonstrated significant effects on the benthos the fallowing of sites may be an appropriate mitigation.

Of particular concern, however, is the potential for smothering of critical seabed habitats. Several marine biotopes have been identified as priority national marine habitats in the UK by the National Biodiversity Action Planning Steering Group and special considerations should apply when siting cages adjacent to these (e.g., *Mya truncata*/*Venerupis senegalensis* communities in fully marine conditions, a rare association of species found on mixed sediments). Similarly some areas of the seabed may be particularly important as nursery grounds for fish and other marine species (e.g., flatfish nursery grounds in enclosed sandy bays, and cobbled seabeds which are essential habitats for newly-settled juvenile lobsters).

9.1.2 Nutrients dispersed in the water column

Although solid material falls toward the seabed other excretory products are dispersed directly in the water column. Biological activity on the seabed also releases nutrients into the water column. It has been estimated that up to 60% of total phosphorus and 80% of total nitrogen wastes from farming operations will end up in the water column (Holby and Hall, 1992; Hall *et al.*, 1992). Some temporary elevation of ammonia levels may be evident around marine sites not subject to much tidal movement, but generally studies have failed to demonstrate clear effects on productivity in marine waters and only weak relationships with other factors such as total nutrient loadings. Some studies have indicated strong correlations between total fish farm loading and dissolved nutrient levels (Wallin and Håkanson, 1991), but generally at marine sites dilution is rapid and subsequent dispersion is immediate. Concerns continue to exist, however, regarding these nutrient effects, particularly in relation to toxic algal blooms, although it is widely recognised that in many areas nutrient inputs from the land (especially from agricultural land) well exceed those from fish farming operations. It has been estimated that in Scapa Flow, Orkney, for example, only some 6% of the total nutrient load is derived from marine fish farming with approaching 60% from agricultural sources (Chadwick, 1999).

9.1.3 Chemical use

A range of chemicals is used in marine fish farming operations, principally chemotherapeutants, antifouling treatments and cleaning materials such as disinfectants.

Antifouling treatments are by their nature toxic to marine organisms. Many treatments are based on copper, and studies in Norway by Vikla and Kaasa (1995) have estimated that some 156 tonnes of copper were released into the environment from the use of antifouling treatments in salmon farms in 1994. Where nets are cleaned *in situ* (by methods such as high pressure hosing), an additional organic load occurs from the deposit of the fouling organisms removed. Research continues into environmentally-friendly antifoulants and other methods of reducing the impact of fouling organisms (Clare, 1995).

Chemotherapeutants are used as antibacterial, antifungal and antiparasite treatments. Records of use of antibacterial agents have been kept in Norway and, following the introduction of effective vaccines and improved husbandry, show significant reductions in use from around 1 kg per tonne of fish produced in 1987 to present-day levels of 3 g per tonne of fish produced. The half-life of these chemicals varies considerably from a few hours in the case of Nifurazolidon, for example, to 6–12 months in the case of oxolinic acid (Samuelson *et al.*, 1992). A range of treatments is used in the treatment of sea lice infestation, with the earlier short-lived but highly toxic, organophosphates (dichlorvos; Nuvan$^{\circledR}$) being phased out. Hydrogen peroxide is currently used as a potentially less harmful treatment for sea lice infestations but is not always effective and may even be hazardous to fish and human health. Non-chemical methods have also been explored. Some effort has been spent researching the efficacy of wrasse as 'cleaner fish', stocked alongside farmed salmon (Treasurer, 1993; Kvenseth, 1996). Their use in Norway is increasing, although elsewhere, for example in Scotland, the use of wrasse to control sea lice numbers on farmed salmon is rare.

9.1.3.1 Antibiotic resistance

The development of new chemotherapeutants is driven both by the need to meet increasingly stringent environmental standards and by the tendency for pathogens to develop resistance to chemical treatments over time. Intense chemical use exerts a severe selective pressure on infectious agents. Resistance to chemical treatments has been reported in sea lice (Jones *et al.*, 1992), *Vibrio salmonicida*, which causes cold water vibriosis (Husevåg *et al.*, 1991) and *Aeromonas salmonicida* (Hjeltnes *et al.*, 1987). This creates problems for fish farmers, but is also potentially damaging to wild salmonids if their immune function cannot cope with altered mechanisms of pathogenicity. There is no current evidence to suggest that these 'mutated' agents cause any more damage in the wild than the previous agent of the same species, assuming that it is a species which is already indigenous to a region (McVicar, 1997). It is likely that mutated agents are only damaging under stressful conditions, e.g., the farmed environment, and that in the wild their pathogenicity is much reduced or insignificant. While the precise bioavailability of antibacterial substances trapped in the sediments is a matter of some conjecture, those which break down slowly in the marine environment, or which are used for extensive periods, can only lead to an increase in the proportion of resistant bacteria. Antibiotic half-life may be an important selection criterion in the future.

9.1.4 Escapee farmed salmon

In the relatively short time (possibly less than 10 generations) over which the Atlantic salmon (*Salmo salar*) has become domesticated, its character has been altered by exposure to artificial conditions and selective breeding programmes. Changes in the genetic character of farmed salmon (expanded in Chapter 12) manifest as altered behavioural, morphological and life history traits, relative to their wild counterparts. Yet certain fundamental life history instincts appear unchanged, e.g., the urge to migrate and to spawn. Escapee farmed salmon have been observed exhibiting similar patterns of sea and freshwater migration as wild salmon. Some concern exists regarding the overall effect of interactions between farmed and wild salmon, especially during freshwater migration, spawning and subsequently in the early juvenile stages. Escapee farmed salmon may breed and compete with wild salmon. Possibly the most worrying consequences of this phenomenon are changes in the genetic character of wild stocks as a result, particularly where genetic modification of farmed fish is planned. The significance of this possibility largely depends on the theory of local adaptation, which is examined in Section 9.1.4.1. The potential for interactions between farmed and wild salmon at the adult and juvenile stages to impinge on locally adapted populations of Atlantic salmon is then reviewed.

9.1.4.1 Local adaptation in wild salmon

The potential for farmed salmon to have a genetic impact on wild populations depends largely on the degree of biological diversity that exists between farmed and wild salmon as well as between different stocks of wild salmon (Verspoor, 1997). The homing instinct of Atlantic salmon serves to segregate wild salmon into distinct populations native to individual rivers or even individual tributaries within a single river system (Youngson *et al.*, 1994). It is generally accepted that strong genetic differentiation exists between wild stocks segregated in this manner (Jordan and Youngson, 1991; Taylor, 1991; Youngson *et al.*, 1991; Jordan *et al.*, 1992). Such differentiation occurs as a result of reproductive isolation and appears to be temporally stable, at least in the short to medium term (Jordan *et al.*, 1992). However, evidence of historical gene flow between different populations exists, which has enabled the identification of regional 'meta-populations' of Atlantic salmon, i.e., North American, European Atlantic and European Baltic strains. Tagging studies suggest that current rates of gene flow are very low (Youngson *et al.*, 1994; Hay, 1995), although such temporally discrete studies might miss episodes of gene flow between populations, which might arise as a result of unusual demographic or environmental conditions. The recent recolonisation of the River Clyde, Scotland, exemplifies such a phenomenon.

Pressures of natural selection owing to variable environmental conditions also contribute to genetic differentiation over successive generations. Wild salmon populations have been progressively equipped with the traits that allow them to survive successfully under the prevailing environmental conditions in their natal river. Whether this constitutes qualitative genetic differences or simply quantitative variation in gene expression is debated (McGinnity *et al.*, 1997). It seems clear that variation in quantitative traits is crucial to survival and recruitment under local conditions and, consequently, such traits are strongly heritable. Morphological traits such as body shape and fin size vary with water flow characteristics. Salmon in the Miramichi river, in the New Brunswick region of Canada, have been found to possess more fusiform bodies and larger fins, complementing the fast-flowing conditions present in the river (Riddell *et al.*, 1981). One might expect similar adaptations in salmon populations in the steep, fast-flowing rivers characteristic of the north-west coast of Scotland relative to the slower flowing waters in most east-coast rivers. Timing of juveniles migrating to sea as smolts has been associated with growth rates (Fleming, 1996) although Youngson *et al.* (1994) suggest that the timing of migration also has a strong heritable, thus genetic, basis. In rivers where pH levels are typically low, local populations have adapted to produce eggs that survive more successfully under such conditions rather than at more neutral pH values (Donaghy and Verspoor, 1997). Variable tolerance to parasitic infection has also been noticed in Baltic Sea populations of Atlantic salmon which are more resistant to infection by the monogenean fluke *Gyrodactylus salaris*, relative to wild Norwegian and Scottish strains (Bakke and MacKenzie, 1993; Rintamäki-Kinnunen and Valtonen, 1996). Studies have also indicated that variation in expression of the MEP-2* gene, which codes for malic enzyme, or a very similar gene, is strongly related to growth. The fact that growth is strongly dependent on temperature, and temperature varies with latitude, underpins the theory that genetic differentiation between populations is an adaptive response mediated by natural selection (Jordan *et al.*, 1990; Jordan and Youngson, 1991). So, local adaptations may develop on both a micro- and macro-geographical scale and a substantial body of evidence has accumulated, firmly indicating that this genetic plasticity, which controls the ultimate form and behaviour of the Atlantic salmon, is fundamental to survival throughout its range.

9.1.4.2 Farmed salmon genetics

Farmed salmon strains, derived mostly from wild Norwegian salmon, are genetically distinct and lack the freshwater experiences of their wild conspecifics. Selective breeding has also evolved faster-growing individuals that generally mature at an older age relative to wild salmon. Observations that life history behaviour is similar in escapee farmed fish mean they may interact with wild salmon at sea and in freshwater. Concern at the potential resulting impacts on wild populations mainly relates to genetic impacts incurred through interbreeding. Interbreeding was first noted in a study by Webb *et al.* (1991) and has been commonly recorded since in Scotland and elsewhere (Hindar *et al.*, 1991; Crozier, 1993; Webb *et al.*, 1993). As genetic character importantly reflects the environmental conditions and requirements in a salmon population's natal river, the erosion of such adaptive traits through interbreeding may affect survival and performance of wild populations. Additionally, the success of native populations may also be affected by physical competition between wild juveniles and hybrid progeny and/or farmed juveniles, the latter occurring as a result of escapes from freshwater juvenile rearing units.

9.1.4.3 Behaviour of adult escapees

Adult salmon that escape from sea cages generally exhibit behaviour typical of wild populations, depending on the time of year. Early in the year, escapees join oceanic migrating wild salmon, heading for feeding grounds in the far North Atlantic. Winter escapes suffer from the prevailing conditions and tend to have a much lower survival rate than those escaping during summer (Hansen and Jonsson, 1991). Those that reach the northern feeding grounds are commonly caught as part of the commercial fishery for wild salmon in these areas. Currently, farmed salmon are thought to make up around 20% of the annual catch in the commercial Faroese fishery, but this figure is thought to have been as high as 40% in previous years (Hansen *et al.*, 1999). Therefore, it is important that numbers of farmed salmon in a fishery are accounted for when trying to arrive at stock estimates for wild salmon and quota limits should be set accordingly. From feeding grounds, farmed salmon will return as adults to the general area from where they escaped. The actual time that is spent at sea varies, as well as their homing ability, which depends largely on the time of year the fish escaped and how old it was. Winter escapees exhibit poor homing ability, as do older fish (Hansen and Jonsson, 1994). However, some escaped fish at least will return to coastal areas with varying degrees of accuracy and will migrate into nearby rivers.

Farmed salmon seem to exhibit erratic behaviour when moving around in the freshwater environment. This apparent inefficiency is perhaps unsurprising: farmed fish have no experience of natural freshwater conditions. Farmed salmon have also been observed to arrive late to the spawning environment by which time much of the available space has been occupied by other fish. This may also be related to the timing of escape, as cultured salmon which have escaped as juveniles would appear to enter rivers before those which escape as adults (Jonsson *et al.*, 1990; Webb *et al.*, 1991). Confronted with the usual competitive superiority of wild adult salmon (research into the competitive abilities of cultured and wild juvenile salmon suggests a different scenario and this is discussed later), farmed fish are often forced to search widely for available spawning habitat. A further consequence of this late arrival is that when spawning, farmed females may excavate and destroy nests (redds) already created by wild salmon (Webb *et al.*, 1991). As well as having a competitive disadvantage, farmed fish also appear to have less success in the various aspects of the spawning ritual. In a review of the reproductive behaviour and success of cultured and wild Atlantic salmon, Fleming (1996) notes that farmed females exhibit less digging activity and construct fewer nests. These physical processes seem influential in attracting a mate and wild males have been shown to exhibit a preference for courting more active females. However, when farmed females do spawn, they are capable of producing as many eggs as wild fish. Farmed male fish would appear to be much less capable of spawning, even in the absence of wild males. Reproductive performance may be worsened by a lack of aggression relative to wild males. It is suggested that reduced aggression in cultured adults may be a result of artificial breeding programmes, where aggressive traits are relatively less important than high growth rates and high age of maturity in the selection process. Consequently, the presence of wild fish—especially active wild males—is important to the reproductive success of farmed females and the farmed female X wild male combination would be the most likely result of mixed spawning populations. Assuming that both wild and farmed fish are present in a river, the extent of interbreeding will also depend on the relative proportions of wild and farmed fish present. Although some large-scale escapes have occurred, e.g., in Loch Eriboll on the north coast of Scotland, only a very small proportion may enter nearby rivers (Webb *et al.*, 1991, 1993). However, many salmon rivers in Scotland are relatively small, especially those on the west coast, and ordinarily may support much fewer than 100 spawning females (Webb *et al.*, 1993). In various rivers on the west coast of Scotland, wild salmon runs have declined significantly (WRFT, 1999). Although there may be various reasons for such declines, the intrusion of farmed salmon into rivers with already depleted native populations may have the most noticeable effects.

9.1.4.4 Impact of hybrid and farmed juveniles

Whether or not the interaction described above will have an impact on native populations of Atlantic salmon also depends on the success of the resultant offspring. However, it is important to note at this stage that although many studies relate to the behaviour of hybrid salmon progeny (farm × wild cross), juveniles of pure farm origin should also be considered. Although the latter group may result from the less common combination of farm females × farm males in the wild, their presence is more commonly attributed to escapes from freshwater rearing units into adjacent rivers. It was mentioned earlier that homing accuracy and ability to enter the freshwater environment might be better in fish which escape at a younger age. These observations underpin research into other salmonid species that suggests that the reproductive success of cultured fish in the wild increases with time spent in the natural environment before maturing sexually, i.e., fish which escape earlier in their life history are likely to be more successful in survival and reproduction than fish which escape at a later stage (Taggart and Ferguson, 1986; Fleming *et al.*, 1997). In this light, escapes of juvenile parr should be perhaps be regarded as seriously as escapes of adult fish, yet little information exists regarding the effects of the former.

Most research into the impacts of farmed and hybrid juveniles on wild populations has taken place under closely-monitored hatchery conditions, where the behaviour of individual fish could be compared. Some vary from simple tank experiments to those involving the construction of complex simulated stream environments. Traits examined in hatchery experiments include aggression, dominance and response to predators, characteristics that probably have a significant bearing on juvenile survival and growth in the wild. Results vary depending on the trait examined and the degree of genetic differentiation between the farmed and wild strains being examined. Where some authors have observed cultured salmonid juveniles to be more aggressive and/or dominate wild fish (Swain and Riddell, 1990; Johnsson *et al.*, 1996; Einum and Fleming, 1997), the opposite pattern has also been observed (Berejikian *et al.*, 1996; Fleming and Einum, 1997). Fleming and Einum (1997) suggest that the outcome of such aggression/dominance experiments is context-dependent, i.e., wild juveniles may dominate farmed fish in more natural environments and vice versa. In each case, it is usually the stronger group that grows fastest in both artificial and natural conditions. It is also suggested that the genetic origins of wild and farmed salmon may have as strong an influence on the outcome of competition and growth experiments as the effects of the culture environment alone. Whatever the outcome of farm versus wild, hybrid fish in most cases exhibit an intermediate performance in the trait being examined. So, where Utter *et al.* (1993) may contend that 'interbreedings among genetically diverged salmonid populations are generally disadvantageous to the natural populations', the evidence above highlights the spurious nature of this statement, at least in terms of juvenile performance in artificial conditions.

More recent advances in DNA technology can enable the parentage of any individual fish to be determined accurately, removing the need for distinguishing tags or markers. Therefore, it has become possible to release mixed populations into natural freshwater environments and study their subsequent development in terms of survival, growth and territorial preference on recapture. Research on various salmonid species suggests that cultured offspring will survive less successfully in the wild relative to native offspring (Reisenbichler and MacIntyre, 1977; Chilicote *et al.*, 1986; McGinnity *et al.*, 1997). In certain instances, poor survival of juvenile farmed salmon can mostly be attributed to high rates of mortality between the eyed ova stage and the first summer (McGinnity *et al.*, 1997). However, Einum and Fleming (1997) have demonstrated that in the subsequent parr stage, survival of farmed and wild individuals in the wild can be similar. Salmonid parr are highly territorial and compete vigorously for available food and refuge resources. Territorial limits set during this stage are crucial to subsequent survival, growth and emigration. Given a similar geographic distribution of farm, hybrid and wild parr in a river, competition for space will probably occur and it is at this juncture that differential abilities in the traits examined under hatchery conditions may have noticeable consequences.

Greater growth rates are often noticeable in farmed and hybrid parr relative to wild parr and this is not surprising given that farmed strains have been selected to become very fast growing. Consequently, a situation may arise where hybrid or farmed juveniles may outcompete and displace wild fish (Einum and Fleming, 1997). McGinnity *et al.* (1997) noted that in a release experiment involving farmed, hybrid and wild parr, rates of wild parr emigration to other parts of a river were highest among wild fish, which also happened to be the smallest of the three groups of fish. Whether or not there is an alternative habitat to occupy may determine the overall effect in terms of, for example, overall smolt production from a river. Where parr numbers are naturally below the carrying capacity of a river or stream, the introduction of non-indigenous juveniles may increase the overall smolt production. When parr numbers are close to the local carrying capacity, farmed or hybrid fish may replace wild individuals. Whilst native smolt output may fall, overall smolt output may remain similar if farmed/hybrid fish replace an equivalent number of wild fish. Farmed salmon are known for their relatively high growth rates, for which they need an abundant food source. If, due to this greater energy demand, farmed salmon feed more actively in the wild, more than an equivalent number of wild juveniles may be replaced and overall smolt production may fall.

In an experiment conducted over seven years in the River Imsa, Norway, hatchery smolts derived from crosses of wild Imsa stock and released at the same time as seaward migrating wild smolts exhibited less than a 50% survival rate relative to the wild fishes (Jonsson *et al.*, 1991). However, there is little data on smolting rates and returning success of farmed or hybrid smolts which result from earlier introductions, i.e., the progeny of escaped adult salmon or escapes of cultured parr. Cultured juveniles that escaped into a river in Northern Ireland successfully smolted, migrated and returned to breed with other escapee and native fish (Clifford *et al.*, 1998). This demonstrates the ability of cultured salmon to succeed in the wild, thus propagating non-native genetic lines among wild populations.

9.1.4.5 Summary: potential effects of farmed escapees

Research into actual impacts of escapee Atlantic salmon remains at an embryonic and hypothetical level. No instances exist where the presence of farmed fish and non-indigenous genetic lines have been linked directly to population changes. In practice, such changes may prove difficult to distil from the effects of other problems that affect wild salmon stocks. Several variables may influence the overall effect of escaped fish, e.g., the extent of genetic differentiation between native and escaped fish, competitive ability, the prevailing environmental conditions, relative numbers of native and escaped fish, to name a few. It is known that farmed salmon, whether escaping as juveniles or adults, will survive to breed with wild fish. Significant numbers of juvenile and adult fish continue to escape (Scottish Office, 1998). Although the reproductive success of adult escapes seems to be less successful relative to those that escape as juveniles, a proportion do succeed and, in certain situations, many of their offspring will survive. If the presence of farmed adults is sustained by continual escapes, a gradual process of genetic erosion may proceed. Given the importance of local adaptations discussed earlier, one may regard this as an undesirable possibility in situations where specific characteristics are fundamental to the survival of native populations. Moreover, a reduction in genetic diversity within regional meta-populations and the species as a whole may compromise the ability of Atlantic salmon to cope with environmental change.

9.1.5 Sea lice

During the marine phase of their life cycle, wild salmonids are commonly affected by two species of the crustacean louse, *Lepeophtheirus salmonis* and *Caligus elongatus* (Copepoda, Caligidae). The latter species is a ubiquitous parasite found on various common species of inshore fish (e.g., saithe (*Pollachius virens*), pollack (*Pollachius pollachius*)) and is rarely found on wild salmonids in any great abundance. However, *L. salmonis*, also known as the salmon louse, is found exclusively on salmonids, usually in low numbers. There has been intense speculation concerning the link between the prevalence of lice on farmed salmon and the health of wild salmonid populations (McVicar *et al.*, 1993; Tully *et al.*, 1993a, b; Birkeland, 1996; ICES, 1997; Northcott and Walker, 1995). This has mainly focussed on the decline of sea trout stocks which has occurred in areas of the north-west coast of Scotland, as well as in western areas of Ireland and Norway. Salmon are more difficult to study as they quickly head out to sea after leaving their natal rivers, but lice have also been implicated in their declines in the same areas noted above. For a review of population changes in wild salmonids in Scotland, see Atlantic Salmon Trust (1993). Much research suggests that poorer rates of marine survival are mainly responsible. Yet it has proven difficult to collect information on the exact nature of the causative factor(s) for this. Existing literature on the subject of salmon lice and wild salmonid declines is characterised by uncertainty. The debate has polarised, with wild fishery interests arguing for a more responsible and precautionary approach by the industry which, in the absence of hard data, maintains that the effects of salmon lice on wild salmonids are negligible. The detrimental effects of salmon lice infestation of salmonids are described below, in terms of their development, host relationship and pathogenicity. This is followed by a review of research that is concerned with qualifying and quantifying the relationship between sea lice and the sudden decline in some wild salmonid stocks.

9.1.5.1 Development and host relationship

Pike and Wadsworth (1999) provide a thorough review of the biology of *L. salmonis*. Its life cycle comprises ten developmental stages. Generation time for *L. salmonis* exhibits a strong relationship with temperature. Wootten *et al.* (1982) reported generation times of around 42 days at temperatures varying between 9 and 12°C. Johnson and Albright (1991) recorded differential generation times between male and female *L. salmonis* at 10°C of 40 and 52 days, respectively. As these figures vary with water temperature, it is estimated that five or six generations may be completed annually. Naupliar larvae are free swimming and settlement on a host occurs at the copepodid stage, when a hooked attachment filament is secreted, anchoring the louse to the host's epidermis. Development proceeds through chalimus stages I to IV during which the louse is immobile on its host. In the transition to the first pre-adult stage the louse becomes mobile and may also swim between hosts (Ritchie, 1997). This is followed by a second pre-adult stage before the louse becomes a mature adult. Settlement of copepodids on sea trout and salmon appears to be non-selective, followed by a differential mortality rate through the chalimus stages between the two hosts, with sea trout tending to accumulate a greater number of pre-adult and adult lice than salmon. Of the two hosts, sea trout appear more vulnerable to salmon lice infestation. It is suggested that salmon may exhibit a greater immunological response than sea trout to lice infection. This is supported by observations of high levels of lice infection on farmed salmon 'runts' which initially exhibit poor growth and condition (ICES, 1997; Dawson *et al.*, 1997).

9.1.5.2 Pathogenicity

Pathogenicity of salmon lice is generally proportional to the parasite burden and the duration spent in salt water, although nutrition, stress, genetically-determined resistance and immunocompetency may also be influential (MacKinnon, 1998). The potential for pathological damage is greater on smaller hosts and, consequently, wild salmonid smolts entering seawater for the first time in spring are particularly vulnerable. Settlement occurs predominantly on the dorsal area of the host, and also—but less frequently—on the operculum, head and anal regions. Pathogenicity also depends on the stage of lice development. Although the progression of lice through chalimus stages results in damage to the epidermal layer and fin tissue as the louse feeds, few corresponding physiological effects have been noted in sea trout or salmon (Dawson, 1998; Grimnes and Jacobsen, 1996). However, during development from the chalimus IV to the first pre-adult stage, lice become mobile and much more capable of inflicting mechanical damage to the epidermis and underlying flesh (Jones *et al.*, 1990; Jónsdóttir *et al.*, 1992; Dawson *et al.*, 1997; Dawson, 1998). Experiments on both salmon and sea trout indicated that such damage results in severe osmoregulatory stress, which may be sufficient to cause death. Where salmon may induce an immunological response, sea trout have been observed to react with a behavioural response following infection, such as agitated or circular swimming patterns or leaping behaviour at the surface (ICES, 1997). This may also make them more vulnerable to predation by birds or seals. Furthermore, the primary infection may have a sufficiently debilitating effect so allowing secondary infection by other forms of disease, although it is important to note that this process also occurs in reverse, i.e., sea lice infestation results only after a host is weakened by some other affliction.

Sea trout which have been observed to return early to freshwater often carry high lice burdens (McVicar *et al.*, 1993; ICES, 1997; Birkeland and Jacobsen, 1997). Salmon lice cannot tolerate lowered salinity and smolts have been shown to use this behavioural mechanism to de-louse before returning to sea (Birkeland, 1996). Although sea trout post-smolts may return to freshwater several times (whether infected with lice or not) before reaching maturity (MacKenzie *et al.*, 1998), this behaviour is commonly ascribed to smolts which are infested with lice. The early return phenomenon has been exclusively associated with lice infestation in Norway (ICES, 1997). Decreased marine residency will reduce the duration of the sea trout's main growth phase. Walker (1994), for example, has observed that the average size of returning sea trout sampled in the River Ewe fell between 1982 and 1992 from 432 mm to 341 mm, but it is uncertain whether salmon lice infection is associated with this trend. As fecundity (reproductive output) varies positively with size and condition factor, smaller fish returning to spawn will produce fewer eggs overall. Therefore, salmon lice can kill sea trout but they could also affect the productivity of remaining individuals.

9.1.5.3 The role of lice in wild salmonid declines

It is unclear at this stage to what extent salmon lice have contributed to declines in wild salmonid populations. There are other factors that may affect the productivity of salmonids whilst at sea. Industrial fisheries remove prey items such as sand eels, juvenile herring and sprat from inshore waters. Global climate change and associated changes in sea temperature and salinity may have a more widespread influence on oceanic and coastal productivity. In freshwater, factors like redd washout—the destruction of the gravel nests that contain salmon and sea trout eggs—during periods of high water flow may also affect salmonid populations. The steep, fast-flowing spate rivers characteristic of the north-west of Scotland are particularly susceptible to this phenomenon (WRFT, 1999). This problem may become increasingly significant given the decreasing average size of mature sea trout in the populations of the north-west coast of Scotland, noted earlier, combined with a trend of increasing winter rainfall in the west coast area. In light of this, it is difficult to quantify the impact of salmon lice. It would seem that excessive infection can cause death or the premature return of sea trout post-smolts, yet it is difficult to estimate what effect this has had on the overall production of any particular sea trout population. The salmon's life history and mortality rates are particularly hard to study as smolts spend very little time in coastal waters before embarking on an oceanic migration. An ICES workshop, convened in 1996 to exclusively study interactions between salmon lice and wild salmonids stated that lice may 'significantly and detrimentally affect the physiology of post-smolts [salmon and sea trout]'. Moreover, the workshop stated that 'it is probable that the heavy infection of sea trout with chalimus seen in epizootics leading to early return of post-smolts would lead to increased host mortalities' (ICES, 1997). However, the workshop could not state conclusively that salmon lice were the main cause of salmonid stock crashes.

9.1.5.4 Salmon farms as a potential reservoir for sea lice infestation of wild stocks

A further conclusion of the ICES workshop was that 'although no direct evidence [was presented] that lice from farm fish infect wild salmonid populations... indirect evidence in this Report and the STWG Reports indicate that it would be reasonable to conclude that there is a contribution from farms'. The sea trout crashes of the late 1980s correlate with a time of rapid expansion in the salmon farming industry in Scotland; however, long-term declines evident prior to this indicates the influence of other factors (Walker, 1994). Establishing whether natural levels of salmon lice have been elevated by the development of salmon farming is hampered by the lack of historical data on lice abundance. Few studies exist concerning numbers of salmon lice in the wild for the period before the industry's growth began to accelerate in the 1980s. Pemberton (1976) details the ecology of sea trout in the north Argyll area of Scotland but lacks quantitative data on the occurrence of lice. However, Boxshall (1974) details lice prevalence and abundance on salmonid hosts during this period. Concentrating on a relatively small number of sea trout sampled off the north-east coast of England, lice prevalence was measured at 81% (i.e., lice were present on 81% of all fish sampled) with a mean intensity of four lice per fish (range, 1–12). In a later study of sea trout in the same area, Tingley *et al.* (1997) produced very similar results to those of Boxshall (1974). Prevalence of *L. salmonis* rose from 81% to 89% in 1992 and 1993 respectively. Mean abundance of lice per fish was calculated to be 4.66 and 4.42. A wider range of lice numbers infecting trout was found, up to 55, though this may be partly attributable to the higher number of fish sampled by Tingley *et al.* (1997) colleagues relative to Boxshall (1974). Similar contemporary studies have relied on the measurement of lice abundance on wild salmonids in areas with no salmon farming, in the absence of more suitable time series data. Schram *et al.* (1998) studied *L. salmonis* prevalence on sea trout in fjords along the south coast of Norway during 1992–95 and found the median abundance of lice per fish to range from 1–8, depending on the time of year and location. However, these studies concentrate on older fish in relatively open sea areas. Arguably, they fail to capture information from the more relevant time window during the host-pathogen relationship, which occurs when smolting sea trout first enter the sea.

MacKenzie *et al.* (1998) collected information on lice infestation of sea trout smolts and post smolts around the Scottish coast. Where salmon farming was absent, average numbers of lice per individual varied from <0.1–8. Equivalent figures obtained from the west and north-west coasts, where salmon farming production is concentrated, were much higher, varying from an average of 0 to 77 between different areas (maximum recorded was 258). Taking levels of lice data from farm-free areas as being representative of 'background' levels, it seems clear that elevated levels of lice infestation on sea trout only occur in regions where salmon farming is active. However, temporal observations of sea lice infection on farmed salmon and sea trout sampled nearby failed to produce any evidence to suggest that the prevalence of lice on farms can be correlated with infection levels on wild fish. The development of lice infection on sea trout varies widely between different salmon farming localities and it is worth noting that very low infection levels may also be found (Tully *et al.*, 1993a, b; MacKenzie *et al.*, 1998).

Two main factors are suggested that influence patterns of lice infection. The first is the source and number of infectious agents (copepodid larvae) to which fish are exposed. This will vary with the number of gravid females on previously-infected fish, the number of eggs produced per female and environmental conditions such as water temperature and local current regime. The second factor is the susceptibility of the fish to infection, which will take into account stress levels, nutrition and immunocompetancy (MacKinnon, 1998). Host susceptibility has been shown to vary considerably in sea trout. The process is further complicated by the ability of sea trout to visit less saline or freshwater environments to rid themselves of lice burdens before returning to the sea. As lice larvae tend to accumulate in discrete swarms (ICES, 1997), a high degree of chance will also influence infection patterns, depending on the probability of a fish encountering such a swarm.

Given the possibility that salmon farms serve as reservoirs of infection, several attempts have been made to correlate numbers of lice on wild salmonids with distance from a farm. In some cases, numbers of lice larvae (nauplii and copepodids) in the water column and on wild fish have been found to exhibit a significant inverse relationship with distance to the nearest farm (Anon, 1994; Costelloe *et al.*, 1996). Boxaspen (1997) also found this relationship in Norway but only during periods when sea temperature exceeded 6°C, yet no such relationship has been found in other studies (Costelloe *et al.*, 1998; MacKenzie *et al.*, 1998) and the 1996 ICES workshop concluded that 'the extent and mechanism of their [nauplii and copepodid] dispersion are unknown'.

Attempts have also been made to directly measure occurrence of lice on wild fish which may have originated from farms. Comparison of lice genetics has been researched as one technique that may be used to distinguish lice of natural and farm origin. Marine invertebrates that produce planktonic larvae allow for individuals to be dispersed over a large area. As a result, there is extensive gene flow throughout that area and individuals of a particular species exhibit a high degree of genetic homogeneity. Whilst tentative examination of allozyme (protein) variation reinforces this characteristic in salmon lice populations sampled around the Scottish coast, other techniques have produced more unexpected results. Preliminary studies of Randon Amplified Polymorphic DNA (RAPD) marker variation in lice taken from 16 sources suggest that some distinction exists between the genetics of lice taken from farmed salmon and wild salmonids (Todd *et al.*, 1997). The founder effect (derived from a small number of ancestors) and subsequent reinfection provides for genetic divergence relative to natural lice populations. Intense selection pressure created by the use of various antilice chemicals may also stimulate genetic change and there are various examples where the lice on farmed salmon have developed resistance to chemical treatments, e.g., the organophosphate pesticide dichlorvos (Jones *et al.*, 1992). This work is continuing in Scotland and Norway.

9.1.5.5 Summary: potential environmental effects from sea lice infestation

In summarising the above discussion, one can list few basic facts. Sea trout stock collapses have occurred in areas of western Scotland and Ireland, coinciding with the expansion of the salmon farming industry in this area. Such crashes have only occurred in areas where the salmon farming industry is active and well developed, although not in all areas. Salmon lice cause mechanical and physiological damage to sea trout. High numbers of lice on sea trout have only been found in areas adjacent to farms, relative to 'background' samples collected in areas with no salmon farming. No other problem common to areas where sea trout stocks have crashed has been identified which might have such a serious effect. ICES (1997) concluded that lice infection can lead to host mortality as well as cause sea trout to return early to freshwater. Furthermore, lice emanating from farms may contribute to the infection of wild sea trout. However, this link could not be quantified and other efforts to more accurately define the relationship between salmon lice and wild salmonids are confounded by uncertainty. The collection of more direct evidence on patterns of infection is hampered by the difficulty in tracking the planktonic naupliar and copepodid stages of lice at sea. The 1996 ICES workshop highlighted a number of research needs concerning lice and salmonid biology as well as interactions between lice, host and the environment. Work in these areas is ongoing in Scotland Ireland and Norway. It has recently been suggested that the link between lice and population crashes 'should now be accepted as beyond reasonable doubt' (Mackay, 1999). However, in the absence of direct evidence, this issue is likely to remain contentious.

9.1.6 Other diseases and parasites

The manifestation of disease and parasitic infection on farmed salmon generally becomes a more serious problem as rearing conditions become more intense (see Chapter 10). Historically, most infections in farmed salmon mirror those found naturally amongst wild salmonid populations. Disease seldom results from a single cause but from a combination of interactions between the environment, host and infectious agent. Of course, the fish farm environment is highly modified and the potential for fish to become stressed principally due to crowded conditions is much higher than that found in the wild. Disease outbreaks often follow discrete events such as grading of fish or water temperature rises. Stress generally results in impaired immune function and, consequently, farmed fish become more susceptible to infection in the presence of an infectious agent. Several different diseases have caused problems in the historical development of salmon farming. Concern exists that disease harboured in salmon cages may spread to the surrounding environment. This concern extends mainly to wild salmonids, as there are no known instances where diseases found in salmon farms have spread to any other type of marine organism. The potential for wild fish to act as marine reservoirs of infection, facilitating the spread of disease between farms also needs to be appreciated, especially in the design of management plans militating against spread of infection.

Disease may spread through the water column, although other vectors include blood from slaughtered fish, escapee fish and sea lice. There are three different scenarios in which diseases affect wild salmonid populations. Locally-occurring indigenous infections may reinfect wild fish. Given the concentration of fish contained in fish farms, bio-magnification of infectious agents may occur concurrently to reinfection, exposing wild fish to greater numbers of infectious particles than would occur naturally. Alternatively, local pathogens may be altered under farm conditions, e.g., intensive antibiotic or pesticide use, so that their relationship with wild (and farmed) fish is changed to the detriment of the host. Possibly more serious is the exposure of fish to exotic pathogens. Farmed fish, if moved to new locations, may be exposed to a different set of pathogens to which they have no exposure history. More pertinent to wild salmonids is the introduction of exotic pathogens with the movement of infected fish, e.g., from other countries. Fortunately, from both a commercial and environmental viewpoint, most infections—such as furunculosis—have been managed successfully. However, the resilience of salmon lice (discussed in Section 9.1.5) and the recent problems associated with the emergence of infectious salmon anaemia (ISA) in Scotland represent continuing concerns for the industry as well as wild salmonid interests. The actual and potential impacts on wild salmonids of these infectious agents and others are discussed below.

9.1.6.1 Furunculosis

Furunculosis is a disease caused by the bacterium *Aeromonas salmonicida* and is primarily a disease of salmonids. Fishes usually become infected in freshwater. Although there are a few cases of the gross pathology associated with the disease developing in freshwater, it usually manifests when fishes are transferred into seawater. *A. salmonicida* is considered endemic in British waters and Mackie *et al.*. (1935) reported several conspicuous epidemics among wild salmonids in the early years of this century. Since this period, however, the occurrence of furunculosis in wild salmonids has become a much rarer event and is only associated with stressful environmental conditions, such as low water flow, high water temperature and low dissolved oxygen levels (McVicar, 1997). The conditions found in salmon farms lend themselves much more readily to the development of disease. As the intensity of rearing conditions increased with the development of Scotland's salmon farming industry in the 1980s, furunculosis became a common problem and frequently resulted in mass mortalities of farmed fish at sea. In 1989, it was estimated that over 40% of all salmon smolts moved to the sea in Scotland died before harvest (Munro and Gauld, 1996). It has been almost impossible to isolate *A. salmonicida* from seawater samples although lateral transmission occurring between populations is noted (Effendi and Austin, 1994). It was assumed that, during such outbreaks, wild salmonids would be exposed to *A. salmonicida* infection, and it was calculated that the bacterium may spread up to 10 km from salmon cages (Turrell and Munro, 1988). No outbreaks of furunculosis epidemics were noticed in wild salmonids during such periods and McVicar (1997) suggests that, given the epidemics of the early 1900s and the apparent absence of furunculosis observed since, wild salmonids may have developed, or evolved, an increased tolerance to the disease.

This theory of developed resistance through constant exposure is supported by the outbreak of furunculosis in Norway in 1985. Previously, *A. salmonicida* had not been recorded in coastal waters. The bacterium allegedly arrived in an import of infected Scottish salmon smolts (Hastein and Linstad, 1991). Subsequently, wild salmonids became infected and by 1991 fish deaths were recorded in more than 66 rivers (Heggberget *et al.*, 1993). Although furunculosis is now managed very effectively on salmon farms, for example by vaccination, the Norwegian case illustrates the severe consequences that can result when wild salmonids come into contact with pathogens to which they have had no previous exposure.

9.1.6.2 Gyrodactylus salaris

Another infection that has had particularly dramatic consequences following the movement of infected fish is associated with the monogean fluke, *Gyrodactylus salaris* Malmberg, 1957. This microscopic ectoparasite may infect various salmonid host species, although on most, the development of infection is limited by a host mediated immune response. However, on certain populations of Atlantic salmon, the infection will advance unchecked until the host dies (Bakke *et al.*, 1992). Measurements taken during hatchery experiments on salmon parr have shown that infected fish have a thinner epidermal layer and a decreased number of mucus-producing cells compared with uninfected control fish. Damage to the epidermal layer and mucus may affect the osmoregulatory function of an individual but, perhaps more importantly, will make infected individuals more susceptible to secondary infections. Where mortalities among salmon have been recorded in the wild, superabundant concentrations of *G. salaris* are often associated with secondary pathogens, such as the fungus *Saproglegnia sp.* (Heggberget and Johnson, 1982). The first incidence of *G. salaris* was noted in the early 1950s at a fish farm in northern Sweden. Since then it has been widely recorded on wild and farmed fish throughout the Baltic region and is regarded as an indigenous parasite. Baltic populations of Atlantic salmon are relatively resistant to infestation, a trait which has a strong genetic basis (Bakke *et al.*, 1990; Rintamäki-Kinnunen and Valtonen, 1996).

In 1975, *G. salaris* was found for the first time in Norway, on salmon parr in the wild and in a hatchery (Johnsen, 1978; Johnsen and Jensen, 1986). Although it was first suggested that the appearance of the parasite in the wild was the result of changes in the freshwater environment, it was later discovered that the distribution of *G. salaris* could be connected to the stocking of fish from infected salmon hatcheries. The infection of these hatcheries was traced to imports of Atlantic salmon parr and smolts from Sweden, which were used in wild salmon enhancement programmes as well as to feed a growing Norwegian salmon farming industry (Johnsen and Jensen, 1986; Malmberg, 1989). It spread amongst wild salmon, and by 1991 30 populations had been completely wiped out. Equally drastic was the response of the Norwegian government, which was forced to use the chemical rotenone to kill almost all life in infected rivers before leaving them to recover naturally (Johnsen and Jensen, 1991). Although the pathological effects of *G. salaris* may only develop in freshwater and it dies rapidly in full strength seawater, the organism has been shown to tolerate intermediate salinity levels. In water of 5‰ salinity, *G. salaris* has been shown to survive indefinitely (Malmberg, 1988, cited in Rintamäki-Kinnunen and Valtonen, 1996). Soleng *et al.* (1998) demonstrated that *G. salaris* could be transmitted from salmon smolts to parr in water up to 20‰ salinity. In water of 7.5‰ populations of *G. salaris* were found to survive for 56 days. This tolerance to brackish water, albeit transiently, at higher salinities, allows the parasite to transfer between salmon which originate from different rivers running into brackish water sea lochs or fjords (Soleng and Bakke, 1997; Soleng *et al.*, 1998) and probably aided the spread of the parasite once it had been introduced to the wild in Norway.

The inability of *G. salaris* to survive under fully saline conditions effectively limits its distribution to fresh and mildly brackish water environments, such as those found across much of the Baltic Sea. Constant exposure to this organism has probably contributed to the development of resistance amongst strains of Atlantic salmon found in this area. The potential remains for *G. salaris* to be spread by the movement of infected batches of salmon eggs, juveniles or carrier adults, as well as on equipment associated with fish farming and angling. Mortality rates similar to those observed in Norwegian strains of Atlantic salmon have been demonstrated in salmon populations taken from Scotland (Bakke and MacKenzie, 1993). The *G. salaris* story illustrates the potential damage that exotic pathogens can inflict on indigenous wild salmonid populations.

9.1.6.3 Infectious salmon anaemia virus

Infectious salmon anaemia virus (ISAv) was first recorded in 1984 in farmed Atlantic salmon parr in a Norwegian hatchery and subsequently in other hatcheries following the use of raw seawater (Thorud and Djupvik, 1988). The clinical pathology associated with the virus includes severe anaemia, accumulation of fluid in the body cavity, haemorrhaging of the visceral organs, darkening of the liver, an enlarged, darkened spleen and high rates of mortality. The spread of ISAv to marine salmon farms followed the transfer of fish from infected hatcheries. A ban on the use of untreated seawater in hatcheries was implemented in 1989 and, since then, all new cases of ISAv have only occurred in farmed Atlantic salmon at sea. The condition haemorrhagic kidney syndrome (HKS), first diagnosed in 1996 in Atlantic salmon farms along the east coast of Canada, was shown to be due to ISAv in 1997 (Mullins *et al.*, 1998). In May 1998 ISAv was first identified in Scotland (Rodger *et al.*, 1998). All cases of ISAv have been associated with marine sites or hatcheries using untreated seawater.

ISAv is thought to be spread by a number of vectors. Seawater is thought to be the principle medium in which viral particles spread from infected sites. The transmission of the virus between marine salmon farms in Norway was particularly associated with the presence of shore-based salmon processing stations, which discharged untreated wastewater to the sea (Jarp and Karlsen, 1997). The virus can remain infectious for 20 hours in seawater (Nylund *et al.*, 1994). Blood and skin mucus have been shown to be particularly infectious when used to experimentally infect salmon parr. Faeces and urine are infectious to a lesser degree (Totland *et al.*, 1996; Rolland and Nylund, 1998). It is thought that the main routes of infection are through the skin mucus and gill epithelium. Infected escapee salmon may also facilitate the spread of the virus. Parasites of farmed fish, e.g., the sea lice *Lepeophtheirus salmonis* and *Caligus elongatus*, have been used experimentally to transfer the virus between infected and healthy fish (Nylund *et al.*, 1994; Nylund and Jakobsen, 1995), although the significance of these vectors in practice is less well known.

In 1999, the ISAv was found for the first time in wild salmonids in Scotland. Isolates of the virus have been obtained from sea trout, *Salmo trutta*, the freshwater eel, *Anguilla anguilla*, and in a saithe, *Pollachius virens*, caught in a salmon cage (SERAD, 2000). It should be appreciated that no specific monitoring occurred until the virus became a problem on salmon farms and it is unknown whether or not the virus has been present in the wild since a time pre-dating its appearance on farmed salmon. If it has, wild salmonids may have been responsible for the initial infection of farmed salmon, although there is currently no evidence that can accurately pinpoint the origins of the virus. Given this uncertainty, there is some concern about the effects of the spread of the ISAv and infection of wild salmonid populations.

Experimental evidence illustrates that the ISAv will propagate in both sea trout and rainbow trout (*Oncorhynchus mykis*) without showing the gross clinical pathology associated with the infection of Atlantic salmon (Nylund and Jakobsen, 1995; Nylund *et al.*, 1997). However, the virus is capable, of transferring from these 'carrier' hosts to salmon where the normal pathology will develop with high mortalities (Nylund and Jakobsen, 1995). Chronic infection of brown trout (*S. trutta*) has also been demonstrated where the virus has been isolated from individual fish seven months after inoculation. Where the virus exists in this latent form, its host is regarded as a life-long carrier, and although similar data do not yet exist, it is suggested that *O. mykis* should be regarded in a similar light (Nylund *et al.*, 1995, 1997). This pattern of infection suggests a long-term relationship between the ISAv and these two species. However, the sudden and dramatic impact that ISA has had on farmed Atlantic salmon stocks suggests that it is a new virus to this species.

Further study is being undertaken in the UK to determine more accurately the occurrence and distribution of the ISAv in wild fish. The presence of marine reservoirs for the virus will have an effect on management strategies that aim to control ISA. Although the virus appears not to induce gross pathology in trout, it does cause blood haematocrit levels (ratio of the volume of red blood cells to total volume of blood sample) to fall. Red blood cells account for *inter alia* the distribution of gases, e.g., oxygen, around body tissues and given such observations, more study as to the effects of the virus in trout are called for (Nylund *et al.*, 1997).

9.1.7 Aesthetic/visual impacts

Aesthetic concerns over fish farm development may take several forms. The introduction of a new feature on an otherwise undeveloped landscape is often resisted.

Even where the landscape has been subject to other forms of man-made alteration there have been concerns about the 'industrial character' of some fish farm developments. There are, as well, landscapes that are considered to be of national importance that may have specific designations (e.g., National Scenic Areas in Scotland). Some guidance on visual impacts and landscape character assessment is given by SERAD (1999) and advice on addressing these within Environmental Impact Assessments is given by the Crown Estate (1999). In Scotland, Local Framework Plans (see Section 9.2.5) may also provide an opportunity for local authorities to give some special consideration to the importance of local landscape features and provide additional guidance to potential developers. There are methodologies for visual impact analysis which assume that man-made and natural landform can be described by a common set of terms (Aylward, 1975) and some examples of these analyses can be found (e.g., Cairns, 1992) though the cost generally precludes their more widespread use in marine fish farming. Where sensitive sites are concerned a landscape assessment is usually undertaken so that mitigation in the design, siting and choice of materials, can be considered. Further details for such assessments are given by SERAD (1999). Once operational, litter can be a source of particular concern, and although little beach litter is attributable to fish farms, there have been complaints about litter around shore facilities (e.g., feed bags and scrap netting, etc.) and from net cleaning operations.

9.1.8 Interaction with other users of the coastal zone

In recent years controversies over possible infection of wild salmonid stocks by sea lice (Sections 9.1.5.3 and 9.1.5.4) have meant that many applications have resulted in opposition from anglers associations. Many areas where cages are installed are suitable grounds for commercial fishing operations, particularly creel fishing. Similarly conflicts may arise with a range of recreational sea uses, from recreational diving, windsurfing, dinghy sailing and yachting interests. Important anchorages are usually recorded on charts and the significance of recreational interests in an area can usually be given by national and local associations representing such interests. General navigational interests are taken into account as part of the requirements for licensing (see Section 9.2.1). It is often possible to make adjustments to siting locations to reduce potential conflicts with other sea users, and on occasion facilities constructed for fish farming (e.g., jetties) can be used by recreational interests.

9.1.9 Disturbance and antipredator measures

Disturbance of the surrounding environment caused by a salmon farm will vary according to the size of any particular development and nature of the activities being undertaken. Following the establishment of a farm, which may itself be disruptive, routine activities such as boat traffic, automated feeding equipment and human presence may also disrupt local wildlife. The coastal location of most salmon farms coincides with the distribution of various marine mammals and birds. Access to feeding, breeding and haul-out/roosting sites is important to local populations of these animals. Rather than be disturbed, however, certain species may be attracted by the feeding potential offered by salmon farms. Food sources include food pellets, the salmon in the cage, or wild fish which are attracted to the salmon cage to profit from waste food falling through the nets. Where the salmon is the target, farmers necessarily implement antipredator measures to protect their stocks. These are likely to have the most direct effects if they result in the death of the predator, as both seals and birds can be shot by salmon farmers under certain circumstances, subject to compliance with appropriate regulations (see Section 9.2.9.1).

9.1.9.1 Effects on birds

The coastline and adjacent sea around Scotland are very important areas for numerous species of bird at different times of the year. Particularly important areas are those where large numbers of birds gather. These include breeding/nesting colonies, feeding areas and moulting areas. Huge colonies of nesting birds are present during spring and summer around Scotland's coasts, especially the Western Isles, Orkney and Shetland. These mostly occur on cliff habitat and, as the physical exposure to weather and sea in such an environment tends to be high, they are unsuitable and so remain undisturbed by fish farming development. Certain species such as the common and arctic terns prefer more level coast and colonies inhabiting small offshore islands may be more at risk from the disturbance sometimes associated with fish farms.

Birds leave breeding colonies when their young have fledged, generally around July and August. Many species will then undergo a moult, during which they are flightless. Large groups of birds accumulate and depend on the availability of sheltered, undisturbed areas of sea where there is an adequate food supply. Less common species such as the red-throated diver, the great northern diver and grebes are particularly reliant on such areas until the are able to fly again. Although some species, e.g., fulmars and guillemots, may return to the colonies during winter, most will wait until early spring.

NCC (1989) reported that some species of bird have been known to desert important breeding and feeding areas as a result of fish farming activities. Rarer species which seek undisturbed areas during their moult would be particularly vulnerable to the development of salmon farming in these areas. Beyond this, there is very little information that describes how fish farming activities may disturb local bird populations or what knock-on effects this may have.

Various species of bird are attracted to salmon cages as a potential food source, and a more direct relationship is evident here. Species such as cormorants, shags and herons feed around fish cages and may attempt to take salmon from the cages. Although non-lethal methods of deterring birds from salmon cages are encouraged by organisations such as the Royal Society for the Protection of Birds (RSPB), some birds may be shot if they constitute a persistent nuisance. Pillay (1992) suggests that greater mortality results from entanglement in nets suspended above and below the water. There are no current data on bird mortality associated with salmon farms in Scotland, but it is not likely to be significant.

9.1.9.2 Effects on marine mammals

Large populations of the common seal (*Phoca vitulina*—sometimes referred to as the harbour seal) and the grey seal (*Halichoerus grypus*) exist around the coast of Scotland. Both species are included in Annex II of the Habitats Directive (92/43/EEC), meaning that their conservation requires the designation of special areas of conservation (SACs) and several are currently proposed around the Scottish coast for exactly that purpose. Major concentrations of harbour seal tend to be found in more sheltered inshore environments and they breed from June through to August. Although the grey seal inhabits more exposed regions further offshore, it also moves inshore during its breeding season, which lasts from September to December. Grey seals especially require undisturbed breeding sites, as their pups have to spend several hours or days out of water before they are able to swim. In contrast, common seal pups are able to swim immediately after birth and both young and adults spend much less time out of water compared with the grey seal. Although it is possible that salmon farming activities may have a disruptive impact on local seal colonies, no data exist that suggest this is the case in practice.

However, the relationship between salmon farms and seals which try to prey on salmon is more obvious. Generally, it may only involve rogue individuals and will depend to some degree on the availability of food from elsewhere. Seals preying on farmed salmon are liable to be shot or killed by becoming entangled and drowned in antipredator nets which are commonly suspended around salmon cages. Given steady increases in seal populations through the 1990s, it is unlikely that mortality associated with salmon farms has been great enough to have any noticeable effect.

9.1.10 Consumption of industrial fish

At present the salmon farming industry relies on industrial fisheries for fishmeal. Assuming it takes 2.8 tonnes of industrial fish to produce 1 tonne of farmed salmon, then the total production of farmed Atlantic salmon by Norway and Scotland alone now requires some 1 million tonnes of industrial fish. This figure represents between one-twelfth and one-tenth of the total biomass of fish in the North Sea (Side and Jowitt, 2000). The conversion efficiencies have increased significantly during the period of growth in the industry, and it would be wrong to suggest that this is an impact of marine fish farming, as industrial fisheries predate the salmon farming industry by many years. It does, however, suggest a medium-to-long-term constraint on the industry's future expansion if alternative (nonfish) feed ingredients cannot be developed, and means the fish farming industry must be aware of environmental concerns arising from the exploitation of some industrial species such as sandeels. Sandeels are an important source of food for many birds, particularly for coastal breeding colonies.

9.2 LEGISLATION

While many other countries with salmon farming have developed regulations and a legal regime that govern such activities it would be difficult to provide a comprehensive worldwide review. Instead Scotland has been taken as a case study so that the detail rather than just the generality of legal provisions can be included.

9.2.1 Overview for Scotland

There are numerous regulations and agencies with statutory responsibilities under the legislation, which influence the development of marine fish farms and their operation. The principal permits required and jurisdiction of agencies with a responsibility for marine fish farms are discussed in detail in the Scottish Executive Advice Note *Marine Fish Farming and the Environment* (most recent version, December 1999). An outline of these, is given below.

- In all areas below the low water mark a lease is required from the Crown Estate Commissioners (CEC).
- In Orkney in the areas of Scapa Flow and the Wide Firth (designated Harbour Areas) a works licence is required from Orkney Islands Council (OIC), under the Orkney County Council Act 1974. In Shetland a similar provision exists in the Zetland County Council Act 1974 for coastal areas.
- Any discharge from a marine fish farm requires a prior consent to discharge under the Control of Pollution legislation from SEPA.
- A permit under the Coast Protection Act 1949 is required to ensure developments do not present hazards to navigation, etc. This is currently the responsibility of the Scottish Executive Development Department (SEDD).
- The protection and enhancement of natural heritage is a statutory responsibility of Scottish Natural Heritage (SNH).
- Ensuring necessary compliance with the Diseases of Fish Acts and related EC fish health directives is the responsibility of the Scottish Executive Rural Affairs Department which additionally has been responsible for issuing recent national guidance on marine fish farming.
- Ensuring necessary compliance with Health and Safety legislation is the responsibility of the Health and Safety Executive (HSE).
- Any onshore (i.e., above low-water mark) facilities are subject to controls under the land planning system and hence require planning permission from the local planning authority. Onshore facilities may also require a consent to discharge from SEPA.

Each of these elements of the legal regime may have particular requirements, many of which are environmental, which must be fulfilled by any prospective fish farm development.

9.2.1.1 Proposed changes to the legal regime governing marine fish farming

New legislation has been proposed that will transfer planning responsibility for the authorisation of new fish farm developments, and for the authorisation of, expansion of, or modification to, existing farms from the Crown Estate to the Scottish Local Authorities. The Crown Estate will retain its seabed leasing role. Pending this change, an interim agreement, which took effect on 1 December 1998, provides for a greater role for local authorities in the decision-making process. A flowchart illustrating the applications procedure under this interim agreement is provided in Figure 9.1.

9.2.2 Historical development of the legal regime

Historically, the principal controls over the siting of fish farms in the UK have been issued by the Crown Estate. The Crown Estate is in effect the landlord, leasing areas of the seabed to any prospective developer for which it receives a rent. Its role as both landlord (where it might reasonably be expected to maximise rents), and planning authority, where other matters arising from a consideration of the public good may conflict with this, has been the subject of frequent criticism (e.g., House of Commons Environment Committee, 1992). Despite this criticism the groundwork for the present siting controls has been largely established by the Crown Estate during this period. One of the first development measures was that of indicative siting distances for new farms. These are reproduced in their current form as Table 9.2.

These are indicative and clearly the wide variety of hydrographical conditions which are found in Scottish coastal waters means that often much closer siting of new farms to adjacent existing ones has been permitted. Growing concerns over environmental impacts from the new salmon farming industry then led to the adoption of a series of zones, within which particular development presumptions were made. Originally these were concerned predominantly with west coast sea lochs, but now in its Policy Guidance Note *Locational Guidelines for the Authorisation of Marine Fish Farms in Scottish Waters* SERAD has adopted four categories of Scottish coastal waters to which specific development presumptions are applied. The first is the north and east coasts of the Scottish mainland where the presumption is against any further development of marine fish farms. The present categorisation of Scottish coastal areas and national guidance on the development presumptions for fish farms in these area categories are as follows:

- **Category 1**, where the development of new or the expansion of existing marine farms will only be acceptable in exceptional circumstances. These are only likely to arise where it can be demonstrated conclusively by the applicant that the development will not have a significant adverse effect on the qualities of the area.
- **Category 2**, where the prospects for further substantial developments are likely to be limited although there may be potential for modifications of existing operations or limited expansion of existing sites, particularly where proposals

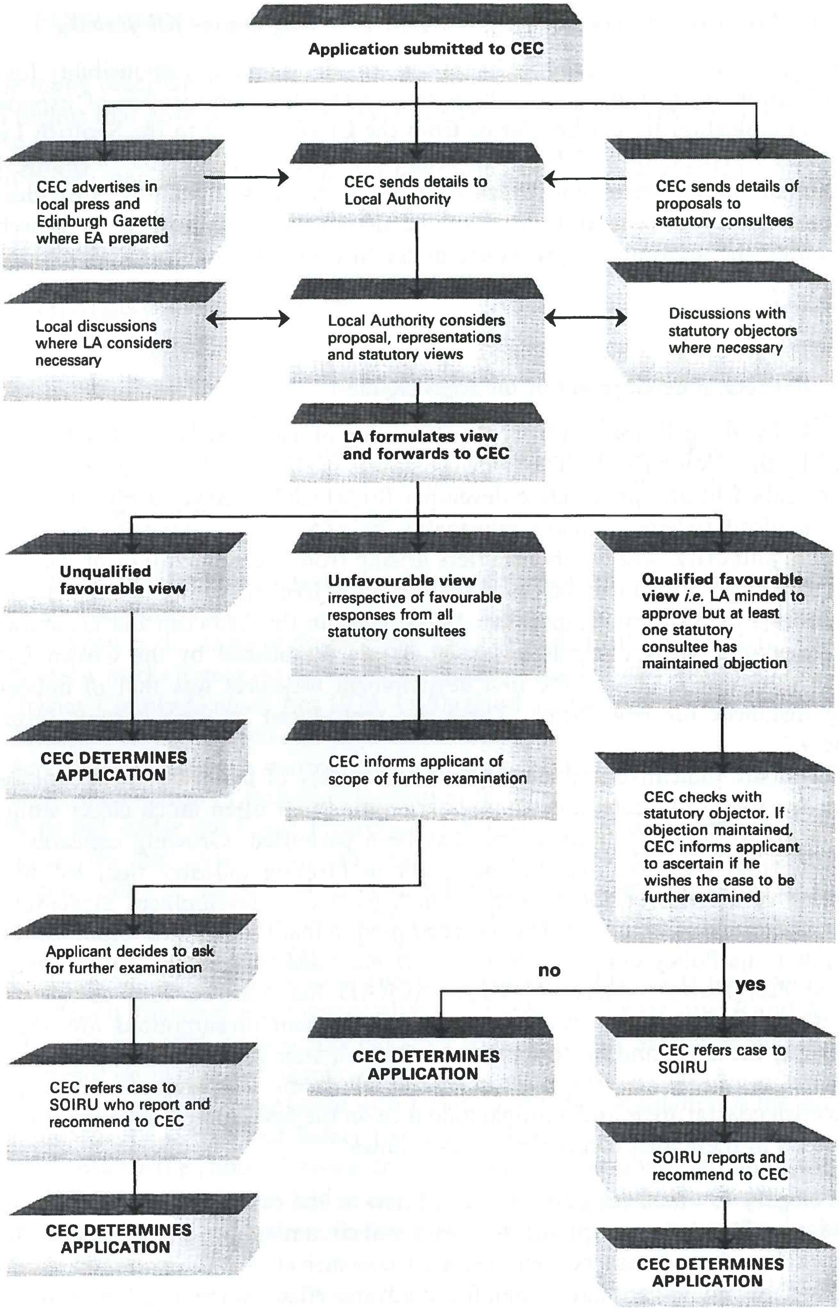


Figure 9.1. The seabed lease application process for a marine salmon farm under the interim agreement. Note the involvement of both the Crown Estate and the Local Authority (after SOAEFD, 1998a).

Table 9.2. Indicative separation distances for marine farms.

Distance from/distance to	Finfish farms (approx kms)	Shellfish farms (approx kms)	Qualifications
Salmon farms	8	3	Closer siting may be possible between small-scale farms, and in large loch systems or open water
Shellfish farms	3	1.5	
Public view points	1.5	0.8	Screening by buildings, landform or woodlands may permit closer siting
Hotels/tourist centres	1.5	0.8	
Houses (other than staff houses)	0.8	0.5	Attitudes of residents should be taken into account; closer siting may be acceptable in some areas
Vulnerable wildlife	0.8	0.5	Assuming adequate antipredator measures
Anchorages/approaches	0.5	0.5	Subject to the assessment of the DETR Marine Division
Fishing grounds/ netting stations	0.5	0.5	Assuming specific productive areas in frequent use

Source: Crown Estate Commission, as amended by SERAD 1999.
Notes:
1. These are not rigid standards for selecting sites or assessing applications.
2. Variations may be justified by local conditions in hydrography, topography, access and existing developments.
3. Management agreements or other forms of cooperation may make closer siting feasible.

will result in an overall reduction in environmental effect, so enhancing the qualities of the areas and hydrological conditions.

- **Category 3**, where there appear to be better prospects of satisfying environmental requirements, although detailed circumstances will always need to be examined carefully. (Category 3 includes all sea lochs and other enclosed sea areas that are not designated Categories 1 or 2, and open sea coasts out to a distance of 2 km).

SERAD (1999) contains information on the distribution of Category 1 and 2 areas around Scotland. The designation protocol accepts that it may only impose development restrictions on areas where there is existing salmon farming activity. Other marine systems, which may be as or more sensitive to aquaculture development, are not identified in these restrictions simply because there is no existing development.

The protection of sites not provided for in the above depends partly on the existence of designated conservation areas. Further constraints are imposed where a proposed fish farm development may have a significant adverse effect on the interests for which a Special Protection Area (SPA) or Special Area of Conservation (SAC) was designated, under the EC Birds and Habitats Directives, respectively. Any proposal which is likely to have significant adverse effects on such interests can only proceed in very exceptional circumstances.

In addition to the establishment of development presumptions within a zoning scheme, the Crown Estate also linked to these requirements the needs for environmental impact assessment (EIA). This feature remains today with national guidance requiring EIA for each category zone as follows:

- **Category 1**: all proposals for new sites or modifications to existing marine fish farm sites or equipment.
- **Category 2**: all proposals for new fish farm sites or significant modifications at existing sites (where 'significant modification' is indicated by any single or cumulative increase in tonnage of more than 25%, or increase in equipment which would result in development designed to hold 250 tonnes or more, or a cage area of more than 2000 m^2).
- **Category 3**: all proposals subject to the normal screening procedures provided for in the EIA Regulations.

The operation of EIA for marine farming activities has recently been described in a manual issued by the Crown Estate (Crown Estate, 1999), which incorporates changes made by the introduction of the Environmental Impact Assessment (Fish Farming in Marine Waters) Regulations 1999. While this explains what has become now a fairly complex process (for determining whether an EIA is required and the generality of what it should cover) it provides little in the way of detailed guidance on the execution of an environmental assessment for an individual fish farm. In many respects it is the latter which is critical to better environmental practice within the industry, and case study illustrations of good practice in EIA would be widely welcomed.

9.2.3 Harbours legislation

The Orkney and Zetland County Council Acts were not designed to provide for the approval of fish farms but do require that in Orkney within designated harbour areas a 'works licence' is obtained where a permanent facility is being established. Similar provisions exist in Shetland for coastal waters. In these areas then, as both a lease and a works authorisation is required, there has inevitably been some duplication of effort in aspects such as public consultation. Both procedures require consultation but different information and statutory consultees are involved.

9.2.4 Coast protection legislation

The Coast Protection Act 1949 requires that an additional permit is obtained under Section 34 and this requirement is to ensure that development does not constitute a hazard to navigation. Since Scottish Devolution this responsibility has been exercised by the SEDD, but the Crown Estate has usually coordinated such applications when applications for seabed leases have been made.

9.2.5 Non-statutory framework plans

Guidance from national government has for some time encouraged local uthorities to develop their own framework plans for marine fish farming. This has not been an easy task given that no additional resources have been provided with which to do it. However, some progress has been made in the Highland Region, Shetland and Orkney. The approaches differ: in Highland Region specific lochs have been selected and plans are being developed for these. Within each area a series of further zones has been constructed with presumptions about the scale and nature of fish farm development within each being applied (see for example the creation of 13 zones within the "Loch Eriboll Fish Farming Framework Plan" produced as a consultative draft in January 2000). In Orkney the approach has been one which has involved the participation of local stakeholder groups in a forum to gather information on and discuss the relative importance of environmental sensitivities throughout the whole island archipelago, so that new applicants are aware of specific environmental sensitivities that must be addressed. The opportunities to link these local framework plans with greater participation in coastal zone management in general has been widely welcomed.

The transfer of responsibility to local authorities will raise a number of issues. At present, the first applicant for a site is given priority by both the Crown Estate and SEPA in their considerations over any other later applications. There is some suggestion that local planning authorities would look to find the 'best application' for any site, in a manner similar to arrangements often pursued on land. There is some doubt, however, whether simultaneous applications for the same site are likely. Another issue is the sequence to be followed in applications to the various regulatory authorities. At the present time for example, it is possible to have a SEPA consent to discharge for a site without a lease from the Crown Estate, which may prevent another development on an adjacent site from obtaining the necessary SEPA consent.

Where management agreements exist it is probable that one requirement of framework plans will be that any new applicant has satisfied existing parties to any management agreement in the area so that the agreement can be renegotiated to include the new farm development if subsequent statutory approvals are granted.

9.2.5.1 Voluntary management agreements

The Scottish Salmon Growers Association (SSGA) (now Scottish Quality Salmon), initiated a national treatment strategy for the control of lice on salmon farms. The strategy was based on research that suggested that the reproductive capacity of female lice is reduced for a period during spring, and that coordinated action to lower lice levels during this time could have significant benefits in terms of reduced fish mortality and downgrading at harvest. The Scottish coastline was divided into 22 areas, in each of which a management group comprising fish farmers and local veterinarians was established. Each management group aimed to monitor lice levels on farmed salmon stocks at agreed intervals and regional lice treatments were encouraged according to agreements made between neighbouring farms.The strategy depends on the voluntary cooperation of all farmers in an area and also on the actual lice treatment methods which were available. Seventeen management groups had been established by early 1998 but the only lice treatments legally available at this time were hydrogen peroxide and dichlorvos (Aquagard). Variable success rates have been reported (Rae, 1999), but this may improve as new antilice chemotherapeautants become available.

In addition to these efforts, the Tripartite Working Group (TWG), in which government, fish farming and wild fishery interests are represented, was convened in 1999 to address *inter alia* the control of lice on farmed salmon.The TWG was formed in light of increasing pressure on the industry and the government to address the perceived link between the spread of lice from salmon farms and stock crashes in the wild salmon and sea trout population in north-west Scotland. Several coastal areas have been designated with the intention of establishing an area management agreement (AMA) for each, amongst farmers and other local interests, e.g., wild fishery managers. Beyond lice treatment strategies, synchronised harvesting and fallowing routines are to be encouraged to break cycles of infection. It is significant that this scheme aims to achieve zero lice levels on farmed fish, when previously low numbers of lice in a salmon cage would have been regarded as acceptable from the farmer's perspective. AMAs also cover the issues of escapee salmon, the spread of ISA and furunculosis vaccination.

The first AMA was established for Loch Laxford in July 2000 (Scottish Executive, 2000) and it is planned to extend this scheme to areas throughout the west coast and the Western Isles. Again the process is fundamentally underpinned by the voluntary cooperation of all involved. The development of new treatments to reduce lice infection remains an important factor in achieving success.

9.2.6 Consents to discharge

Before a fish farm can operate it is required to hold a Consent to Discharge issued by SEPA. Through the Environment Act 1995, SEPA is bound 'to promote the cleanliness of the tidal waters of Scotland' (section 34, 1(b)). Its main duties, however, are related to the Control of Pollution Act (COPA) 1974. Waste from fish farming was recognised as a trade waste under schedule 23 of the Water Resources Act (1989). However, in practice, SEPA is only obliged to consider the effects of organic waste (waste food and faeces), nutrients, medicines and chemicals on the water column and/or the seabed. Other environmental impacts associated with fish farming are not directly covered by COPA 1974 and consequently are not a statutory concern for SEPA.

On receipt of a consent to discharge application, SEPA is required to advertise applications in the *Edinburgh Gazette* and the appropriate local paper. Copies of the application are also distributed to the relevant local authority, the Scottish Executive and Scottish Natural Heritage. Comments made either by the statutory consultees or the public on any particular application must be considered by SEPA. Each respondent must be kept up-to-date on the application process and, where SEPA decides to approve a consent, must be provided with a draft copy of the proposed consent conditions. Respondents are notified of their right to appeal to the First Minister and should they do so, SEPA may not issue a consent until the First Minister expresses their intention with regard to an appeal.

SEPA is listed as a competent authority with regard to SACs and SPAs designated through the Habitats Directive and the Birds Directive, respectively, collectively known as NATURA 2000 sites. Any Ramsar site, i.e., a site designated under the Ramsar 1971 Convention on Wetlands of International Importance especially as Waterfowl Habitats, is to be regarded as an SPA. Where a discharge is to be located in or near a NATURA site, SEPA is charged with undertaking an appropriate assessment of the possible effects that discharge may have on that site. SEPA may not issue a consent for any discharge that would adversely affect the integrity of a NATURA site. For sites of special scientific interest, SEPA must consult with SNH as to the effects of a discharge. SEPA is also encouraged to protect the interests of non-statutory conservation sites, such as Marine Consultation Areas (MCAs), as well as other valuable examples of marine natural heritage, and effects of any discharge on these should also be considered in the application process. SEPA may also consider the aesthetic effects of fish farming as well as its effects on other coastal users, such as fish/shellfish farms, commercial inshore fisheries, sport fisheries and water sports (but see note below Table 9.3). Where the application relates to an increase or modification to an existing facility, the present physical, chemical and biological status of the surrounding water column and seabed is examined in light of the potential to increase consented discharge.

Setting limits for biomass makes up the main part of the consent, as the volume of all discharges will vary directly with the size of the fish farm and the quantity of fish kept there (see Table 9.3). Bathymetry and hydrography mainly influence the biomass limits. Ideally, the water depth at a proposed site should be at least twice the net depth so that there is adequate space for wastes to be dispersed by horizontal currents. Hydrographic data have to be supplied to SEPA with the application to demonstrate that the local currents are sufficient to disperse waste.

The local current regime is the main determinant of the biomass which will be allowed at a site. Table 9.3 shows the general relationship between current speed and the maximum consented biomass. It is suggested that in very well flushed areas, even higher biomasses may be allowed. Furthermore, higher biomass may be allowed if, after harvest, the site is fallowed for a significant period, in a rotational production programme which utilises more than one site.

Although SEPA may take other non-statutory coastal zone interests into account during the application process, it would be unreasonable for it to withhold a consent where its conditions in terms of organic deposition, nutrients, medicines and chemicals are met even though there may be other environmental or social concerns suggesting the site is unsuitable. Representations are often made

Table 9.3. Provisional SEPA guidelines for maximum consented biomass (t = tonnes). Source: SEPA (1998).

Mean speed ($cm\,s^{-1}$)	High risk site no fallowing; fine sediments; enclosed waters; existing effects; 'sensitive' site	Average risk site no fallowing; no existing effect	Low risk site long fallowing; coarse sediments; no existing effects
<3	50t	100t	250t
3–5	250t	500t	750t
5–10	500t	1000t	1500t
>10	750t	1500t	2000t

Note: Many other factors are considered in the SEPA consent to discharge decision-making process. These include site exposure and wind-driven currents; sites of high biomass and those near NATURA 2000 sites are required to submit more extensive survey data with the application to consent. Legally it would be unreasonable for SEPA to withhold consents where its conditions are met even though there may be other environmental or social concerns suggesting that the site is unsuitable. In addition to consents relating to the total biomass, consents to discharge are also issued for all medicines and other chemicals that may be discharged into the marine environment.

concerning the spread of infection, e.g., sea lice, from fish farms. Although SEPA may appreciate this worry, it is bound by the text of COPA 1974, which does not provide for such parameters in the consent procedure.

9.2.7 SEPA requirements for monitoring

Marine fish farming carries the potential to affect the surrounding environment in a number of ways. These vary from biological effects on the seabed to aesthetic landscape effects. Methods to gauge the significance of these effects vary from, for example, quantitative measures of biological diversity and community trends to more subjective estimates concerning visual impacts. Although EIA should properly address such issues and suggest mitigative steps, the requirement for EIA is only just beginning to be applied more rigorously with respect to the marine fish farming industry. In any case, our understanding of coastal marine ecosystems is far from complete and there will always be a degree of uncertainty attached to the prediction of impacts resulting from fish farming. Environmental monitoring is often suggested as a means of following the effects of aquaculture in practice and would seem to be most appropriate where significant risks or uncertainties have been identified.

Statutory environmental monitoring of marine fish farming in Scotland follows the traditional environmental quality standards (EQS) approach preferred by the UK, which takes account of *inter alia* the assimilative capacity of the environment receiving a discharge. Statutory monitoring seeks either to check the compliance of the operator with EQS or to verify the accuracy of predictive modelling. Physical, chemical and biological data may be collected in baseline surveys, during operation or following the removal of the fish farm installation to assess site recovery. Monitoring is carried out in the immediate vicinity of fish farm cages or more generally, for example where several fish farms in an enclosed sea area may collectively affect the entire system. SEPA acknowledges that it cannot undertake all the monitoring necessary at marine fish farm sites throughout Scotland. In certain instances, operators are invited to 'self-monitor' their activities through protocols prescribed by SEPA.

9.2.7.1 Water column

Nutrient monitoring

Consented biomass limits are set with the aim of preventing such increases in nutrients that may result in greater phytoplankton (primary production) growth with associated water quality problems. Nutrients in a dissolved form have the potential to spread relatively far from the source of discharge. The area in which monitoring is to occur must be defined, and as nutrients are likely to disperse widely, samples are usually collected throughout the area in which a fish farm is located, i.e., in a sea loch or an enclosed sea area. The frequency and extent of monitoring is further defined by the biomass of fish held at a site and the local hydrography. Variations in primary production are related to the flushing time of a system, i.e., the time it takes for all the water in a system to be replaced as a result of tidal movements. The lower the flushing time, the longer phytoplankton cells and nutrients will remain resident in the system. Monitoring protocols for different biomasses and flushing times are shown in Table 9.4.

Depending on the review of the first year's data, more or less monitoring may be called for, as appropriate. Not all areas can be monitored, so they are done on a sequential basis, with the most sensitive systems (according to a ranking system used by the Scottish Executive's Fisheries Research Services laboratory in Aberdeen) receiving priority.

Water samples are tested for nitrate and phosphate (being the main nutrients required for primary production), nitrite, ammonia and chlorophyll-a. Temperature and salinity are also recorded. Observed values are measured against the relevant EQS (see Table 9.5).

Dissolved oxygen

Dissolved oxygen (DO) monitoring occurs only during summer in systems where the biomass of farmed fish exceeds 1000 tonnes and the flushing time is greater than three days. SEPA generally requests that the operator measures DO in a near field sampling protocol. SEPA may collect additional DO measurements from various depths in the water column in more vulnerable deep-basin locations.

Table 9.4. SEPA monitoring requirements. *Source:* SEPA (1998).

Total biomass/ tonnes	Flushing time/days	Category	Monitoring required
<1000	—	—	No regular monitoring
>1000	<3	1	1 winter, 1 summer survey *Nutrient sampling at 4 stations:* 1 station at cages 1 station distant control 2 stations at X distance from cages (uptide and downtide)
>1000	>3	2	1 winter, 1 summer survey *Nutrient sampling at 8 stations:* 1 at cages 1 distant control 2 at X[1] distance from cages (uptide and downtide) 2 at Y[1] distance from cages (uptide and downtide) 2 at Z[1] distance from cages (uptide and downtide)

Notes:
[1] Distances X,Y and Z are likely to be proportional distances along the two uptide and downtide transect lengths of the system selected to cover length from cages to edge of system boundary. Distant control site should be a location external to the system.

Table 9.5. Environmental Quality Standards used by SEPA. *Source:* SEPA (1998).

Parameter	EQS	Application
Dissolved available inorganic nitrogen	168 µg/L	winter values
Dissolved available inorganic phosphorous	6.2 µg/L	winter values
Chlorophyll-a	10 µg/L	summer values
Dissolved oxygen	7 mg/L or 80% air saturated value	whichever is least
Zinc	40 µg/L	dissolved, annual mean
Copper	5 µg/L	dissolved annual mean

Medicines and chemicals

Medicines are mostly regulated by predictive modelling which sets limits based on the expected amounts of therapeutant used and the flushing characteristics of the local environment. Some monitoring may occur during the 1–3 hour period following use within and close to cages, although this might only be carried out to check the accuracy of the models being used.

EQS do not exist for all chemicals used around fish farms, e.g., in antifoulants. SEPA is currently developing its own EQS approach to this situation. However, copper is a List II substance in the EC Dangerous Substances Directive and its concentration in water samples must conform with national EQS. Water samples for chemical analysis can occur during nutrient sampling, although the sampling procedure will vary according to the properties and environmental fate of a substance, as well as the local hydrography.

9.2.7.2 Seabed monitoring

Waste deposition

Organic deposition on the seabed, comprising waste food and faeces, is generally restricted to an area not far from the overhead cages. Consequently, seabed monitoring occurs on a smaller scale compared with water column monitoring and is often carried out by the operator or a suitable third party. Again, the frequency and type of sampling depends upon the biomass of fish in the cages as well as the local hydrography (see Table 9.6).

- Survey Category 1: video/photographic seabed survey or small scale biological survey under cages, in the second year or the last year of the growth cycle at peak biomass.
- Survey Category 2: annual seabed video/photographic survey, or small scale biological survey in the cage vicinity.
- Survey Category 3: annual seabed video/photographic survey, plus a larger scale biological survey and a sediment chemical survey.

It is recognised that there will be some impact on the seabed as a result of routine fish farm operations. The area within which such effects are to be limited is called the allowable zone of effect (AZE). This assumption is also used in relation to impacts from point sources of pollution, e.g., a sewage outfall. In such cases, the AZE is generally to be contained within 25 m of an outfall. The application of this definition to fish farm cages is seen as being over-simplified. Seabed effects often take an elliptical shape in a direction, which corresponds to the prevailing current. Cages

Table 9.6. Biomass sensitivity matrix for seabed monitoring used by SEPA.

Biomass/tonnes	Mean current speed at farm/ms^{-1}		
	0–0.05	0.05–0.10	>0.10
0–499	Cat.1	Cat.1	Cat.1
500–999	Cat.2	Cat.1	Cat.1
$\geq$1000	Cat.3	Cat.3	Cat.2

Source: SEPA (1998).

Table 9.7. Sediment quality criteria action levels used by SEPA.

Component	Parameter	Action level within AZE	Action level outside AZE
Benthos	number of taxa	less than two polychaete taxa present (replicates bulked)	must be at least 50% of reference value
	number of taxa	two or more replicates with no taxa present	—
	abundance	organic enrichment polychaetes present in abnormally low densities	organic enrichment polychaetes must not exceed 200% of reference station value
	Shannon-Weiner Diversity Index	n/a	must be at least 60% of reference station value
Sea bed	feed pellets	accumulation of pellets	pellets present
	Beggiatoa	n/a	mats present
Sediment	copper	390 mg kg^{-1} (dry wt)	n/a
	zinc	270 mg kg^{-1} (dry wt)	n/a
	organic carbon	9%	n/a
	redox potential	values lower than −150 mV (as depth average profile) *or* values less than −125 mV (in surface sediment 0-3 cm)	n/a

Source: SEPA (1998).

may also move around with this current, depending on the type of mooring system in use. Although recognising these limitations, and in the absence of detailed hydrographic data which would allow a more accurate approach, SEPA will generally define the AZE to cover a distance of 25 m in all directions from overhead cages.

Nationally-accepted sediment quality standards similar to those for water do not exist. However, there are a number of thresholds for sediment quality (biological, physical and chemical) which apply to both the AZE and beyond (see Table 9.7). SEPA is likely to act if any of these thresholds are broken.

An AZE also exists for the water column. As the effects of dissolved components may be noticeable over a much greater area than the deposition of organic waste, the corresponding AZE is much larger. Different provisions are made for substances being discharged to the water column intermittently (e.g., sea lice bath treatments) and continuously (e.g., antifouling chemicals).

Intermittent discharges

Very little monitoring is associated with intermittent discharges, the consent conditions relying mainly on predictive modelling over a three hour period.

Continuous discharges

Continuous discharges are grouped with conventional marine outfalls and, as such, the relevant EQS should not be exceeded beyond 100 m of the source.

Medicines and chemicals

SEPA will occasionally monitor concentrations of medicines and chemicals in sediments and compare to sediment criteria and action levels. For new substances, appropriate monitoring protocols will be introduced according to the properties of the substance and the sensitivity of the surrounding environment.

9.2.7.3 Self monitoring

Self-monitoring plans comprise a subset of the protocols that would normally be used by SEPA. These generally involve the collection of data from the immediate vicinity of fish cages. Although this may be seen as a conflict of interests, SEPA enforces various audit options to encourage sound science and the collection of satisfactory data.

9.2.7.4 Review of consents

The results of monitoring are fed back into monitoring procedures. Depending on the results, the frequency of monitoring may be changed. For example, for a parameter which continually passes an EQS, sampling frequency may be reduced, and vice versa. Where results show continual breaches of quality standards, a number of further options are available to SEPA. These options include moving a farm to a site where the dispersion potential is higher, fallowing a site, review of the consent conditions or, in severe cases, revoking the consent. The Environment Act 1995 extended the period within which a consent cannot be reviewed from two to four years (sooner with the agreement of the operator). However, a consent can be revoked at any time if it is considered that such action is necessary to provide protection to persons likely to be affected by a discharge or as a result of representations made to SEPA or the First Minister by any concerned party regarding the consequences of a specific discharge.

9.2.8 Disease and reporting requirements

9.2.8.1 Diseases of Fish Acts 1937 and 1983

The Diseases of Fish Acts 1937 and 1983 require that where reasonable grounds exist for suspecting that any inland or marine waters are or may become infected, a designated area order may be made. This effectively prevents all movements of live fish, live eggs of fish and fish feed into or out of the designated area without the prior written consent of the First Minister. Although primarily designed to restrict the spread of furunculosis, contingency was included to allow the power of the Act to be extended to other diseases, as appropriate. A current list of notifiable diseases can be found in both the Diseases of Fish (Control) Regulations 1994 and the Fish Health Regulation 1997 (see below) and those relevant to the movement of live salmonids (live fish, eggs and gametes) including ISA, IHN, VHS and gyrodactylosis.

9.2.8.2 Registration of Fish Farming and Shellfish Farming Business Order 1985

Made under the Diseases of Fish Act 1983, this Order requires anyone who initiates a salmon farming business to register that business with Fisheries Research Services in Aberdeen, Scotland, and subsequently to keep records of fish stocking and movements.

9.2.8.3 Marketing Authorisations for Veterinary Medicinal Products Regulations 1994

Formerly, the Medicines Act 1968 required that chemicals used as veterinary treatments had a product licence. The above regulations came into force on 1 January 1995 and introduced a similar regime except that product licences were replaced with marketing authorisations. A pharmaceutical company must have a marketing authorisation in order to place any product on the market. A vet is usually obliged to prescribe chemicals authorised in this way. However, in exceptional circumstances and applying the cascade method (established by the Medicines (Restrictions on the Administration of Veterinary Medicinal Products) Regulations 1994), a vet may prescribe other substances not authorised for use in salmon, providing it is administered in the same way as it would be to other animals, e.g., in feed or injection. Ecotoxicological data have to be submitted with an application for a marketing authorisation which indicate any potential risks that the product may pose to the environment. Where the relevant authority in one country grants a marketing authorisation, applications may be made in other EU member states for identical authorisations to be granted under the principle of 'mutual recognition'. When a veterinary product is to be used on a fish farm, a consent to discharge is also required from SEPA, who will set limits based upon the local environmental conditions and the relevant environmental quality standards.

9.2.8.4 Diseases of Fish (Control) Regulations 1994

These regulations implement European Directive 93/53/EEC introducing minimum Community measures for the control of certain fish diseases. They apply as necessary to List I and List II diseases contained in Directive 91/67/EEC (see below). List I diseases are exotic to the European Union and would have severe economic consequences (for farmed and wild stocks), were they to occur. List II diseases (e.g. VHS), which may also have severe economic implications, are present in some parts of the EU but are exotic to others. Should a List I or List II disease be confirmed in

Great Britain, the measures in these regulations would come into effect. Such measures include the compulsory slaughter of salmon infected with the ISA virus, which was added to List I diseases by Directive 93/54/EEC.

9.2.8.5 Fish Health Regulations 1997

These regulations enact in Great Britain EU Directive 91/67/EEC concerning the animal health conditions governing the placing on the market of aquaculture animals and products (as amended). They control the movement of all live fish, their eggs and gametes and certain species of dead fish. No aquaculture animal that shows clinical signs of disease on the day of loading, or is due for slaughter under a scheme for the eradication of the disease listed in Annex A of 91/67/EEC, e.g., ISA. Appropriate transport and documentation conditions are also set to govern the movement of fish into and out of Great Britain.

Both the Diseases of Fish (Control) Regulations 1994 and the Fish Health Regulations 1997 are soon to be amended. This is partly to reflect the change in the approved status of Great Britain under EU legislation for certain diseases but also to introduce provisions that allow for the use of vaccines in the control of ISA as well as to allow for some discretion concerning the actions required following the confirmation of ISA at a site.

9.2.8.6 Animal By-Products Order 1999

The Animal By-Products Order 1999 was made under the Animal Health Act 1981 and implements European Directive 90/667/EEC, laying down the rules for the disposal and processing of animal waste, for its placing on the market and for the prevention of pathogens in feedstuffs of animal or fish origin. Animal byproducts are divided into low risk and high risk material. In salmon farming, waste from a salmon processing station is classified as low risk, whereas salmon killed in the context of disease control measures, e.g., ISA infected fish, are classified as high-risk waste. Many of the disposal options, such as rendering and incineration, apply equally to both low- and high-risk material, although only the former may be used further in the production of pharmaceutical and technical products or pet food. Rendering or incineration may be the most effective way to dispose of waste, although burning (other than in an incinerator) and burying are allowed if the quantity of the waste or the distance to the disposal facility do not justify transporting it.

9.2.9 Miscellaneous

9.2.9.1 Control of predators

Under section 1(1)(a) of the Wildlife and Countryside Act, it is an offence to kill, injure or take any wild bird. However, section 4(3)(c) makes it legal to shoot any wild bird (with the exception of species listed in schedule one of the Act) if it is 'necessary for the purpose of preventing serious damage to... fisheries'. Section 16 of the Act states that licences may be granted which allow the killing of birds for the same reason as given in section 4(3)(c). Although it is not specified, the issuance of a licence may allow farmers to shoot certain species of bird in the vicinity of a farm rather than just those that pose an immediate danger to their fish stocks. Licences are still granted to fish farmers to shoot birds.

Otters are also protected by section 9 of the Wildlife and Countryside Act as a schedule five species. However, as with birds, a person is not guilty of an offence if it can be demonstrated that an otter has been killed in order to prevent serious damage to *inter alia* fisheries (section 10(3)(c)). However, the otter is included in Annex IV of the Habitats Directive (92/43/EEC) as a species of Community interest in need of strict protection. Article 12 of the Directive prohibits the deliberate killing of all Annex IV species and this was implemented in Great Britain by the Conservation (Natural Habitats, &c.) Regulations 1994.

The Conservation of Seals Act 1970 sets restrictions on the methods which may legally be used to kill common and grey seals. The Act introduces open and closed seasons for both species, the closed periods broadly corresponding to the duration of the breeding season for each species. For common seals, this occurs between 1 June and 31 August, and for grey seals, between 1 September and 31 December and the killing of either species within these seasons is illegal. These provisions applied throughout Scotland, except in Shetland, where a moratorium on the killing of common seals was introduced in the early 1970s in response to population declines. This ban was lifted on 29 April 1998 (Conservation of Seals (Common Seals) (Shetland Island Area) Order 1991 Revocation Order 1998) when seal numbers had been judged to have recovered sufficiently.

Despite the existence of closed season for both species, section 9 of the Act makes it legal to kill a seal (with the appropriate gun and ammunition) at any time if it is done to *inter alia* to 'prevent it from causing damage to a fishing net . . . or any fish in such fishing net, provided that at the time the seal was in the vicinity'. This would seem to provide the fish farmer with an opportunity to shoot only those seals judged to be on the verge of or in the act of causing damage (although how this intent could be established in retrospect is unclear). However, section 10 allows licences to be granted which empower the licensee to shoot seals more generally, in an area specified in the licence, for the 'prevention of damage to fisheries'. For example, a licence would have been granted to a salmon farmer to shoot any seal venturing into a designated area around his salmon farm, whether or not it was about to or in the act of causing damage. The development of salmon farming in Scotland has occurred since this legislation was enacted and one may argue whether or not fishing nets and fisheries include any form of aquaculture. Although none have been issued to salmon farmers for some years, licences to shoot seals have been granted in the past on the basis of section 10. Together with references made to 'fisheries' in the Wildlife and Countryside Act 1981, the relevance of sections 9 and 10 of the Conservation of Seals Act 1970 to aquaculture is somewhat spurious, but occasion to challenge this situation has never arisen in the courts.

Both the common and grey seal are listed on Annex II of the Habitats Directive as species whose conservation requires the designation of SACs. Candidate SACs (cSACs) nominated in Great Britain for their importance to common seal haul out and pupping areas include sites on Sanday (Orkney), the Wash and North Norfolk coast and Mousa (Shetland). Grey seal cSACs include Faray and the Holm of Faray (Orkney), the Monach Islands (Outer Hebrides), North Rona, Berwichshire and North Northumberland coast and the Pembrokeshire islands.

9.2.9.2 Health and safety

Under the provisions of the Health and Safety at Work Act 1974, the Health and Safety Executive will periodically inspect marine fish farms. The HSE issues advice on minimum health and safety standards for the construction and use of floating fish farm installations in inshore waters.

10

Health and disease in Atlantic salmon farming

10.1 INTRODUCTION

Infectious diseases are one of the major causes of loss in fish farms. Some diseases are caused by pathogens that are commonly present in the aquatic environment. Fortunately, such pathogens are 'opportunistic' and do not normally infect fish and cause disease unless the fish's defence mechanisms are compromised. The usual cause of this is poor environmental quality and poor husbandry. Other diseases are caused by pathogens that cannot survive well in the environment away from their hosts, e.g., *Aeromonas salmonicida*, the causative bacterium of furunculosis. Such pathogens have evolved sophisticated ways of surviving on or in their hosts and can produce mortalities in catastrophic proportions. On the other hand, infected fish may show no signs of disease. Such 'carrier' fish may shed the pathogen which can spread and infect other individuals but disease can be triggered by a variety of factors, often associated with stress.

This chapter addresses the practical measures that a fish farmer can take to avoid or minimise losses from opportunistic and specialised pathogens of Atlantic salmon, and what remedial action to take should a disease outbreak occur. The fish's immunological defence mechanisms are described in Chapter 11.

10.2 APPROACHES TO DISEASE MANAGEMENT

10.2.1 Management of the host: stress management

10.2.1.1 The stress concept

Stress is an animal's response to change in its environment. This response is useful to the fish when its relationship to the environment is brought back to a steady-state of

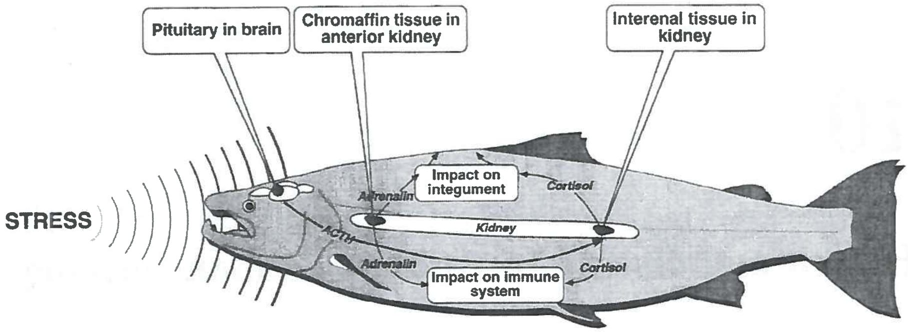


Figure 10.1. Stress response in fish. Stress acts via the brain to cause release of stress hormones such as aderenalin and cortisol from tissues in the kidney. These hormones, if secreted for prolonged periods, can adversely affect defence mechanisms in the integument or the immune system predisposing the fish to diseases.

'normality'. Thus the stress response allows the animal to adapt to a changing environment. However, as with all responses, it is metabolically costly and can only be sustained for a certain period of time. If normality is not achieved within this period, metabolic processes are stretched and begin to break down so that the health of the animal is compromised.

The changes that occur during stress are mediated by hormonal and nervous reactions, principally by release of adrenocorticotropic hormone (ACTH) from the pituitary, which causes a release of corticosteroid hormone from the interrenal tissue in fish. Nervous responses in the alarm reaction also produce release of catecholamines (e.g., adrenaline) from chromaffin tissue also in the anterior kidney of salmonids (see Figure 10.1). These stress responses can cause changes in the fish's defence (e.g., mucus production, properties of epithelial surfaces, immune response), favouring attack by opportunistic pathogens (e.g., *Saprolegnia*, ectoparasites, vibrios) which may be constantly present in water supplies. It is therefore vitally important to maintain the well being of fish by following management practices that do not lead to the fish's defence mechanisms becoming compromised.

10.2.1.2 Key stressors in the aquaculture environment

Water quality. Salmonids have high oxygen requirements (a minimum of about $6\,mg\,l^{-1}$) and circumstances which reduce the available oxygen levels in water, such as high temperature or microbial blooms, induce respiratory stress.

Crowding affects water quality by reducing oxygen and increasing toxic waste products in the water. Fin nipping and aggressive encounters, which may occur in crowded populations, especially when underfed, are common stressors in intensive aquaculture.

Handling such as netting, grading, marking, transport, etc. are all forms of physical stress.

Disturbance by farm workers or predators such as herons or seals can cause stress in Atlantic salmon.

Nutrition is important for good health, and problems have been encountered with certain vitamin deficiencies, especially when food is stored badly. Vitamins E and C are particularly important for efficient healing and immune responses.

Hierarchy. Effects may develop at certain population densities or between fish of different sizes, leading to aggressive encounters.

10.2.1.3 Consequences of stress

The hormonal changes occurring in stress mediate physiological changes primarily in the respiratory, circulatory and osmoregulatory systems. The most immediate consequences of stress (e.g., from netting, grading, transport, etc.) are on the respiratory system. For instance, the oxygen consumption of salmonids is still elevated by 50% one day after fish have been graded (Pickering, 1993). Problems of oxygen demand are exacerbated at high temperature when the fish's requirement for metabolism is increased while the oxygen-carrying capacity of the water is decreased. In extreme circumstances, for example transport at high stocking density, respiratory stress can be directly responsible for mortality. Even when dissolved oxygen levels are adequate, at high stocking density toxic metabolic products, e.g., ammonia or carbon dioxide, can build up and contribute to respiratory stress.

A further consequence of the respiratory adjustments of stressed fish may lead to salt imbalance. In freshwater, salts are lost and in seawater there is an influx of salts. This imbalance places pressure on the osmoregulatory systems and mortality can occur directly from osmoregulatory failure following severe stress.

Changes also occur in the defence mechanisms during stress, and under chronic stressful conditions a breakdown in the defence mechanisms can result in increased susceptibility to all kinds of infectious diseases, many of which would not normally cause disease problems in salmonids (see Pickering, 1997).

A further hazard of stress in disease control is that associated with vaccination. As the specific immune response may be suppressed by stressful circumstances it is important to minimise stress before, during and after the vaccination procedure.

10.2.1.4 Reducing stress in the aquaculture environment

It is not possible to eliminate from aquaculture all the procedures which are known to induce stress in salmon, as many are integral components of fish farming, e.g., netting, grading and transport. However, it is possible to minimise the effects of these stressors and others, such as overcrowding and variable or poor water quality, can be avoided. Farmers are familiar with the guidelines on stocking densities, water flow, feeding rates and so on for salmon cultivation and severe consequences from stress will follow from exceeding those limits. In cases where stressors are unavoidable the farmer can employ certain strategies to minimise the stress:

Permit recovery. Generally the duration of the recovery period is proportional to the duration of the stressor. Thus, reducing the duration of netting, grading or transport will result in recovery in a shorter time. Nevertheless, it should be noted that recovery can take an appreciable time, for example some of the secondary effects of a 30-second handling stress may last for several days and recovery periods of two weeks are recommended for salmonids (Pickering, 1997).

Avoid multiple stressors. The effects of multiple stressors can be additive or even synergistic, for example sudden temperature changes should be avoided during or after transport. Repeated handling stresses up to three hours apart can have a cumulative effect on the fish's stress responses (Pickering, 1993).

Avoid stressors at high temperatures. Stress-induced mortality increases at high water temperature, so it is safer to carry out netting, grading and transport at low water temperatures.

Withdraw food prior to handling. Following a meal the oxygen requirement of salmonids increases to provide the energy demands of digestion. Withdrawal of food two or three days prior to handling will therefore minimise respiratory stress. It also avoids fouling the water with faecal material and regurgitated food.

Reduce osmotic stress. In freshwater, the use of dilute salt solutions during transport has been shown to limit the loss of ions from the fish and significantly reduce stress-associated mortality (Pickering, 1997).

Use of anaesthesia. Although anaesthesia itself can disturb the fish's physiology, light anaesthesia can have a calming effect on fish during handling exercises and reduce the stress resulting from them.

Mimic the natural environment. Overhead cover is an important component of the young salmon's environment, particularly during winter months. Provision of a floating overhead cover can double the growth rate of Atlantic salmon parr, increase the proportion of potential S1 smolts, minimise haematological signs of stress and halve the mortality rate of potential S2 smolts during the first winter (Pickering, 1997).

Future development: selective breeding. It is now established that the magnitude of the stress response is a heritable characteristic in salmonids and programmes have begun to select broodstock that have a low cortisol response to handling stress. In this way the process of domestication can be accelerated to produce stocks more suitable to tolerating aquaculture stressors with resultant benefits of increased health, survival and productivity. Such breeding programmes have been conducted in Norway for some years to improve resistance to furunculosis and infectious salmon anaemia (ISA) in Atlantic salmon (Gjedrem, 1997).

10.3 VACCINATION

Vaccination has played an important role in the success of salmonid culture but it is not a panacea. In all forms of intensive agriculture where many individuals of a single species are reared in densely-populated circumstances, infectious agents can build up rapidly if the general health status of the population is low. If the animals' defence systems are compromised by stress, the protection afforded by vaccination can be overwhelmed. Thus, vaccination should be used as part of a broad-based husbandry strategy emphasising hygiene (to minimise exposure to pathogens) and the fish's biology (to minimise the stress induced by certain integral aspects of farming) as discussed above.

10.3.1 Current status of vaccination of Atlantic salmon

The vaccines which are currently used commercially in salmonid culture are all against bacterial diseases. Often these are multivalent and provide protection against more than one disease. There has been some recent progress in development of viral vaccines against infectious salmon anaemia (ISA), infectious pancreatic necrosis (IPN) and pancreas disease (PD) (Table 10.1). The main reason for the lack of available viral vaccines is production costs. Obviously, the cost per dose of vaccine must be very small and it is inexpensive to culture most bacteria in large fermenters and to inactivate the toxins and bacterial cells chemically (usually with formalin treatment). It is much more expensive to culture viruses in tissue culture but molecular biological techniques to produce viral vaccines in recombinant bacteria and yeast are opening the way to making these vaccines affordable for use in aquaculture.

Table 10.1. Current status of salmonid vaccination.

Commercial vaccines		Experimental vaccines
Disease	Agent	Viral
Vibriosis	*Vibrio anguillarum*	IPN
Winter ulcers	*Vibrio viscosus*	ISA
Cold water vibriosis	*Vibrio salmonicida*	PD
Enteric Redmouth (ERM)	*Yersinia ruckeri*	
Furunculosis	*Aeromonas salmonicida*	

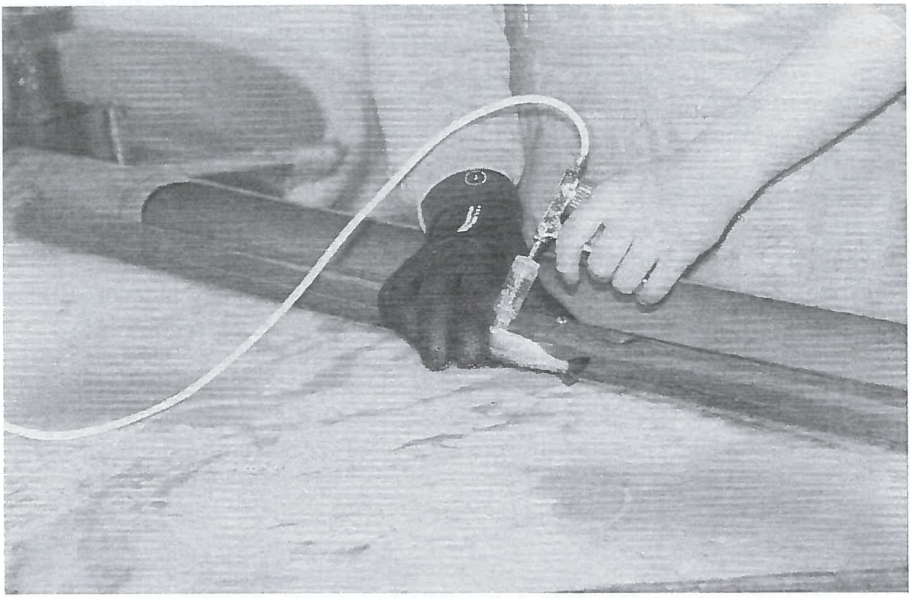


Figure 10.2. Fish vaccination. Fish are injected intraperitoneally with the vaccine using a multidose syringe. Many vaccines contain oil adjuvants which can cause persistent inflammation if injected into tissues. Note the gauntlet worn by the person vaccinating the fish to prevent self injection.

10.3.2 Methods of vaccination

Current commercial vaccines for Atlantic salmon are usually delivered by injection into the body cavity in an oil emulsion which serves as an adjuvant to enhance and prolong the immune response. It is essential for injection vaccination that fish are anaesthetised, not merely to facilitate handling but to avoid excessive stress.

The vaccine is usually injected using multi-dose syringes (Figures 10.2 and 10.3). Fish are injected immediately anterio-laterally to the pelvic fins, with the syringe held at an angle of about 25° to the body surface so that the vaccine enters the peritoneal cavity with a minimum risk of damaging the underlying organs. Commercially-available vaccines are mostly formulated for a dose rate of 0.1 ml independently of the fish size.

The rate of injection achieved depends on the individual weight of the fish and the skill of the team. Over a sustained period an experienced handler will inject 1000–1200 fish per hour while semi-automated machines can inject up to 4000 fish per hour.

Injection vaccination induces long-term protection and the cost per dose is very small. Atlantic salmon are usually vaccinated some months prior to transfer to seawater so that the protective immunity has time to develop before the fish faces the stress of transportation and exposure to the pathogens encountered in the marine

Figure 10.3. Fish vaccination. Fish are injected intraperitoneally with the vaccine using a multidose syringe. Many vaccines contain oil adjuvants which can cause persistent inflammation if injected into tissues. Note the gauntlet worn by the person vaccinating the fish to prevent self injection.

environment. However, it is labour intensive and relatively slow and becomes impractical when fish are below 15 g. Furthermore, these vaccines are not without side-effects and visceral adhesions have sometimes caused down-grading of carcasses and lower growth rates have been reported (Midtlyng *et al.*, 1996; Midtlyng and Lillehaug, 1998).

10.4 MANAGEMENT OF THE PATHOGEN

10.4.1 Avoidance or elimination of the pathogen

10.4.1.1 Use of pathogen-free water

Most water supplies usually contain wild fish which may act as a reservoir of pathogens, placing a farm at risk. However, some water supplies are free of potential sources of infection; these are mainly groundwater supplies like natural springs or artesian wells. These so-called 'protected water supplies' are very limited but are invaluable for hatcheries where fry can be reared to a more resistant age before being placed into exposed sites. This is particularly useful in controlling losses from certain diseases like IPN where first feeding fry are highly susceptible but older fry are more resistant.

10.4.1.2 Disinfection of water supply

As an alternative to natural sources of pathogen-free water, water supplies can be disinfected. There are three methods of achieving this (for details see Section 10.7): namely, ultraviolet light (UV), filtration and ozonation. Ultraviolet light has its limitations since only relatively small volumes of water can be treated. Some viral pathogens, e.g., IPNV, are quite resistant to inactivation by UV, but the method is employed in salmonid hatcheries to control certain bacterial pathogens such as *Flexibacter*, *Aeromonas* and *Renibacterium*. Filtration systems include sand filters to avoid parasitic diseases and possibly bacteria. More sophisticated and expensive methods are a series of filter plates with micropores to remove particles as small as bacteria. Ozone treatment has recently been introduced in salmon smolt units in both Scotland and Norway. These have capacities to disinfect 25,000 litres/minute. Retention tanks are required to retain treated water until the ozone converts to oxygen before supplying the fish. This has the bonus of enriching the oxygen in the water.

10.4.1.3 Eliminate vertical transmission of pathogens

Several pathogens can be present in the gonadal fluids of infected brood fish and persist either in or on the eggs to infect the next generation of fry. Pathogens that can persist within the ova are IPNV and *Renibacterium salmoninarum*. Others may persist on the ova and infect fry on hatching, e.g., *A. salmonicida*.

Disinfection of eyed-ova to remove pathogens on the surface is relatively simple, safe and effective (see Section 10.7.1 for details). Iodine-based disinfectants (iodophores) are usually used at the eyed stage of ova. However, disinfection procedures to remove pathogens which might be inside the egg are not so straightforward. These have been practised to control IPN where eggs and milt are treated with iodophore before and during fertilisation to prevent the virus entering the micropore with the sperm at the moment of fertilisation. While this procedure is considered to decrease the chances of vertical transmission, it is not completely effective and toxicity of the disinfectant to the gametes can also result in considerable egg mortality or abnormal development of the embryos. Egg-disinfection procedures are not effective when the pathogen is already inside the egg before spawning, as may occur with *R. salmoninarum*, the causative agent of bacterial kidney disease (BKD).

A relatively successful strategy of significantly reducing, but not eliminating, vertical transmission of *R. salmoninarum*, has been to inject broodstock females with certain antibiotics, e.g., erythromycin, oxytetracycline or rifampicin, into the dorsal sinus, 2–3 weeks prior to spawning. Brown *et al.* (1990), have demonstrated this to be effective using infected stocks.

The most effective means of controlling vertical transfer is to test for pathogens in broodstock at the time of stripping. Ovarian fluid, milt and blood can be sampled from live fish and kidney samples taken from fish which are killed after spawning. These should be tested by laboratory techniques for the suspect pathogen. While this is being done, the batches of eggs are incubated separately in the hatchery and, if subsequently the samples are found to be infected, the eggs should be destroyed.

Such practice has been applied in Scotland with respect to IPN and BKD and the extremely low prevalence of IPN in freshwater in this country can be attributed to this policy.

10.4.1.4 Eradication of infected stock

Obviously, commercially this is a drastic step to take, especially when no country provides state compensation even when state regulations might require eradication of stock. It is practised only rarely and when potentially calamitous circumstances may result, for instance the introduction of an important exotic pathogen into an area previously free of that disease. This has occurred in Scotland where the European Commission directives have required compulsory slaughter of stock infected with ISA.

10.4.1.5 Avoid infected stock: certification programmes

Many countries employ regulations to prevent the movement of eggs or fish infected with certain so-called 'notifiable' diseases from an infected to a non-infected site. These policies are designed to limit the spread of the disease but require specialised sampling procedures and laboratory facilities to perform the diagnostic techniques. These facilities can perform frequent tests and stocks can be certified to be free of certain diseases. Such certification is required for international trade in live fish and eggs but within a country it is widely practised voluntarily since stock certified to be 'disease-free' command premium prices.

10.4.1.6 Facility design

Farms and husbandry practices can be designed in such a way as to avoid the introduction of disease agents and to restrict their spread within a farm in various ways.

Isolate the hatchery. If a pathogen-free, protected water supply can be used to supply a hatchery, it is important not to introduce infections from the surface water supplying the growers in other parts of the farm. The hatchery should stand apart and strict hygiene standards applied to all equipment and personnel entering it.

Hygiene practice. Limiting the spread of disease agents on a farm should be practised at all times. Such practices include having hand nets for each tank and disinfecting the net after each use. Disinfection footbaths at the farm entrance and between buildings, restricted movement of personnel, protective clothing and other equipment are important management practices. Prompt removal and safe disposal of dead and moribund fish is essential as large numbers of pathogens are shed into the water from such fish. In small tanks this is easy to do with hand nets, but in large sea cages lifting the nets is very stressful to the fish and to use divers is expensive. Recent modifications to the construction of cages fitted with 'dead-socks' have proven highly successful. These nets are constructed with a funnel-shaped extension (a holster) to the bottom of the cage in which rests a net lining or 'sock'. Dead fish fall into the sock and, with a pulley system, the sock can be hoisted out of the water and the dead fish removed. By this method dead fish can be removed daily with little effort to farm personnel and little stress on the fish. Another method of removing dead fish is by airlift pump systems. Proper disposal of dead fish is essential. Methods used include incineration, rendering, ensiling and, on a small scale, in limed pits.

10.4.1.7 Breaking the pathogen's life cycle

This is referred to as all-in, all-out practice, or fallowing (see Section 10.4.1.8). If a disease is introduced onto a site, it is important to restrict horizontal spread, especially to different year classes of fish. Hence, before a new year class of fish is introduced to a part of the farm, all tanks, equipment, etc. should be thoroughly cleaned and disinfected. In sea-cage sites it is a useful technique to physically separate year classes to break the infection cycle.

10.4.1.8 Fallowing and management agreements

Most specialised pathogens do not survive for long periods outside their hosts, and allowing a site to fallow for a period may eliminate or drastically reduce the pathogen load. In seawater Atlantic salmon farming, this principle has led to companies sharing a sea loch infected with furunculosis to arrange for simultaneous harvesting of stock and to allow several weeks to pass before introducing new smolts which are certified free of furunculosis. This has contributed to the dramatic fall in annual outbreaks of clinical furunculosis on marine farms. Furthermore, serious outbreaks of sea lice have also been reduced, at least in the first year in seawater, the lice population building up again in the second year but to levels requiring fewer treatments before harvesting fish. The practice of fallowing has proved very effective in controlling furunculosis and salmon lice, with the attendant improvement in stock growth and survival and the decreased need to employ expensive medicinal treatments with their problems associated with tissue residues, environmental effects and resistance to chemotherapeutants in the pathogens.

10.5 DEALING WITH DISEASE PROBLEMS

Fish should be observed closely at all times to monitor their health. The first signs of a problem include lack of a feeding response, lethargy, darkening of skin colouration, abnormal swimming, pale gills, frayed and eroded fins and loss of good skin condition. Such observations should then lead to a detailed examination of the fish and collection of samples for further analysis. Depending on the nature of the disease problem and facilities available on the farm, the involvement of specialist diagnostic laboratories may be necessary to deal with the problem. The first stage is to examine and record all the signs and then perform tests leading to a diagnosis. Following this, remedial action should be taken to control and alleviate the problem.

10.5.1 Methods of examining fish and what to look for

10.5.1.1 External examination

A dissection kit, microscope and slides, fixative and bacteriological culture plates are required. Select at least five live fish exhibiting abnormal signs. Dead fish can be examined but are not usually suitable for taking samples for further analysis because within 10–20 minutes of death the tissues break down and become invaded by environmental bacteria which mask the presence of the primary cause of the disease. Before sampling live fish, behavioural patterns should be noted. An anaesthetic agent (e.g., benzocaine, MS-222) dissolved in water is the recommended method of killing fish.

Some of the common lesions to look for are illustrated in Plates I and II. Note and record the general condition of all external surfaces of the fish, paying particular attention to raised or lost scales, areas of discolouration, parasites, location of any lesions, swelling of the abdomen and any suggestion of skeletal deformity or muscle atrophy. Examine the eyes for cloudiness of the cornea, cataract, exophthalmia and any signs of blood, exudate or oedema. All fins should be examined for evidence of erosion, fraying, necrosis, small coloured spots, raised areas or haemorrhage. Both the normal skin surface and the margins of any lesion should be examined, and bacteriological samples taken from developing wounds rather than larger lesions as these are subject to secondary contamination. Swabs should be plated aseptically onto an appropriate culture medium (see Appendix 10.1) for later bacteriological examination. Examine fresh skin scrapes microscopically for bacteria, protozoa or fungal hyphae. Samples from the edge of lesions may be fixed for light microscopy. Examine the oral cavity and anus for any discolouration, raised areas or parasites. Faecal material, if present, should be examined microscopically. The weight and length of the fish should be determined and other relevant information recorded including group and year class, feeding regime, stocking density, water temperature, percent mortality, first observation of disease signs, any recent treatments or handling and changes in water quality.

10.5.1.2 Internal examination

If required, a blood sample should be taken before dissecting the fish. During dissection examine each organ and note any abnormalities concerning size, colour, consistency, presence of haemorrhages and fluid in body cavities. Bacteriological samples should be taken with a sterile loop and spread on a suitable culture medium (see Appendix 10.1). Portions of the organs can then be removed and fixed for light microscopy. Buffered formal saline is a good general purpose fixative (see Appendix 10.1).

10.5.2 Further analysis and diagnosis

10.5.2.1 On site

Fresh material spread on microscope slides can be examined immediately under the microscope and the presence of bacteria, fungi and microparasites can be readily observed in skin, gill and gut scrapings. Many abnormalities of gill filaments, e.g., swelling, fusion, aneurysms and erosion, can also be seen in fresh preparations. Smears of internal organs (especially kidney) suitably fixed and stained (e.g., by Giemsa or Gram stains, see Appendix 10.1) can reveal the presence of bacteria, fungi and protozoan parasites.

Many diseases, especially in salmon hatcheries, are caused by opportunistic pathogens following a stressful event (e.g., exposure to poor water quality during a spate). These include the Cytophaga group of bacteria, the fungus *Saprolegnia* and several protozoan ectoparasites. Many of these can be presumptively diagnosed on the site from examination of the fish as described above. An examination of the farm records to see whether any changes occurred in husbandry and the environment will also be helpful. Remedial actions can then be determined including treatments (see Section 10.6) if necessary, but bear in mind that most of these diseases are caused by suboptimal environmental factors and if these are not remedied the problem will persist even after treatment. Remedies mainly comprise bathing in chemicals such as salt, formalin, copper sulphate, chloramine T and malachite green which are frequently (but not always, see Section 10.6) available to the farmer. In the marine environment, the most common and significant parasitic problem is sea lice, which are easily diagnosed. Therapies for lice infestations include a variety of bath as well as in-feed treatments, all of which are subject to veterinary and environmental controls.

Further diagnostic procedures require specialised laboratory facilities and tests, and treatments require veterinary prescriptions.

10.5.2.2 In the laboratory

Laboratory tests require special skills and equipment and a detailed description of these methodologies falls beyond the scope of this book. Therefore, only a brief description of these methods and their applications will follow.

10.5.3 Microscopy and histopathology

Many protozoan ecto- and endo-parasites and fungal pathogens can be identified by microscopic examination of smears and histological sections. Bacteria may be observed but for species identification, and more importantly, for deciding on treatment, antibiotic sensitivity testing requires other kinds of tests including culture.

The main value of microscopy is to analyse the histopathology of a disease which, to a trained pathologist, can provide important clues to the nature of the cause because different diseases produce different pathologies and some features may be associated only with certain diseases. However, other confirmatory tests are usually required to make a definitive diagnosis with respect to bacterial and viral pathogens.

This technique requires tissues to be fixed (12–24 hours), embedded in paraffin wax (24 hours) sectioned and stained (12 hours).

10.5.4 Culture methods

10.5.4.1 Bacteria

Tissues from the fish are sampled with a sterile loop and spread on nutrient agar plates, usually tryptic soya agar (TSA), which is supplemented with 2% NaCl for isolation of marine bacteria [see Appendix 10.1]. The plates are incubated at about 20°C for 48 hours to grow up bacterial colonies. The bacteria can be identified by a variety of morphological criteria and biochemical characteristics for which commercial kits are available. This species identification takes another 48 hours. However, the most important aspect of bacterial culture is determining the antibiogram in order to select the appropriate antibiotic for treatment. Following initial isolation on plates from the fish, colonies are sub-cultured as a lawn on a fresh plate upon which are placed filter paper discs containing a range of antibiotics. The antibiotic diffuses into the agar medium and prevents the growth of sensitive bacteria around the disc (Figure 10.4). This test can usually be read after about 24 hours.

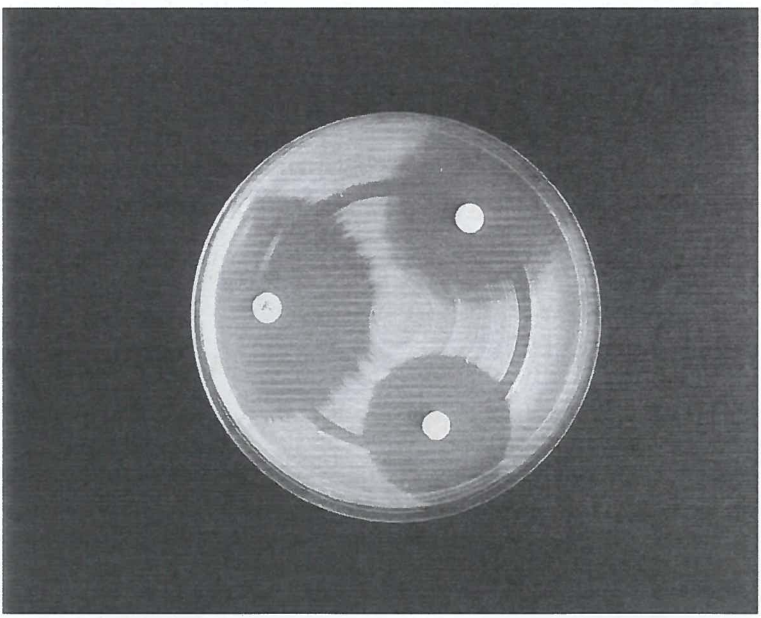


Figure 10.4. Antibiogram to determine the resistance/susceptibility of bacteria to antibiotics. Filter paper discs containing different antibiotics are placed on a nutrient agar plate which has been spread with a dilute suspension of the test bacterium. The antibiotics diffuse into the agar and inhibit the growth of susceptible bacteria. At a distance the bacteria grow and produce a cloudy film on the agar surface.

10.5.4.2 Viruses

Isolation of viruses is performed in tissue culture (Figure 10.5). Various tissues, but most commonly kidney, are excised from the fish, homogenised, centrifuged and the supernatant filtered through a micropore filter (0.45 µm) to exclude any contaminating bacteria. The filtrate is then inoculated into horizontal tissue culture flasks containing a nutrient medium overlying a monolayer of immortalised fish cells. The latter were originally obtained from fish embryos and are commercially available. After 7–14 days of viral replication in the cells, degenerative changes occur, termed a cytopathic effect (CPE), which may be characteristic of a particular virus and can be used for an initial diagnosis. However, confirmation is still required and this involves identifying the virus with a panel of antibodies specific for different viruses. A particular virus will be recognised only by its specific antiserum. The antibody reagents used may be whole antisera, usually produced in rabbits, or mouse monoclonal antibodies. These reagents can be used to neutralise the infectivity of the virus in tissue culture or to identify the virus by immuno-fluorescent antibody techniques (IFAT) or enzyme-linked immunosorbant assays (ELISA) techniques (see Sections 10.5.5.1 and 10.5.5.2).

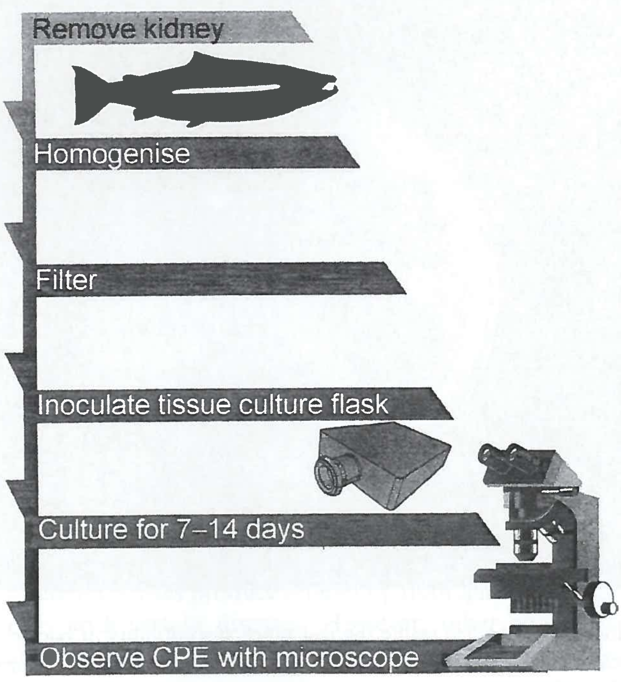


Figure 10.5. Method of viral diagnosis by tissue culture. Cytopathic effects (CPE; degenerative changes) observed using a microscope.

10.5.5 Indirect diagnostic methods

One problem with culture techniques is the length of time taken to identify a pathogen, but they are the most sensitive and accurate methods, and for bacteria it is essential for determining the antibiogram, especially when the bacteria may have developed resistance to some of the commonly-used antibiotics. However, to speed up the process of pathogen identification two other approaches have been developed using antibody or nucleic acid probes.

10.5.5.1 Immuno-fluorescent antibody techniques

Antisera produced in rabbits or mice to specific pathogens are incubated with tissue smears or sections from infected fish. If the bacterial or viral antigens are present in the sample the specific antibodies will bind to them. The sample is washed and the remaining antibodies are detected using a commercial secondary antibody, specific for the first antibody, conjugated to a fluorescent dye which can be visualised in a microscope using UV light.

This technique is fairly sensitive and very rapid. However, there are three drawbacks. First, antibodies can sometimes cross-react with other material present in the sample, giving a false positive. Second, the technique does not distinguish between live and dead pathogens and some antigens can persist in fish tissue for many weeks after an infection or vaccination. Thus, this technique would detect persisting antigen unassociated with a current infection. And third, for bacterial infections, it gives no information on antibiotic sensitivity profiles.

10.5.5.2 Enzyme-linked immunosorbant assays

This is a variation of IFAT, but instead of using a fluorescent-conjugated antibody it uses antibody conjugated to an enzyme which on reaction with a substrate gives a colour reaction that can be read by eye or in a spectrophotometer. It has the same drawbacks as IFAT.

10.5.5.3 Nucleic acid probes

Besides possessing specific antigens, all species contain portions of genetic material (DNA or RNA) that are species specific and can be detected using species-specific gene probes. Using an amplification technique, called the polymerase chain reaction (PCR), this method can theoretically detect the presence of a single copy of a gene sequence in a sample and so has the potential of being exquisitely sensitive. However, when using DNA or RNA extracts of whole fish tissues, this degree of sensitivity is difficult to achieve in practice because of inhibitors of the PCR in the tissues.

10.5.5.4 Application of antibody and nucleic acid probes

Although these techniques have their limitations compared with culture techniques they have an advantage when the pathogen is difficult to culture. Such is the case for *R. salmoninarum*, which can take up to ten weeks to grow in culture, and some viral pathogens like PDV and ISAV which are very difficult to culture from infected fish or produce no or slight CPE in tissue culture cells. In the latter case, a combination of culture isolation with IFAT or PCR on infected tissue culture cells can be used.

10.6 TREATMENTS

The use of chemotherapeutants is becoming ever more restricted and different countries have different licensing regulations. It is therefore difficult to provide definitive information on treatment methods and this chapter is based on what is currently allowed in the EU. The reasons for restriction concern the safety of the consumer and protection of the environment.

Consumer-based regulations have two aspects. Firstly, to guarantee the fish for human consumption are not toxic to eat, a maximum residue level (MRL) has been defined for each drug and for each species and tissues of food animals. Thus, if salmon are treated with chemotherapeutants, a certain withdrawal period must be defined (usually in degree-days which is water temperature multiplied by number of days) to allow the drug to be eliminated from the tissues to below the MRL before the fish can be marketed for eating. This allows a further cautionary measure to be taken since the ingestion of low levels of certain drugs can induce development of resistance in pathogens. Thus the MRL regulations avert the possibility of drug resistance in potential human pathogens.

Environmental regulations are enforced through 'discharge consents' given by Environmental Agencies. This ensures that the level of chemotherapeutants discharged by a fish farmer into the environment is safe for other organisms in the vicinity. A good example of this is the use of chemicals to control sea lice in Atlantic salmon sea cages. These chemicals are also toxic to other crustacea and care must be taken not to affect these organisms in the environments of the farm.

Apart from the above concerns with chemotherapy, a further difficulty with this method of disease control is the development of resistance to the drugs. During the late 1980s *Aeromonas salmonicida* developed resistance to many of the approved antibiotics and cases of sea lice developing resistance to dichlorvos (Aquagard) have been reported (Jones *et al.*, 1992). To avoid this a regular rotation of drugs should be used but this requires a varied arsenal of drugs to be available and the cost of defining MRLs and discharge consents is prohibitive for the licencing of many new chemotherapeutants. Thus, the emphasis for disease control is on improved management techniques and vaccination.

Table 10.2 lists the most common diseases of Atlantic salmon, the principal signs of these diseases and recommended methods of control and treatment.

10.7 DISINFECTION PROCEDURES

In aquaculture disinfection is an important procedure to control infectious diseases but care and skill is essential to avoid damage to fish, equipment, personnel and the

Table 10.2. Freshwater stages.

Cause	Signs	Prevention	Treatment
Environmentally Based Diseases			
Gill inflammation: irritation from poor water quality or incorrect use of chemotherapeutant baths. Excess mucus production can lead to secondary growth of environmental bacteria, protozoa or fungi which exacerbate the condition (see below).	Fish swim at surface, near water inlet, gasping; flared operculum. Inappetance. Excess mucus on gills. Gills pale with blood spots. In severe cases gill lamella become clubbed at the tips and fuse together.	Maintain good water quality.	Increase water flow, reduce fish density, remove particulate matter in water supply and tanks; aerate. Secondary colonisation of inflamed gills treated with Chloramine-T. Protozoan infestation treated by bathing in salt or formalin.
Gas-bubble disease: occurs in hatcheries using bore-hole water. Caused by supersaturation of water with gases mainly N_2.	Inappetance, no other clear signs. Small bubbles on gills seen in microscope. Damage to gills and other blood vessels lead to secondary infections.	Ensure water supply is not supersaturated with gases.	Remove excess gas with de-aeration cascade systems which by breaking up the water equilibrates it with air.
Opportunistic Pathogens			
Bacteria			
Cytophage-like bacteria (CLB). Cold water disease; fin rot, tail rot, gill disease, 'saddleback'.	Whitish appearance on fins leading to fraying, erosion and loss. 'Saddleback'—loss of dorsal fin and surrounding skin. Gills pale, excess mucus, haemorrhage. Occurs at low temperature: late winter, early spring.	Maintain good water quality. Avoid overcrowding, low O_2, suspended solids, high ammonia.	As for gill inflammation. Bacteria killed in 1–5% NaCl bath for 1–2 minutes.

(*continued*)

Table 10.2—(*continued*)

Cause	Signs	Prevention	Treatment
Fungi *Saprolegnia*: A secondary pathogen infecting fish in poor health or following physical trauma, e.g., following injection vaccination in loch systems. Also affects unfertilised and dead eggs, overgrowing and killing neighbouring eggs. Male broodstock susceptible.	Fluffy white masses occurring on fins, skin, gills and eggs.	As for opportunistic bacteria.	Eggs and fish can be treated by bathing in malachite green 1–2 ppm for one hour. Remove affected eggs. Use of malachite green is restricted in fish. A useful alternative may be bronopol formulated as Pyceze (Pottinger and Day, 1999) 50 ppm for one hour.
Ectoparasites *Protozoa*: Severe infestation is usually indicative of adverse environmental conditions which should be improved. Bath treatments can produce additional stress and worsen the situation. Healthy fish can thrive well even when infected with many of these parasites.			
Costia:	White-blue cloudy layer on skin. A flagellate parasite attached to skin or gills can be identified in fresh scrapings with microscope.	As above.	Immerse fish in formalin bath: 1 ml commercial formalin (37% formaldehyde) in 4–6 l water for one hour.
Hexamita:	Nervous behaviour of fish. Dark colour. Faecal pseudo-casts. Internally hind gut appears pale. Rapidly-swimming parasite microscopically observed in fresh mounts of hind intestine contents.	As above.	Medicated feed on prescription e.g., Dimetridazol or magnesium sulphate, 200–300 mg/kg food, fed for five days.
Obligate Pathogens *Bacteria:* *Aeromonas salmonicida* Agent of furunculosis. Outbreaks occur at or above 15°C, asymptomatic infection at lower temperatures. Also problem in seawater where it spreads from carriers through water.	Dark colour. Haemorrhagic fin base. Occasionally swelling in muscle which erupts as a haemorrhagic deep abscess. Diagnosis is by culture of bacterium.	Exclude pathogen. Disinfect eggs. Minimise stress. Mortalities are stress-associated in carrier populations. Vaccinate.	Following antibiogram, treat in feed with appropriate antibiotic (may include oxytetracycline, oxolinic acid, potentiated sulphonamides, flumequine or amoxycillins, dependant on local regulations).
Renibacterium salmoninarum Agent of BKD. Can affect Atlantic salmon of all ages and can be vertically transmitted within ova, making egg disinfection useless. Mortalities occur mainly in Spring.	Few external signs. Some fish have exophthalmia and swollen belly. Internally, a pale, opaque membrane encapsulating spleen, liver and heart. Kidney swollen with white/grey nodules. Enlarged spleen. Typical Gram- positive bacteria observed microscopically in kidney smears. Diagnosis by histopathology, culture, IFAT, ELISA.	Exclude pathogen. Purchase eggs from certified broodstock. Eradicate infected broodstock and eggs.	Medicated (erythromycin) feed may control mortalities but does not eliminate the bacterium which persists. In UK, hatchery stock is eradicated and site disinfected.
Viruses *Infectious Pancreatic Necrosis* Mortalities mainly in first-feeding fry. Older fish are asymptomatic carriers (see also Marine Stages). Can be vertically transmitted.	Dark colour, swollen belly, white mucoid, pseudo-faeces trail from anus. Uncoordinated spiral swimming. Internally, pale organs, small haemorrhages amongst caeca, intestine is slack without food and contains milky yellow slime.	Exclude pathogen. Purchase disease-free certified eggs, fry. Iodophore disinfection of eggs effective if performed during fertilisation. Vaccines becoming available.	No treatment. Test broodstock and eradicate carriers and their eggs. Following transfer to already infected sea site disinfect hatchery. Restock with certified eggs/fry.

(*continued*)

Table 10.2—(*continued*)

Cause	Signs	Prevention	Treatment
Seawater (Marine) stages			
Environmentally-based diseases			
Cataracts: Cause attributed to several factors including nutritional deficiencies (methionine, zinc, riboflavin), intoxication, osmoregulatory difficulties, mechanical damage. Cause often not identified. Temporary and permanent cataracts may occur.	Uni- or bi-lateral opacity of lens. Blindness. Mortality usually low.	Not known.	Untreatable.
Planktonic blooms: Physical damage to gills by silicate skeleton of diatoms (e.g., *Chaetoceros, Distephanus*). Some dinoflagellates, e.g., *Alexandrium* (red tides) produce lethal toxins.	Fish gasp at water surface. Erratic swimming. Destruction of gill epithelium, gill haemorrhage. Mortality can be very high. Planktonic organisms can be identified microscopically.	Avoid blooms by towing cages to clean water. Do not feed and keep handling to a minimum.	Affected fish may recover in low stocking density and minimum stress. Secondary bacterial infections (e.g., *Vibrio*) may require treatment. Remove dead fish.
Failed smolts: Incomplete smolting causing poor osmoregulation, stress and poor feeding response.	Thin emaciated post-smolts usually 8–12 weeks following transfer to sea.	Ensure all fish in cage have opportunity to feed to satiation. Appropriate stocking density.	Include a reduced pellet size in feed. Failed smolts can be removed and successfully rehabilitated in fresh water before returning to sea water.
Infectious diseases			
Bacteria			
Vibriosis: Usually caused by *Vibrio anguillarum* which is constantly present in the marine environment. Outbreaks are usually stress related, especially following abrasion of the skin on nets (e.g., following seal attack) or gill damage from poor water quality (plankton blooms, over-stocking, net and bottom fouling).	Anorexia and dark skin. Haemorrhages around anus, base of fins, skin ulceration and underlying muscle necrosis. Pale gills (reflecting anaemia). Internally organs are haemorrhagic and oedematous. Diagnosis by culture of bacterium.	Maintain good husbandry conditions. Vaccination of pre-smolts very effective.	Following antibiogram, treat with appropriately medicated feed, e.g., oxytetracycline, quinolones, potentiated sulphonamides or florfenicol.
Cold Water Vibriosis: Caused by *Vibrio salmonicida*. Mainly present in Norway. Bacteria survive in sediments and sea water for many months.	Occurs mainly during winter. Fish lethargic. Haemorrhages in abdominal skin, especially around fins and anus. Internal organs are pale and haemorrhagic. Liver yellowish with pin-point haemorrhages. Kidney swollen. Spleen brick-red. Anaemia. Diagnosis by culture of bacterium.	Vaccination of pre-smolts very effective.	Following antibiogram, treat with medicated feed.
Winter ulcers: Caused by *Vibrio viscosus* or *Vibrio wodanis*. Occurs in winter/spring.	Superficial circular skin ulcers surrounded by scale loss. Confluent sores may cover large area. Internally, liver is pale, yellowish with pin-point haemorrhages. Kidney and spleen swollen. Diagnosis by culture of bacterium.	Maintain good husbandry. Vaccination.	Following antibiogram, use appropriate medicated feed.

(*continued*)

Table 10.2—(*continued*)

Cause	Signs	Prevention	Treatment
Furunculosis: Transfer of asymptomatic carrier smolts from fresh to seawater can result in high mortalities and spread the disease to neighbouring sites.	As per freshwater.	Vaccination of pre-smolts most effective method. Purchase certified smolts.	Antibiotic treatment as for freshwater. Fallow site.
Bacterial Kidney Disease: As for freshwater. Main problem concerns broodstock selection as bacterium can be transferred within ova and are resistant to disinfection.	Mortality in seawater unusual. Diagnosis by culture, IFAT, ELISA or PCR.	Main source of infection is from carrier stocks infected in freshwater or by vertical transmission. Use certified smolts.	Broodstock should be tested and infected fish and ova destroyed.
Piscirickettsiosis: Caused by *Piscirickettsia salmonis*. Problem mainly in Chile, but reported also in Europe. Is an intracellular pathogen.	Fish are dark and lethargic. Gills pale, raised patches on skin, small shallow ulcers. Internally, fluid in body cavity, swollen spleen and kidney. Liver mottled. Extensive pin-point haemorrhages in viscera and flank muscles. Diagnosis is by culture (in tissue culture cell lines) or by IFAT.	Reduce impact by removing dead fish. Year class separation. Fallowing and disinfecting procedures.	Medicated feed (oxolinic acid, oxytetracycline). Prolonged or repeated treatment may be required, because the pathogen only grows within host cells and is protected from antibiotics.
Virus Diseases			
Infectious Pancreatic Necrosis (IPN): Once considered a cause of mortality only in first-feeding fry, this disease is considered to cause up to 30% mortality in post-smolts in farms in Norway and Shetland, mainly in early–mid summer.	Inappetance, erratic swimming. Sloughing of gut lining, emaciation. Diagnosis by culture of virus in tissue culture cell line (takes up to 14 days). Quicker methods include IFAT, ELISA and PCR.	Transmission can be vertical or horizontal. Carriers excrete virus. Stock away from infected sites and at low densities. Use certified IPN-free smolts. Egg disinfection (iodophores) must be done at time of fertilisation. Test broodstock and gametes, destroy infected eggs. Vaccines becoming available.	Restrict movement of carrier smolts to already infected sites. Safe disposal of dead fish. Incinerate or render. Silaging requires heating to be 60°C for two hours to inactivate virus which is resistant to acid pH. Disinfect equipment with chlorine (200 mg/l for one hour) or iodophores.
Infectious Salmon Anaemia (ISA): Present in Norway, Canada and Scotland. Mortality highest in spring and early summer.	Fish lethargic. Haemorrhaging in eyes, gills pale, often with dark base. Abdomen distended with fluid. Internally, liver very dark, spleen dark and swollen. Pin-point haemorrhages in many visceral organs. Severe anaemia. Diagnosis is by culture of virus but this can be difficult. Supplementary diagnosis is by histopathology, IFAT or PCR.	Transmission is horizontal from fish and slaughter waste. Sea trout can be asymptomatic carriers. Disinfection of slaughter house waste, equipment and well boats. Vaccine available in Canada.	Eradication of stock on cage or site basis. Removal of dead fish and safe disposal. Harvest as soon as possible, disinfect equipment, fallow site. Current European legislation requires eradication only if mortalities occur. Movement of asymptomatic carrier fish is prohibited.
Pancreas Disease: Occurs in post-smolts and growers in Scotland, Ireland and Norway, usually in July/August.	Inappetance, lethargy. Rapid loss of weight. Internally, pin-point haemorrhages in caecal area. Empty gut. Post-smolts can recover quickly but not growers which become emaciated and must be culled. Virus very difficult to culture. Diagnosis by histopathology of pancreas which becomes necrotic with total loss of acinar cells.	A wild reservoir is suspected in the marine environment but horizontal transmission occurs experimentally. Vaccines becoming available.	No known treatment. Starving fish for a few days thought to reduce severity of outbreak. Post-smolts recover quickly and develop long term resistance.

(*continued*)

Table 10.2—(*continued*)

Cause	Signs	Prevention	Treatment
Parasitic Diseases *Protozoa* *Paramoebic Gill Disease*: Caused by *Paramoeba spp.* Problem in Tasmania, mainly in summer and in high salinity water (32–35 ppt).	Inappetance, lethargy. Fish swim with open opercula. Fusion of gill lamellae. Diagnosis by microscopic identification of parasite.	No known prevention.	Low salinity water aids osmotic regulation but 5ppt salinity required to kill pathogen. Hydrogen peroxide (200–400 ppm) may be helpful.
Sealice: Mainly *Lepeophtheirus salmonis* and *Caligus elongatus*.	Early signs are patches on head and base of dorsal fin. Adult lice easily seen by naked eye. Lice graze on skin and can produce large areas of skin loss especially on head. Mortality due to osmotic stress and secondary infections.	Fallowing site breaks life cycle on farm delaying build up which eventually occurs by transmission from wild fish.	Chemotherapy by bathing in organo-phosphates e.g., dichlorvos (Nuvan) 1 ppm for 1 hour; hydrogen peroxide 1500 ppm, 20 mins; cypermethrin (Excis[R]) 5 ppb, 1 hour. Only adults are killed and repeated treatments are necessary. In-feed with Calicide[R] Cleaner fish (wrasse). Fallow site.

environment. The manufacturer's recommended procedures should be followed precisely.

10.7.1 Disinfection of eggs

Iodophores (e.g., Buffodyne®, Wescodyne®) contain iodine and a surfactant. Effective concentration is 100 ppm available iodine. Newly-fertilised and eyed eggs can be disinfected in water but green eggs require the iodophore to be diluted in 0.9% saline. This prevents the influx of the iodophore into the egg before water hardening which would be toxic to the embryo. Eggs should be exposed to the iodophore for ten minutes.

10.7.2 Disinfection of equipment

Equipment must first be cleaned to allow access of the disinfectant.

Iodophores are rather slow acting but less corrosive than sodium hypochlorite (see below). They are suitable for spraying tanks, bins, vehicles, storing nets and footbaths.

Sodium hypochlorite is purchased as dairy hypochlorite. It is cheap, rapid in action and readily available. Dilute with water to 100 ppm available chlorine. Do not store for more than three months. Suitable for nets, boots, tanks. Wash with water after disinfection.

10.7.3 Disinfection of water supplies and hatcheries

10.7.3.1 UV from low-pressure mercury lamps

Effective only up to 6 mm away from lamp. Commercial systems use lamps with about 8700 hours of use and can disinfect about 4000 l water/hour.

10.7.3.2 Ozone

Large ozonaters require specialised installation. Ozone (produced electrically) is injected into water in a closed vessel. Equipment is expensive but the running cost is low. It can disinfect up to 25,000 l/minute. Contact time of 2–6 minutes is sufficient to kill most bacteria and viruses. For safety to fish the residual level must be below 0.002 mg/l. Ozone breaks down naturally but slowly (half life 20 minutes) so sufficient residence time in the holding tank is therefore necessary. Degradation (to oxygen) can be accelerated by addition of hydrogen peroxide (H_2O_2) or exposure to UV. A further problem can be the fact that ozonation of seawater can lead to the liberation of bromide ions which are very toxic to aquatic organisms. However, bromide ions can be removed by passing ozonated water through activated carbon.

10.8 FUTURE PROSPECTS

In spite of the fact that salmon culture is still in its infancy, there have already been a number of marked changes in the profile of diseases that affect the industry across the world. This should not come as any real surprise. It is well known that the relationship between animal and plant species and the diseases which afflict them is highly dynamic, characterised by constant adaptations to the defensive mechanisms in the host and offensive mechanisms in the pathogens. In fish culture, the pace of these adaptations is accelerated by both the sheer numbers of organisms involved and the constant reduction in generation times.

These factors have led to shifts in the economic significance of a variety of salmonid diseases. Figure 10.6 is a schematic diagram representing the relative significance of the major diseases in Atlantic salmon farming over the last 20 years.

In addition to the influence of the host-pathogen relationship, the distribution and impact of disease is also influenced by both environmental and management factors. Local hydrography, water temperature and ambient ecology all impact upon the dissemination and survival of pathogens in the fish farm environment. In addition to this, management decisions regarding the choice and use of chemical therapeutics and vaccines as well as stocking policy all influence the likelihood and outcome of infection.

The prevalence and impact of different diseases appear to be always in a state of flux. For example in the late 1980s furunculosis was the most significant disease facing the Scottish salmon farming industry. This was succeeded in the early to mid 1990s by the salmon louse. More recently, IPNV in post-transfer S1 smolts has become a major concern, particularly in Norway and the Northern Isles of Scotland.

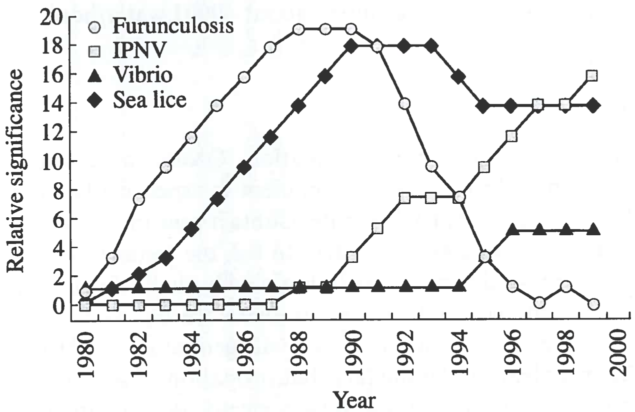


Figure 10.6. Relative significance of major diseases.

Advances in treatments and vaccine technology can explain some of this shift. The elimination or reduction of particular pathogens in farmed salmon stocks opens opportunities for other pathogens to move in. These too become targets for control and elimination and so a succession of diseases is established.

The pace of this succession is largely determined by the dynamics of the disease, and it is here that the farmer has the greatest influence. Stocking strategies (origins, densities and locations) as well as the use of vaccines and chemotherapeutics all influence these and so dictate the nature and pace of change in the disease profile in the salmon farming industry. By deploying sensible tried-and-tested strategies the industry can slow the succession of diseases and so maintain a degree of stability in the important area of health management.

APPENDIX 10.1

Buffered formal saline

Formaldehyde solution (37% w/v)	500 ml
Sodium dihydrogen orthophosphate (NaH_2PO_4-$2H_2O$)	22.75 g
Sodium chloride (NaCl)	22.5 g
Disodium hydrogen orthophosphate (Na_2HPO_4)	32.5 g
Distilled water	2 litres

Bacteriological culture medium

Commercially-available formulations of TSA are generally used for isolation of most freshwater bacteria. However, primary isolation of many marine organisms, particularly *Vibrio* spp, require this medium to be supplemented with 2% (w/v) sodium chloride.

Renibacterium salmoninarum is a special case as it has an absolute requirement for L-cysteine. The presence of serum also enhances growth. The formulation known as KDM2 or Evelyn's medium is usually used and comprises:

Peptone	10 g
Yeast extract	0.5 g
L-cysteine HCl	1.0 g
Agar	15 g
Distilled water to	900 ml

The ingredients are dissolved by heating, the pH adjusted to 6.5 and then sterilised by autoclaving. Cool to 45°C and add 100 ml foetal calf serum. This medium should be used within 1-2 weeks.

Growth of most salmon bacterial pathogens occurs within 24–48 hours when incubated at 20–25°C. However, *Vibrio salmonicida* and *R salmoninarum* should be incubated at 15°C. *R. salmoninarum* is slow growing and may take several weeks for colonies to appear.

Giemsa Stain for Smears

Working solution Add 10 drops Giemsa R66 to 10 ml of distilled water. Mix with the minimum of shaking.

Procedure
1 Smear sample on clean microscope slide and air dry.
2 Fix smears in methanol: 10 minutes.
3 Remove slides and air dry.
4 Stain slides on a rack with working solution: 10 minutes.
5 Holding the smear downwards rinse carefully with distilled water.
6 The slide can be viewed immediately or dried and mounted with a coverslip.

Gram's Stain

Solutions
(a) Crystal violet 2 g; ethyl alcohol 20 ml.
(b) Ammonium oxalate 0.8 g; distilled water 80 ml.

Mix solutions (a) and (b).
(c) iodine 1 g; potassium iodide 2 g; distilled water 5 ml.

When iodine is dissolved add 295 ml distilled water.
(d) Safranin O (2.5% in 95% ethyl alcohol) 10 ml; distilled water 100 ml.

Method
1 The smear is allowed to air dry then fixed by either passing the slide through a Bunsen flame or by pouring methyl alcohol over the slide, draining off the excess and leaving the remainder to evaporate off.
2 Flood with crystal violet solution for one minute.
3 Wash in tap water for a few seconds.
4 Cover with the iodine solution for 30 seconds.
5 Wash in tap water for 15 seconds.
6 Decolorise for approximately 30 seconds with 95% ethyl alcohol incorporating 5% acetone (this stage is critical, requiring skill and experience, otherwise interpretation of the stained smear may prove difficult).
7 Wash with tap water.
8 Counter-stain with safranin for 10 seconds.
9 Wash in tap water.
10 Blot dry and examine using the oil immersion lens.

Results
Gram-positive organisms: blue.
Gram-negative organisms: red.

FURTHER READING

Bruno, D. W., Poppe, T. T. (1996) *A Colour Atlas of Salmonid Diseases*. London: Academic Press.

11

Advances in fish immunology

11.1 INTRODUCTION

Studies of the immune system of fish, and salmonids in particular, have been making rapid progress over recent years. This chapter will give an overview of some of these advances, highlighting pathways of relevance to disease resistance in fish.

The study of immunology grew out of the observation that animals which recover from infection with a particular disease acquire immunity to that disease but not to other unrelated diseases, and this is as true for fish as it is for humans. This highlights two key features of *acquired immunity*, specificity and immunological memory, the latter allowing priming of individuals by vaccination. However, when looking through the animal kingdom (Figure 11.1), it is apparent that invertebrates lack specific defence mechanisms, although they do possess defence mechanisms that can act in a non-specific manner and without a memory component. The same appears to be true for the most primitive, jawless vertebrates, the agnatha, represented today by the lampreys and hagfish. Thus, a relatively rapid and dramatic change in the immune system occurred in early vertebrates, which some describe as a 'big bang' in immunoevolution (Kasahara, 1998; Schluter *et al.*, 1999). Rapid evolutionary change is not typical of single 'point' mutations in genes where individual nucleotides are altered. However, whole sections of DNA can be moved around within the genome by transposase activity, including the transfer of genes from one species to another (horizontal transfer of genes) by the action of retroviruses, with profound effects on the expression of particular genes (Pennisi, 1998). Thus, it is perhaps not surprising that the genes enabling a critical event in the genetic mechanisms necessary for acquired immunity, the recombination activating genes (RAG), have been shown recently to code for proteins that have transposase activity (Agrawal *et al.*, 1998), with one of these genes (RAG2) having regions homologous to a bacterial gene, bacterial integration host factor (Schluter *et al.*, 1999).

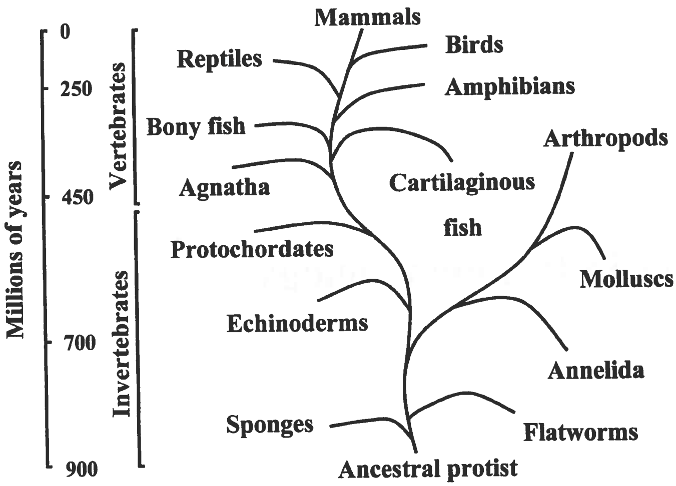


Figure 11.1. Schematic of animal evolution, depicting when the major groups appeared (branch points).

Within the body the white blood cells, or leukocytes, provide an integrated defence against infection. They consist of several different populations: the granulocytes (e.g., neutrophils, eosinophils and basophils), monocytes/macrophages, natural killer cells and lymphocytes. It is this latter population, the lymphocytes, that are the key players in acquired immunity (see Section 11.3). They possess surface receptors that recognise foreign molecules, and once stimulated via these receptors they are triggered into making an immune response. A unique genetic mechanism is used to generate millions of different receptors, so that the repertoire of foreign molecules that may be encountered during a lifetime can be recognised. However, any individual lymphocyte possesses a single receptor type, giving it a precise specificity. Relatively few lymphocytes may be able to recognise any individual molecule but during the early phase of an immune response stimulated lymphocytes undergo clonal expansion generating numerous effector cells, able to mount a response, and memory cells that provide surveillance against a subsequent encounter with the same disease (Figure 11.2). It is the latter that are vital for the protection afforded by vaccination.

Whilst inducible, specific immune responses are a critical component of overall disease resistance, they represent one facet of an integrated system to prevent infection. Prior to entering the host there are a number of barriers that must be breached, including the relatively stable physical and chemical barriers (epithelia and their secretions) that constitute the external surfaces of fish and overlaying the scales (where present). Should these be overcome then inducible non-specific defences come into play, resulting in an inflammatory response if the infection is localised. The relatively slow specific defences act as a third line of defence, providing long-term protection against persistent pathogens.

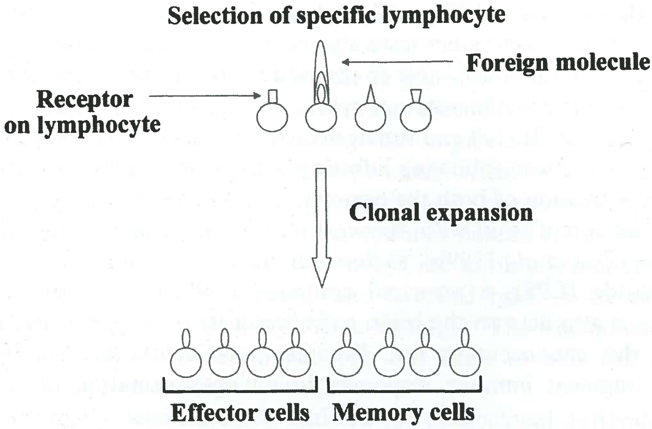


Figure 11.2. Diagram to illustrate clonal expansion of lymphocytes following cell activation by a foreign molecule.

11.2 INFLAMMATION

Inflammation is the cellular response to microbial invasion and/or tissue injury, leading to local accumulation of leukocytes and tissue fluid. A variety of factors are responsible for inducing inflammation, such as vasoactive amines or proteins (e.g., serotonin), eicosanoids (derived from membrane phospholipids) and cytokines (Secombes, 1996). Such molecules typically influence local blood vessels, allowing escape of leukocytes into the infection site, and/or act as attractants for leukocytes. Neutrophils are usually the first leukocyte type to arrive, followed by macrophages. These cells can ingest microbes (are phagocytic) exposing them to an array of antimicrobial substances.

In-depth studies of eicosanoid production by fish leukocytes have been carried out over recent years. Eicosanoids produced include prostaglandins (PG), thromboxanes (TX), leukotrienes (LT) and lipoxins (LX). PGs are formed by the action of cyclooxygenase activity, and in mammals this enzyme exists in two forms: a constitutively expressed enzyme (COX1) found in most tissues and an inducible form (COX2) expressed during inflammatory events. The gene for COX2 has been cloned recently in rainbow trout, and shown to be induced following bacterial challenge (Zou *et al.*, 1999a). Leukotrienes and lipoxins are produced by the action of lipooxygenase enzymes, and whilst these enzymes have still to be isolated in fish, it has been shown that the main products generated following stimulation of blood leukocytes are LTB_4 and LXA_4. Interestingly, dietary lipids have a marked effect on the class of eicosanoids produced, with diets rich in n-3 polyunsaturated fatty acids switching the dominant lipooxygenase products to LTB_5 and LXA_5. LT and LX are potent chemoattractants, and induce the migration of leukocytes.

A sub-group of cytokines, called chemokines, also serve to attract leukocytes during inflammatory events. To date a single member has been cloned and sequenced in salmonids (Dixon *et al.*, 1998), although several genes are known in other fish species. Receptors for chemokines have also been sequenced in trout in recent years, so the tissue distribution of cells able to respond to the produced chemokines will be known shortly. Other proinflammatory cytokines that have been found in salmonids include interleukin-1β (IL-1β) and tumor necrosis factor α. These cytokines are part of a cytokine cascade seen following infection with Gram negative bacteria, and are critical for the activation of both the non-specific and specific defences. It is already known that infection of trout with *Aeromonas salmonicida* induces the expression of the IL-1β gene (Zou *et al.*, 1999b), as does stimulation of leukocytes in culture with lipopolysaccharide (LPS), a principal component of the bacterial cell wall. In mammals, IL-1β also acts on the brain to induce a stress response and preliminary data suggest this can occur in fish. Whether such cytokines may be useful as adjuvants to augment immune responses following vaccination of fish is under investigation.

Breach of the epithelia and release of cytokines also signals to the liver to produce a range of immune proteins, to help bring the infection under control immediately. These proteins, called acute phase proteins (APP), include factors able to bind to the microbe's surface, thereby increasing ingestion by phagocytes which possess receptors to recognise these proteins (a process termed 'opsonisation') and activating the complement system (see Section 11.4), and factors to neutralise the effects of secreted microbial products, particularly antiproteases. C-reactive protein (CRP) and serum amyloid P component (SAP) are classical acute phase proteins, and are both pentraxins, proteins having five subunits arranged in a planar pentagon. However, normally only one of these molecules will act as an APP, and which one depends on the species under study. Both molecules are well known in salmonids, and the gene for SAP has been sequenced. Using antisera raised to purified SAP or CRP it has been shown that relatively moderate increases (2–3-fold) occur in their production following bacterial infection or injection of LPS (Murai *et al.*, 1990; Lund and Olafsen, 1999). Nevertheless, rainbow trout CRP is an important opsonin and can activate the complement system (Nakanishi *et al.*, 1991) suggesting that any increase will have survival value. Produced antiproteases include α_1-antiproteinase and α_2-macroglobulin. It has been shown that production of α_2-macroglobulin in particular is crucial for neutralisation of secreted proteases from virulent strains of *A. salmonicida* and species differences in resistance to furunculosis can be correlated with differences in α_2-macroglobulin activity (Ellis, 1999).

11.3 ACQUIRED IMMUNITY

To date, lymphocytes in fish can be subdivided into two main functional populations, B and T cells. B cells possess immunoglobulin (Ig) genes, that allow them to express surface Ig to recognise foreign molecules on a pathogen's surface or released in a soluble form, and to secrete Ig as antibodies that can bind to the molecule(s) that induced their production. T cells possess genes for the T cell receptor (TcR), which although a related molecule to Ig does not recognise soluble proteins and is not secreted.

To produce a functional Ig molecule the Ig genes, which exist as multiple copies of the different elements needed, must recombine (Secombes and Pilström, 2000). In doing so particular combinations come together to give a unique specificity to the binding domain of the antibody protein they encode. Within a B cell this happens on at least two occasions, to give the two different peptide chains (heavy and light) that subsequently come together to form a heterodimer needed to create the antibody binding site. In bony fish, including salmonids, an antibody molecule containing eight binding sites is typically secreted, and is called IgM. A second form of Ig has been discovered recently in bony fish, called IgD. The functional relevance of this molecule has still to be determined but it is likely to be a cell associated Ig involved in activation of the B cell.

B cells are easily detected using antisera (or monoclonal antibodies) raised to purified Ig. They have been shown to be widely distributed and are found in the blood and lymphoid sites such as the kidney, spleen, gills and gut. Upon stimulation they initially divide, to increase the number of cells capable of reacting to the stimulant, and then transform into cells that can produce and secrete large quantities of protein (i.e., antibodies), termed plasma cells. The largest numbers of plasma cells can be detected in the kidney, where they represent approximately 1.5% of leukocytes, and the antibody they release accounts for 1/40th of blood protein. Following a typical injection immunisation it has been shown that 1–2% of the plasma cells release specific antibody against the injected agent. If a second immunisation is performed, faster and larger numbers of specific plasma cells and blood antibody can be detected. Studies looking at such 'secondary' responses in trout have suggested that relatively large numbers of B memory cells are generated during primary immune responses (c/f mammals) that can divide during secondary responses to give rise to the increased number of effector cells.

The TcR on T cells recognises processed molecules (peptides), presented in association with self-molecules coded for by genes within the major histocompatibility gene complex (MHC) that interact with the intracellular protein processing pathways prior to trafficking to the cell surface. The TcR also exists as a heterodimer and consists of either an α and β chain (type II receptor) or a γ and δ chain (type I receptor). Formal proof for the latter is still needed in bony fish but all four chains exist in sharks. Antisera to the TcR have been difficult to produce to date, so formal confirmation of T cells currently requires the use of TcR gene probes.

Two types of MHC molecules can present peptides, called class I and class II molecules, and both are known to exist in all jawed vertebrates. In mammals T cells are subdivided functionally and this also reflects the type of MHC molecule that is used to activate the cell. Thus, cytotoxic T cells (Tc) that can kill virus-infected host cells and that are responsible for killing grafts (skin or scales grafts in the case of fish) are activated by peptides presented by class I molecules. In contrast, helper T cells (Th) that secrete a range of immunoregulatory molecules (cytokines) that stimulate T and B cell responses and activate the nonspecific defences, require peptides to be presented by class II molecules. To complicate matters further, the MHC molecules are highly polymorphic, such that genetically different individuals will present a different repertoire of peptides from any given protein, with consequences for the specificity of the ensuing immune response. Thus, some individuals will present 'protective' peptides for disease 'A' and be relatively resistant but may be susceptible to disease 'B'. These differences in the MHC molecules can be used as genetic markers to distinguish (type) resistant or susceptible fish strains, and many studies are on-going in salmonids to this end. An interesting difference between bony fish and higher vertebrates is that the class I and II molecules do not co-segregate in offspring in fish (Hansen *et al.*, 1999; Sato *et al.*, 2000).

Both the cytotoxic and helper activities of T cells are well known in salmonids. In the case of Tc, it has been shown that fish can be primed by skin grafting such that a second graft is rejected faster, indicative of immunological memory. More recently the ability to induce specific Tc has been demonstrated using cell lines derived from clonal strains of ginbuna crucian carp (Hasegawa *et al.*, 1998). Whilst the induction of virus-specific Tc has still to be formally shown, the increasing production of clonal fish and derived cell lines make this likely to be achieved in the near future. Additionally, a cell surface marker widely used to detect Tc (CD8) has now been cloned in several fish species, including rainbow trout (Hansen & Strassburger, 2000), and will greatly facilitate the isolation and study of these cells.

The biological activities of Th are also well described in fish, as evidenced by the requirement of T cells for many immune functions *in vitro* and the plethora of reports demonstrating the release of factors from T cells (or cells cultured with T cell stimulants) that can activate specific and nonspecific defences (Miller *et al.*, 1998; Secombes, 1998). Two particularly important cytokine activities described include the ability to increase the proliferation of activated T cells (T cell blasts) akin to the activity of interleukin 2 (IL-2), and the ability to activate macrophages for increased microbicidal activity akin to gamma interferon (IFN-γ). However, the released cytokines that induce these effects are still largely uncharacterised. One cytokine known to be released from Th that is involved primarily in down-regulating responses is transforming growth factor-β (TGF-β), and this molecule has been sequenced in several species including rainbow trout (Hardie *et al.*, 1998). The gene has been shown to be expressed in many tissues (kidney, spleen, blood, gills, brain) but study of the recombinant protein has yet to be undertaken. As more of these molecules are sequenced and specific probes/reagents are developed it will be possible to measure far more precisely this arm of the fish immune system, allowing better analysis of vaccine efficacy.

11.4 ANTIBACTERIAL DEFENCES

A large variety of antimicrobial mechanisms exists in salmonids. Many rely on secreted proteins found in the blood and/or mucus. Some of these proteins are directly lytic for bacteria, as with lysozyme that cleaves molecules in the bacterial cell wall causing osmotic damage. The levels of lysozyme vary considerably between different fish species, being rather low in Atlantic salmon relative to salmonids such as charr and rainbow trout (Grinde *et al.*, 1988). It has been argued that the gene for lysozyme could be a good candidate for transgenic studies, to look at the resistance of salmon with elevated lysozyme by increasing the gene copy number. A series of blood proteins that can result in lysis of bacteria is the complement system (Nonaka and Smith, 2000). Once activated these proteins act in an enzyme cascade to produce products that attract phagocytes to a site of infection, coat bacteria making them more easily ingested by phagocytes, and ultimately form a membrane attack complex that can rupture the bacterial cell membrane resulting in cell death. The complement pathway can be activated by the bacterial surface (which prevents the normal inactivation of particular components), by antibodies bound to the bacterial surface or by a carbohydrate binding protein (called mannan binding lectin) bound to the bacterial surface. Although essentially identical to the complement system of mammals, it has been shown that in bony fish there is an increase in the number of genes for the complement protein C3. Each type of C3 molecule appears to differ in the way it activates the complement cascade, giving bony fish a uniquely increased ability to recognise and respond to foreign molecules by this pathway (Sunyer and Lambris, 1998). An exciting new discovery is the presence of antibacterial peptides in the mucus of fish (Cole *et al.*, 1997). Antibacterial peptides are well known in many animal groups (insects, amphibians, mammals) and have great potential as future 'antibiotics'. Their discovery in fish is not particularly surprising in view of their high levels in the skin and mucus of frogs (e.g., magainins) and the many reports of unusual antimicrobial activity in blood and mucus of fish. Nevertheless, the first sequences represent a breakthrough that will open up a major unstudied defence in fish.

The nonspecific cellular defences also possess a wide range of antimicrobial defences. In addition to the production of molecules such as lysozyme and antibacterial peptides, phagocytes can generate oxygen and nitrogen free radicals (so-called oxygen-dependent defences) that have potent microbicidal action. During phagocytosis there is a marked increase in oxygen uptake by neutrophils and macrophages, reflecting the use of oxygen in these defences. For the generation of oxygen radicals, a membrane associated enzyme called NADPH oxidase is able to reduce oxygen to superoxide anion (O_2^-) (Figure 11.3). This is the start point for the production of hydrogen peroxide (H_2O_2), the hydroxyl radical ($\bullet OH$), singlet oxygen ($'O_2$) and hypohalites (such as hypochlorite, Ocl^-), the latter dependent on the presence of peroxidase within the cell (normally present in neutrophils but not macrophages). Studies have shown that the quantities of oxygen radicals produced from phagocytes can be increased by 'activation' of the cells, and that a range of immunostimulants and cytokines can bring about this effect. Indeed, this is a requirement to kill some virulent strains of fish bacterial pathogens *in vitro*, and suggests that the release of activating cytokines from Th cells is a critical component of protective immune responses.

The production of nitrogen free radicals requires a different enzyme, called nitric oxide synthase (Figure 11.3). This enzyme exists as several isoforms, with the so-called 'inducible' isoform (iNOS) being expressed in macrophages. The enzyme uses the terminal nitrogen atom of the amino acid arginine to convert oxygen to nitric

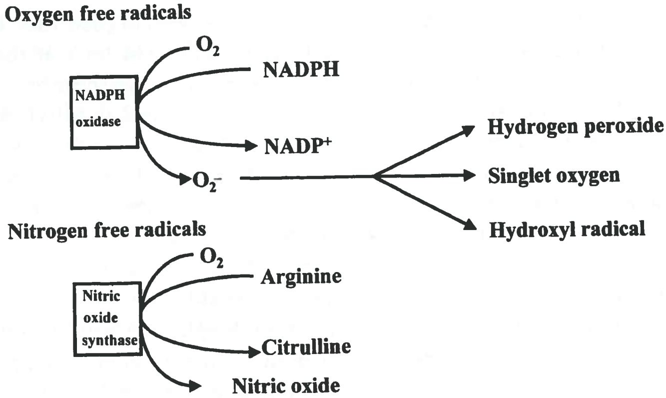


Figure 11.3. Scheme outlining the production of microbicidal free radicals by fish phagocytes.ning the production of microbicidal free radicals by fish phagocytes.

oxide (NO), which is subsequently converted to more potent peroxidising, nitrating and nitrosating agents such as: hydroxyl radicals, nitrogen dioxide (NO_2), nitrogen trioxide (N_2O_3) and the nitronium ion (NO_2^+). In addition, peroxynitrite ($ONOO^-$) can be formed by the reaction of O_2^- and NO; a short lived oxidant with properties similar to the hydroxyl radical. The iNOS gene has been cloned in rainbow trout and expression studies have shown that following challenge with bacteria the gill and kidney are the main sites where detectable transcript is found (Campos-Perez *et al.*, 2000b). Fish macrophage cell lines have also been shown to express the iNOS gene, and to produce a functional enzyme, as evidenced by the detection of nitrite in the cell culture medium. More recently the bactericidal properties of cell-free generated NO have been studied and proven against a range of fish bacterial pathogens (Campos-Perez *et al.*, 2000a).

To expose invading bacteria to such defences it is important that they are phagocytosed as efficiently as possible. To this end a range of opsonins augment uptake by phagocytes, including APP such as CRP, SAP and complement factors (mentioned above) but also specific antibody. Antibodies directed to secreted toxins are also crucial for anti-bacterial defences by neutralising their activities, as seen with the metallo-proteinase released from an atypical strain of *Aeromonas salmonicida* (ssp. *achromogenes*) where antibody responses to this toxin confer resistance in Atlantic salmon (Gudmundsdottir and Magnadottir, 1997).

11.5 ANTIVIRAL DEFENCES

A variety of non-specific and specific defences also exist to combat viral infections in fish. One of the best known non-specific defences is interferon production. Whilst the biological activity of fish interferon is well characterised (Secombes, 1998) the gene(s) has still to be discovered and sequenced. Interferons act to degrade viral RNA and to block translation of proteins from RNA, thus preventing viral replication within host cells. Interferons are able to induce a number of 'resistance' genes once produced and one group of these, the Mx proteins (so-called for their role in myxovirus resistance) have been cloned in fish. To date three Mx genes are known in rainbow trout (Leong *et al.*, 1998) and Atlantic salmon (Robertsen *et al.*, 1997), with probes detecting the transcripts in many other salmonid species. Expression of these genes has been shown after stimulation of cells with virus, synthetic dsRNA polyinosinic polycytidylic acid (poly I:C—a viral mimic) or interferon containing supernatants, presumably due to the induced release of interferon in response to virus or poly I:C since cell line unable to release interferon show no Mx expression after culture with these stimuli (Nygaard *et al.*, in press). A correlation between induction of Mx protein expression by interferon and protection of CHSE cells against IPNV infection is apparent but the mechanism of Mx action remains to be elucidated. Mx protein expression is also seen early following DNA vaccination with viral genes, a procedure that induces good anti-viral protection (Kim *et al.*, 2000).

An important non-specific cellular defence involved in viral resistance is due to the activity of natural killer (NK) cells; often termed non-specific cytotoxic cells (NCC) in fish. These cells resemble lymphocytes, and are found in lymphoid tissues (although levels in blood are usually low) but differ markedly from Tc in being able to kill target cells in a non-specific, non-MHC restricted way. In fish, the ability to kill a variety of cell lines and parasites is attributed to the activity of these cells, which appear to exist as a number of distinct populations in fish, as is enhanced killing of virally infected cell lines (Miller *et al.*, 1998). Such cells are crucial in situations where Tc are not effective. In mammals it is known that many viruses can down-regulate MHC class I expression in host cells, suppressing Tc activity. Whilst this is still to be investigated with respect to fish viruses, it is known that both MHC class I and class II expression can be modulated in fish cells (Knight *et al.*, 1998; Koppang *et al.*, 1998), suggesting that such a strategy would certainly be possible.

Clearly specific immune responses have a large part to play in viral resistance. The role of Tc has already been described and the ability of Th to augment the generation of specific Tc is also a key step in generating a protective immune response. Antibody production by B cells is also crucial, particularly of antibodies able to effectively block viral entry into host cells (virus neutralisation). There are many good examples in the literature of induced virus neutralising antibodies in fish and their correlation with protection (Lorenzen and LaPatra, 1999). In some instances the virus neutralising activity of antibody can be shown to be complement-dependent by use of *in vitro* assays, as seen with neutralisation of the rhabdoviruses IHNV and VHSV. This may relate to the enveloped nature of these viruses, since nonenveloped RNA viruses do not require complement for neutralisation. It has been suggested that virolysis may be the result of an antibody induced complement-mediated membranolytic effect (Lorenzen and LaPatra, 1999), as seen with some mammalian enveloped viruses.

11.6 CONCLUSIONS

Effective non-specific and specific defences exist in salmonids that can be manipulated to improve fish health, e.g., in aquaculture. Knowledge of ways to increase the activity of non-specific defences is useful to allow the development of immunostimulants for use in aquaculture. Specific defences clearly allow fish to be vaccinated. Effective stimulation of appropriate T cells is likely to be crucial for successful vaccination strategies. Consideration of ways to stimulate T cells via MHC class I molecules has led to the current wave of new vaccine delivery methods currently being tested (e.g., DNA vaccines, live attenuated vaccines—see Chapter 10. Cloning and characterisation of the key regulators of the immune system (cytokines) will give new possibilities to augment the effectiveness of vaccines and to direct the ensuing immune response towards effector mechanisms that give immunity to the pathogen under study. There is no doubt that increased knowledge of the immune system of fish has direct benefits for improving fish health in aquaculture.

12

Genetic management

12.1 INTRODUCTION

Traditionally the management of cultured fish has been heavily focussed on disease control and improving rearing conditions (e.g., Piper *et al.*, 1982) and, in Atlantic salmon (*Salmo salar* L.) farming, this has achieved dramatic improvements in productivity and animal welfare. However, the full production potential of the species will only be realised if the genetic character of farm stocks is also managed and optimised to meet production objectives under prevailing farm conditions. The advantage of genetic improvement is that it is permanent and cumulative. However, body characteristics and performance, for farmed salmon just as much as for wild salmon, are the outcome of an interaction between genes and the environment. Thus, to maximise productivity, both genes and environment must be managed in concert.

Tave (1993) has reviewed the general issues related to the genetic management of hatchery fish and others have addressed these issues more specifically for salmonids (Gjerde, 1993; Donaldson and Devlin, 1996; Jørstad and Naevdal, 1996; Pepper and Crim,1996). Gordon *et al.* (1987) include a practical guide to traditional genetic management of salmonids, and one aimed specifically at Atlantic salmon is provided by Friars (1992). The aim of this chapter is to provide an up-dated introduction to genetic management issues and methods which encompasses recent developments. Particularly important developments have occurred in relation to the application of molecular markers and breeding programmes designed to optimise genetic gain over the long term. This chapter is organised into issues associated with the establishment, maintenance and improvement of stocks. However, before addressing these issues, an overview of the genetic nature of Atlantic salmon is provided and the different approaches currently used in genetic management are introduced.

12.2 THE GENETIC NATURE OF ATLANTIC SALMON

A basic appreciation of the genetic nature of salmon and salmon stocks is crucial to understanding genetic management issues associated with the farming of Atlantic salmon. Atlantic salmon show genetic (i.e., heritable) variation for a wide range of traits relevant to farm production, that is, for traits which are economically important (Tave, 1993; Table 12.1). Indeed, it can reasonably be assumed that most aspects of a salmon's characteristics and performance (i.e. its phenotype) are determined to some degree by its genetic constitution (i.e. its genotype). This constitution is defined by a salmon's DNA and its genes, the latter being sections of DNA which, by their make-up, control cellular functions affecting growth, development, survival and reproductive success.

Each salmon has in the order of 50,000–100,000 pairs of genes of which more than 99% are located in its 28–29 pairs of chromosomes, the physical units of inheritance in the cell nucleus into which DNA is packaged (Verspoor, 1997, 1998); one of each pair of genes and chromosomes is inherited from each parent. The remaining genes (<1%) reside in the DNA of the cell's energy-producing organelles, the mitochondria, and are normally inherited only from the female parent. Copies of genes differ within and among individuals. This variation is due to mutation and to reciprocal crossing over and recombination between the DNA of

Table 12.1. A list of variable biological traits of Atlantic salmon of importance to farm production which show heritable variation (after Tave, 1993) giving estimates of % variation attributable to genetics ($h^2 \times 100 \pm$ standard errors).

Trait	% Variation inherited	Trait	% Variation inherited
12-week weight	89 ± 32	12-week length	79 ± 31
6-month weight	40 ± 26	6-month length	57 ± 28
15-month weight	67 ± 32	15-month length	73 ± 32
2-year weight	12 ± 5–38 ± 15	2-year length	8 ± 5–42 ± 16
3-year weight	3810	3-year length	33 ± 10
		3-year length	15 ± 33
3-year gutted weight	44 ± 11	dressing percentage	3 ± 2
% smolting at year 1	0 to 16 ± 5	survival to 2 years in pens	3 ± 7–83 ± 13
age at sexual maturity	48 ± 20–66 ± 8	maturity at 3 years	6 ± 5–39 ± 12
egg size	44 ± 18	egg volume	13 ± 15
egg number	30 ± 16	% dead uneyed eggs	32 ± 6
% dead eyed eggs	5 ± 4	% dead alevins	4 ± 1
% dead fry	0 ± 1	% smolt	85 ± 34
survival in acid water	54 ± 30–62 ± 26	length in acid water	29 ± 18–72 ± 33
susceptibility to *Aeromonas salmonicida*	48 ± 17	tolerance to *Vibrio anguillarum*	11 ± 6
meat colour score	1 ± 3	erythrocyte cell membrane fragility	60 ± 20

paired chromosomes during the production of gametes (i.e., during meiosis) and, in a given salmon stock, up to 100 or more different variants for a given gene may exist. The association of gene variants, during gamete formation and sexual reproduction, to produce individual genotypes is largely random and, when the overall combination of variants each individual possesses is considered, each salmon is likely to be unique. This can easily be appreciated by the following example. Even if each salmon had only 15 nuclear genes each with only four different variants, it would be possible to generate more than 57 billion different genotypes. Given that there are likely to be thousands, if not tens of thousands of variable genes, many with more than four variants, the actual number of different genotypes which could potentially be produced is astronomical.

While each salmon can be expected to be genetically unique, any two salmon in a stock will share many gene variants in common. Furthermore, the actual genotypes present in a stock will depend on the frequencies and association of variants in the broodfish used to establish a stock. These will in turn be determined by chance survival and sampling of fish as well as natural and artificial selection in the cohorts from which the breeders derive their stock.

Studies of genetic variation at the molecular level show genetic differences among stocks to relate largely to differences in variant and genotype frequencies rather than with regard to which variant types are present (Verspoor, 1997). Differences in variant frequencies among stocks, even if they occur at only a small number of genes, can generate large differences in the expected frequencies of different genotypes in the stocks (Figure 12.1). In actual stocks with a finite size of a few thousands of individuals, it is conceivable that few genotypes in relation to sets of genes controlling particular performance variation will be shared in common. Consider, for example, the situation shown in Figure 12.1 where both stocks share the same variants at three genes. If stocks A and B were represented by 1000 randomly-selected fish, less than 10% of the fish in each stock would have genotypes common to both stocks. Extend the same differences in variant frequencies to nine genes and the expected proportion of fish with genotypes common to both stocks becomes <0.1%! This means that differences in variant frequencies alone are sufficient to account for any observed differentiation among stocks. However, it is likely that there will also be some gene variants which are not shared by all stocks and, exceptionally, some gene variants may even be unique to a stock.

The specific genetic basis of performance and character variation is, as yet, poorly understood at the level of the DNA and individual genes. Studies show that most phenotypic variation is continuously distributed (e.g., size at a particular age or stage of development, feed conversion efficiency) and likely to result from a complex interaction between a number of genes and a range of environmental factors. The number of genes determining the heritable component of variation in continuously varying traits could be as few as five (Tave, 1993) or it could be hundreds. Nor is each gene's contribution likely to be equal. Some genes will have major effects and the effects of others will be minor. Furthermore, for a given gene the effect may depend on the environment, both external (e.g., temperature) and internal (i.e., other genes) in which the gene is functioning. For example,

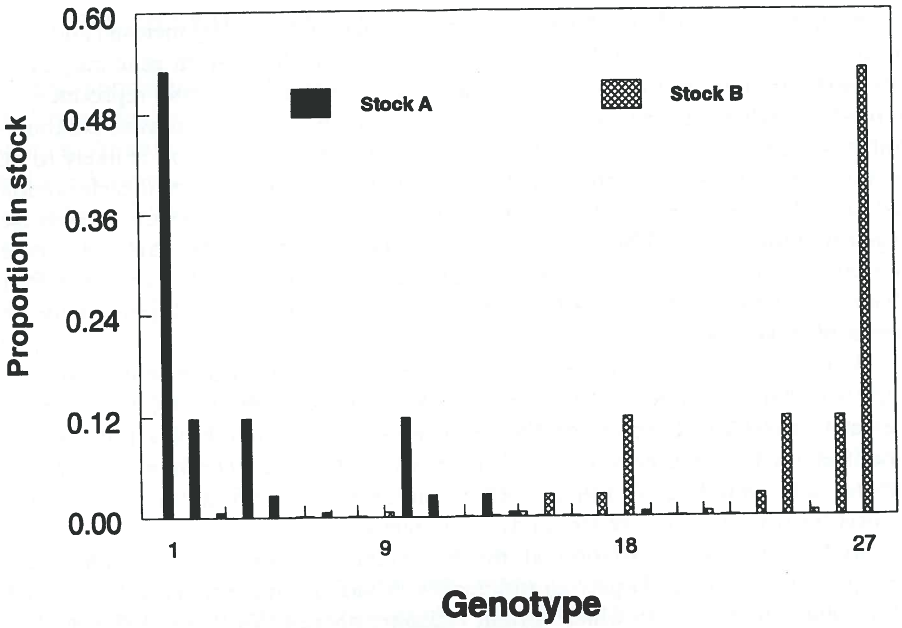


Figure 12.1. A hypothetical example of the differences in genotypes defined by three genes, each with two variants, with regard to their frequencies in two farm stocks where the only difference between them is with regard to variant frequencies. In Stock A, at each gene the frequencies of the variants 1 and 2 are 0.1 and 0.9, respectively, while in Stock B, they are 0.9 and 0.1, respectively.

genotype-environment interactions have been observed in relation to age of maturity in sea water (Saunders *et al.* 1983). Furthermore, the same performance and character state in a fish may potentially be realised by different combinations of genes under the same environmental conditions, or under different environmental conditions. Thus the relationship between phenotype and genotype is potentially complex and would be a difficult challenge even with a better specific knowledge of a salmon's genes and how they interact and vary.

12.3 MANAGEMENT APPROACHES

With our limited specific knowledge of the genetic character of the Atlantic salmon, the direct management of the types and frequencies of gene variants in salmon stocks is largely precluded. Thus, as with other cultivated species, the genetic character of stocks has to be managed indirectly by considering expectations for outcomes of particular actions predicted from quantitative genetics theory. This involves applying genetic principals to the statistical analysis of phenotypic variation to predict genetic outcomes under different management scenarios. However, this indirect approach is being increasingly complemented by specific genetic information, derived from molecular markers. These are molecules which vary heritably and, though their function is poorly understood, can provide particular types of genetic information useful for stock management. In addition to molecular markers, advances in molecular biology now also offer the option, though with a limited scope and highly contentious, to re-engineer the genetic character of salmon. Together these three approaches encompass the options available for the genetic management of farmed salmon stocks.

12.3.1 Quantitative genetics

Quantitative genetics (Falconer and Mackay, 1996; Lynch and Walsh, 1998) is concerned with continuously varying characters. Most performance traits, such as size at a particular age or stage of development, growth, feed conversion efficiency, or proportion of fish smolting at one year of age, fall into this the category. At the heart of quantitative genetics is the measure h^2, the coefficient of heritability. This is the proportion of variation for a performance trait, in a given environment, which is attributable to the additive effects of genes; an h^2 of 0.4 would mean that 40% of the measured variation in performance is estimated to be inherited. Normally, h^2 is estimated from performance comparisons of related individuals, families and stocks reared under controlled environmental conditions. Estimates of h^2, expressed as a percentage, which have been obtained for performance traits in Atlantic salmon are given in Table 12.1. As can be seen in the table, these estimates can vary substantially from study to study as well as from trait to trait.

Estimates of h^2 (i.e., genetic variation), when applied in the context of overall quantitative genetics theory, provide the basis for genetic management by predicting *expected* genetic responses with different numbers of breeders, selection methods and mating patterns. The actual response will deviate from the expected. Provided that the estimates of h^2 and other parameters are accurate, and that the assumptions made in the genetic models used are reasonable, deviations of actual responses from those predicted are likely to be small. However, it is not always possible to know whether assumptions are reasonable and, in reality, the unexpected can happen, giving this indirect approach to management of a stock's genetic composition a degree of uncertainty. In a commercial context, where a major deviation from the expected can be the difference between failure and success, there is clearly an imperative to minimise the chance that the unexpected might occur. How this can be done is considered later.

12.3.2 Molecular markers

Developments in molecular biology over the last three decades now make it possible to study genes and gene variation directly. As a result, it is now possible to resolve a large number of heritable variations in Atlantic salmon at the DNA level. However, the amount of resolved genetic variation still represents a small portion of the salmon's genome (less than 1%) and even understanding of the role that the variation in this portion plays in performance variation is very limited. Thus we are still a long way from being able to manage the genetic character of salmon stocks directly. However, the molecular understanding that has been developed can provide very useful genetic information for stock management (Verspoor, 1998). This is because the molecular variation which can be resolved is able to serve as a heritable marker of individuals or general levels of genetic variation.

The first molecular markers were enzymes and blood proteins, whose AA sequences can vary genetically. In salmon, these were relatively limited in number and revealed only low levels of variability, limiting their usefulness for genetically managing farm stocks. However, in recent years, a larger and more diverse group of molecular markers derived from the direct analysis of nuclear and mitochondrial DNA has been developed. The most useful of these are a class of nuclear DNA markers known as microsatellites.

Microsatellites are localised sequences of DNA characterised by variable numbers of tandemly repeated units of 2–6 bases, the basic units of which DNA is built (Figure 12.2). In most species, including Atlantic salmon, these markers are numerous and show high levels of genetic variability (Park and Moran, 1995; Hancock, 1999) which can be unambiguously resolved (O'Reilly *et al.*, 1996, 1998). Microsatellite regions are also widely distributed across the chromosomes and thereby can be used as markers for a large part of the salmon genome. Furthermore, many microsatellites markers have been resolved in Atlantic salmon and rapid cost-effective methods for their screening are now available (O'Reilly *et al.* 1996, 1998; Verspoor *et al.*, unpublished).

The potential uses for microsatellite markers in the genetic management of farm stocks are numerous and include measuring the relatedness of individuals within a stock, monitoring changes in average levels of genetic diversity among stocks and across generations, serving as markers for gene variation affecting performance, and tracking pedigrees. The latter application is illustrated in Figure 12.3 and an example of the power of microsatellite markers for pedigree analysis is given in Table 12.2.

12.3.3 Genetic engineering

There is no reason to accept that the natural genetic character of Atlantic salmon is the one which is likely to be optimal for achieving production objectives. By changing the numbers, types or organisation of genes and chromosomes, it may be possible to enhance individual performance or character. Such changes fall into the category of genetic engineering and encompasses methodologies such as transgenesis. This involves the introduction of novel genetic material from one species into another to increase, for example, the production of a particular type of gene product. Genetic engineering also encompasses the production of monosex stocks, and ploidy manipulations, including the production of triploid fish, i.e., fish with three sets of chromosomes.

Genetic engineering, recently reviewed by Donaldson and Devlin (1996) and Maclean (1998) in relation to fish generally, is a potentially powerful technique for stock improvement. However, while the basic methodology for genetic engineering

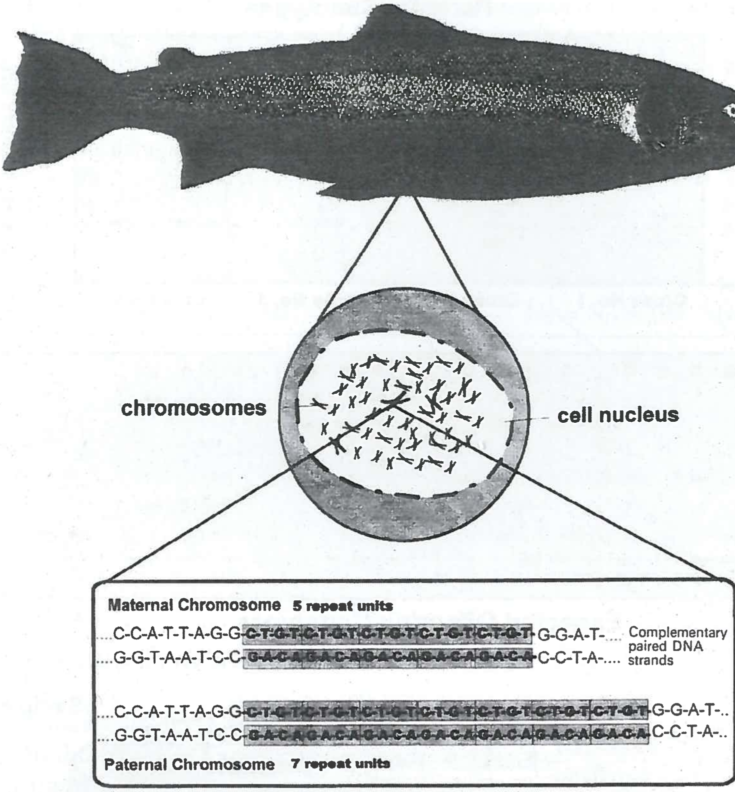


Figure 12.2. A hypothetical example of a microsatellite marker in an Atlantic salmon chromosome, showing how the DNA variation is manifest at the level of the DNA. Each salmon's genome is composed of 28–29 pairs of chromosomes, each of which will contain numerous microsatellite regions; the maternal chromosome of each pair is derived from a salmon's mother, and the paternal chromosome from its father. In a chromosome, the DNA is organised into two complementary strands of DNA made up of the nucleotide bases, adenine (A), thymine (T), guanine (G) and cytosine (C) and in the complementary strands, A is always matched with T, and G with C. The example shows a microsatellite composed of the tandemly repeated four base sequence CTGT (or on the complementary strand GACA). The variation within and among fish occurs with regard to the number of times the four base sequence is repeated. In the example, the fish has two variant types, one composed of five repeat units and the other of seven. In a stock of salmon an actual microsatellite marker might be composed of up to 80 different sizes variants.

exists, its application in the genetic management of farm fish stocks is currently constrained. This is due to the limited understanding which currently exists of gene variation in the Atlantic salmon and the way in which genes influence salmon performance and character. Additionally, public concern may limit the application of these techniques.

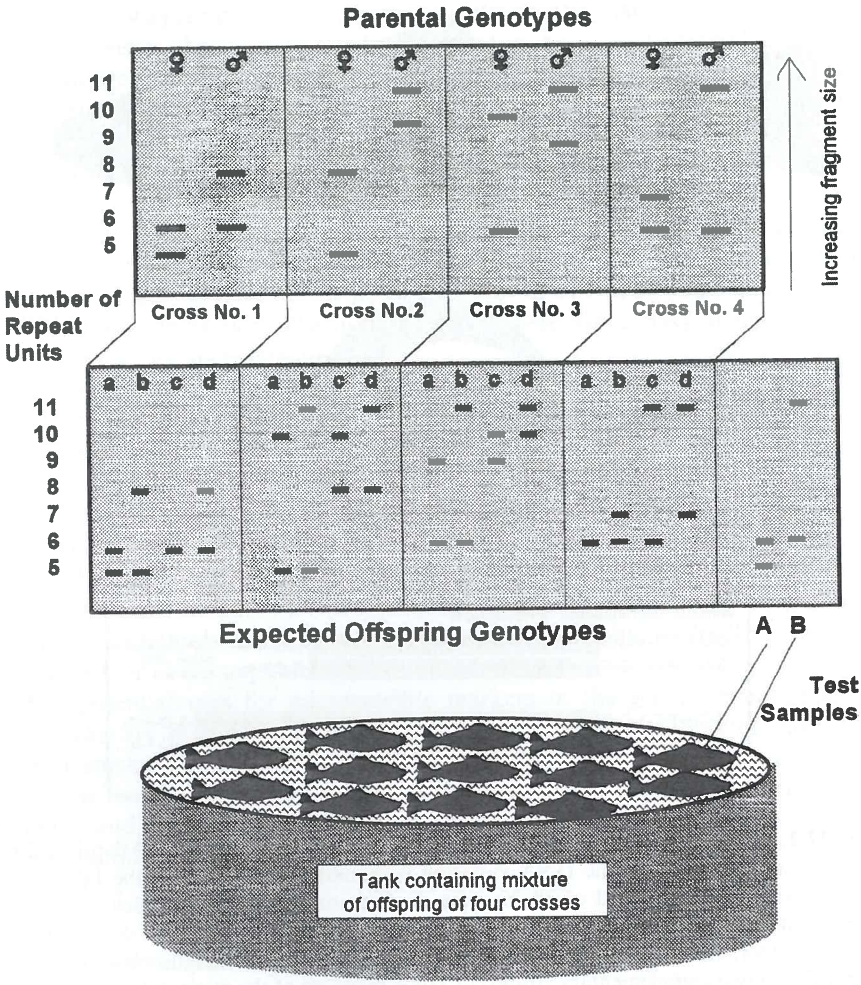


Figure 12.3. An illustration of pedigree analysis using molecular markers. The top box shows parental genotypes for the hypothetical microsatellite illustrated in Fig. 12.2. The bands represent DNA fragments of different sizes, generated by molecular copying of the microsatellite region using PCR technology (see O'Reilly *et al.*, 1996), after separation in a gel matrix subjected to an electric field. The middle box shows the offspring genotypes expected to be produced by each of the crosses and two hypothetical fish sampled from a tank containing the mixed families of the four crosses. For the example shown, fish A is unambiguously assignable as an offspring of Cross No. 1. On the other hand, the microsatellite data only allow fish B to be identified as being from either Cross No. 3 or 4. To decide which of these was the actual family origin of the fish, further microsatellites would have to be screened. Currently-available microsatellite screening systems which have been developed for Atlantic salmon are based on six microsatellite markers providing a capacity to resolve 400 plus families (Villanueva *et al.*, 1996; Verspoor and Visscher, unpublished).

Table 12.2. An example of the percentage of offspring assigned to a single set of parents (i.e., cross) when using different numbers of Atlantic salmon microsatellite markers. Results are based on 800 offspring from 100 crosses for the initial population ($t = 0$) and after five generations of random selection ($t = 5$) for two different mating designs, where the 100 families involve 1) 100 sires (N_S) and 100 dams (N_D); or 2) 10 sires and 10 dams with each sire mated to all dams and each dam mated to all sires. The assignment success is based on the use of actual microsatellite frequency data from a farm stock (Verspoor *et al.*, unpublished). Standard errors ranged from 0.001 to 0.32.

Number of microsatellites	$t = 0$		$t = 5$	
	$N_S = N_D = 100$	$N_S = N_D = 10$	$N_S = N_D = 100$	$N_S = N_D = 10$
1	5.0	3.9	4.4	0.5
2	67.9	50.7	60.6	10.5
3	96.0	87.1	93.2	35.1
4	99.6	96.7	99.0	59.8
5	100.0	99.2	99.8	77.1
6	100.0	99.7	99.9	85.4
7	100.0	99.8	100.0	90.2

12.4 ESTABLISHMENT OF STOCKS

Genetic management, to be most effective, must begin at the time a stock is established. In the absence of genetic engineering, the production potential of a stock will be constrained by the genetic character of the founding individuals, i.e., by the gene variants it contains. A lack of care and consideration in choosing founders may severely compromise success in maintaining or improving a stock's genetic character. In establishing a stock, consideration needs to be given both to the source(s) of founders as well as their number and relatedness (Tave, 1993; Pepper and Crim, 1996; Jørstad and Naevdal, 1996). Wild stocks of Atlantic salmon, and individuals within stocks, vary genetically with regard to traits important to production (Saunders, 1981; Verspoor, 1997) and the same will be true for cultured strains, depending on their origins and genetic history. There is no easy route to making the best selection of source stock(s), or individuals within a stock. Given that genetic character cannot be assessed directly, the best way to decide on the relative merits of different stocks is to make a simultaneous performance comparison of animals from different sources under production conditions. However, this may not always be feasible due to time or cost constraints. In such cases, only an assessment of differences in phenotypic performance among stocks or individuals in their existing environments may be possible. This will give a rough guide but it must be kept in mind that performance variation among stocks and individuals reared under different conditions will have an environmental as well as genetic basis. As such, the relative genetic merits of different source stocks may be obscured by environmental component of performance variation.

Sources of founders may also differ with regard to their potential for continued performance or selective improvement. Sources with low levels of variability, while they may have a high level of current performance, will have a lower potential for selective improvement (Tave, 1993). For example, a high-performing stock may be derived from a small number of high-performing but closely-related individuals. These will contain less variability than will non-related individuals, reducing the scope for generating new, more productive genotype combinations in subsequent generations of fish which might have been rare in the original stock. Just as importantly, the more closely-related the individuals used to found a stock, the greater the level of inbreeding, i.e., the greater the average relatedness of individuals in the stock. As discussed below, excessive levels of inbreeding can lead to a depression of both fitness and productive performance in subsequent generations.

These problems can be overcome by making a genetic evaluation of the relatedness of individuals. This can be achieved for cultivated source stocks, where pedigrees can be established for individual fish (Tave, 1993), either using traditional physical tagging or molecular markers (Verspoor, 1998). Where individual pedigrees are not available, average levels of inbreeding can be predicted if suitable demographic information is available (Tave, 1993; Falconer and Mackay, 1996). The information needed encompasses population sizes and variances, and covariances of the number of progeny per parent in the source stock, as well as family numbers and sizes at the time the stock was established and while in culture. Alternatively, salmon in stocks targeted as a source of broodfish can be typed for microsatellite markers and the degree of relatedness of individuals established (Verspoor, 1998). By choosing fish which share as few of their molecular markers in common as possible, as well as maximising the number of broodfish used, general levels of variability can be maximised and initial levels of inbreeding minimised.

If source stocks with desirable high levels of performance but low levels of variability are used to establish a new farm stock, variation can be increased by crossbreeding of individuals from a number of different candidate sources. Crossbreeding can also be used, as it is in terrestrial livestock management, to combine in a single stock characteristics that differ heritably between stocks, or to exploit 'heterosis' or hybrid vigour (Tave, 1993). Heterosis is the increase in performance above the mean level of the two parents and tends to be observed for 'fitness'characteristics like reproductive success and survival. Heterosis has been observed for interspecific hybrids of some fish species (Tave, 1993; Dunham and Devlin, 1999) but has not been reported as yet with regard to Atlantic salmon stocks. However, crossbreeding may also lead to a depression of fitness and has been reported for hybrids between odd- and even-brood year pink salmon (*Oncorhynchus gorbuscha*) (Gharrett *et al.*, 1999).

12.5 MAINTENANCE OF STOCKS

The genetic character of a farm stock, once established, is dynamic and needs to be managed so that undesirable changes are avoided. Stocks not previously cultivated to any substantive degree, e.g., those established from wild stock, will undergo domesticating selection. This represents a positive change where individuals which are genetically predisposed to survive and perform well in culture will contribute disproportionately to subsequent generations. As a result, the frequencies of domesticated genotypes suited to the farm environment will increase over time. In addition there will be random genetic changes (genetic drift) because animals selected for breeding subsequent generations will be just a subset of the offspring produced in a given generation. This process causes the random loss of gene variants and changes in variant frequencies. The loss of variation will reduce the scope for selective improvement of a stock. Also, inbreeding can cause a loss of general fitness and lower levels of performance in relation to production traits. This is termed inbreeding depression and in cultivated salmonid stocks has been associated with reduced survival and growth performance (Gjerde *et al.*, 1983; Kincaid, 1983; Tave, 1993).

In general, genetic drift and inbreeding increase as numbers of breeders are reduced, as male : female ratios among breeders become more skewed, and the number of offspring contributed by each mating becomes more variable (Tave, 1993). Inbreeding is also expected to increase due to domesticating selection or deliberate selective breeding. This is because relatedness and performance are expected, on average, to be correlated such that when selection occurs, those doing well or chosen for broodfish will be more likely to be siblings or close relatives than would any two fish chosen at random before selection occurred. The potential for problems due to genetic drift and inbreeding is particularly acute for the Atlantic salmon due to its high fecundity. This means there is a greater potential for a highly skewed representation of offspring in subsequent generations among survivors, or those selected for superior performance, than is the case for most terrestrial farm species. There is also less of a need to use large numbers of breeders to generate large numbers of production animals. Such initiatives, which monitor and control inbreeding and genetic drift, need to be at the heart of any genetic management programme for farmed Atlantic salmon.

12.5.1 Measurement of inbreeding

Levels of inbreeding are normally quantified using a statistic denoted F and called the inbreeding coefficient (Falconer and Mackay, 1996). For an individual, F is defined as the probability that two variants at a gene are identical and descended from a common ancestor, and it takes values between zero and one. F is determined by the genetic relationship between an individual's parents in terms of the fraction of genes they share in common. For a stock, F is the average inbreeding coefficient across individuals. Expected values of F for individuals and stocks have traditionally derived from pedigrees (see Van Vleck *et al.*, 1987). For example, the expected inbreeding coefficient of the offspring of a brother-sister mating is 0.25. However, the true values will vary about this mean, being either higher or lower. In the future, molecular markers are likely to prove particularly useful to compute more exact inbreeding coefficients for both individuals and stocks. The proportion of the genome that two individuals have in common or the proportion of the genome that is inbred in one individual could be estimated with a high degree of precision from genotypic data (Visscher *et al.*, 1998).

Inbreeding inevitably occurs sooner or later in a closed population, where no breeding animals from outside are introduced. However, new genes will arise infrequently by mutation, introducing new variation. The balance between new variation by mutation and the loss of variation due to inbreeding will depend on the relative rates of mutation and inbreeding. The rate of inbreeding is thus an important parameter when assessing different strategies for genetic management. The rate of inbreeding per generation can be predicted under different situations but when selection is taking place in the population these predictions are difficult. In the absence of selection, mutation and gene flow among populations, the rate of inbreeding per generation F, is approximately equal to $(1/8N_S) + (1/8N_D)$ where N_S and N_D, respectively, are the number of male and female parents.

12.5.2 Control of inbreeding and genetic drift

A number of strategies are available to control the rate of inbreeding and genetic drift, both in the presence and absence of an active programme of selective improvement. In selection programmes, some of these strategies consider the ranking and choice of selected candidates whereas others consider the 'design' of matings between the selected animals. Selection strategies to limit the accumulation of inbreeding include increasing the number of parents used, limiting the use of each parent, limiting the number of individuals used from a given family, and reducing the relative importance given to family information in the selection criterion (Toro and Perez-Enciso, 1990; Villanueva *et al.*, 1994). Mating systems proposed to reduce the rate of inbreeding include factorial designs (Woolliams, 1989), minimum co-ancestry matings (Toro *et al.*, 1988), and compensatory matings (Santiago and Caballero, 1995). With factorial mating designs, each dam is mated to more than one sire to reduce the rate of inbreeding with no loss in selective response. An example is given in Figure 12.4. Minimum co-ancestry matings involve minimising the relatedness of the individuals that are mated. In compensatory matings, selected individuals from the largest families are mated to those from the smallest families, with families ranked according to the total number of selected individuals within each (Caballero *et al.*, 1996). An alternative approach, based on the use of molecular marker information, has been suggested by Wang and Hill (2000) in the context of conservation programmes. Molecular characterisation of candidate individuals for broodstock allows both the variance in family sizes among contributing families and the variance in contributions of maternal and paternal chromosomes within selected families to be minimised; the higher the variance in both sources of genetic material, the greater will be the level of inbreeding and genetic drift. Finally, optimisation methods that incorporate genetic gain and inbreeding within the same framework have recently been developed for designing breeding programmes to produce maximum genetic gain while restricting the rate of inbreeding (Villanueva *et al.*, 1996; Villanueva and Woolliams, 1997; Meuwissen,

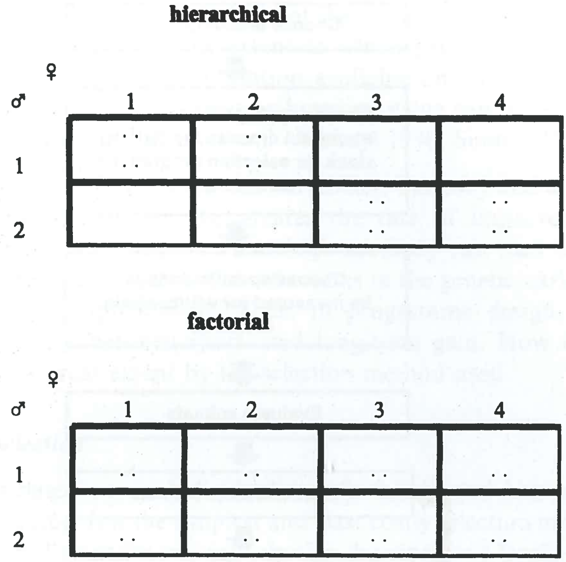


Figure 12.4. Representation of hierarchical and factorial mating systems with 2 sires, 4 dams and 16 offspring. Dots represent offspring.

1997; Grundy *et al.*, 1998). These methods are discussed in more detail later in the chapter.

12.6 GENETIC IMPROVEMENT OF STOCKS

12.6.1 Selective breeding

The traditional approach to genetic improvement of fish stocks is by selectively breeding those individuals that display superior production performance. For production traits that have a genetic component, such selection increases the types and frequencies of gene variants for superior performance among the selected fish and their offspring. The feasibility of using this indirect approach to improve Atlantic salmon stocks has already been demonstrated (Gjedrem *et al.*, 1988; Bentsen and Gjerde, 1994; O'Flynn *et al.*, 1999) and selective breeding currently still represents the best option for genetic improvement.

The steps involved in a selective breeding programme are shown in Figure 12.5. The first step is to clearly define the breeding goal—the set of characteristics which is to be improved—and then identify the strain(s) with the best performance in breeding goal traits from which to start selection. The second step is to decide which traits to measure and use as the basis for selection. In some cases the traits measured may be the same as the goal; in others, for example where traits can only be measured after slaughter, an indirect proxy measurement will be required. Once

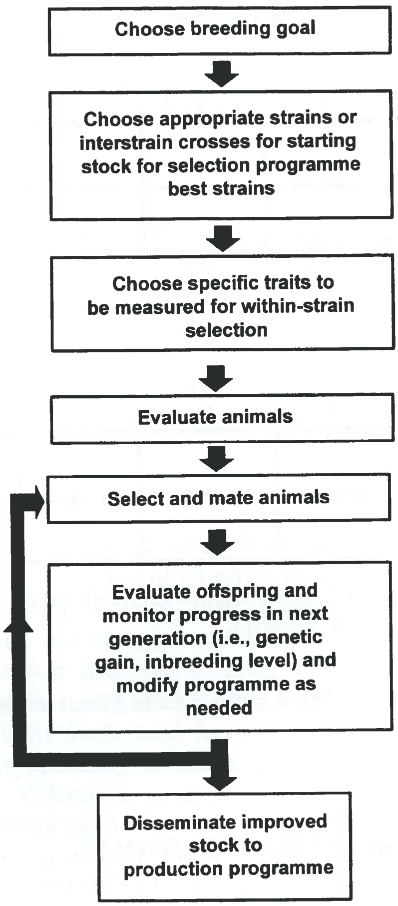


Figure 12.5. A flow diagram showing the basic operational steps involved in a selective breeding programme (after Simm, 1998).

the basis for selection is established, and the fish have been genetically evaluated, then decisions need to be taken on the optimal selection of fish for mating, in terms of numbers of males and females used, their contributions, and pattern of mating. This requires careful consideration to optimise genetic gain whilst limiting inbreeding and limiting the general loss of variation. Once implemented, genetic progress needs to be monitored and the programme modified as appropriate to achieve the breeding goal.

Success in genetic improvement will be affected by four main factors:

1 the amount of genetic variation existing relevant to the traits of interest;
2 the intensity of selection (i.e., the proportion of fish selected to become parents– the lower the proportion, the higher the selection intensity);

3 the accuracy with which genetic merit of the animals is predicted (this depends on the 'heritability' and on the extent to which performance information on relatives is used—the more information available on relatives, the more accurately an individual's genetic merit or breeding value can be predicted); and
4 the generation interval (Falconer and Mackay, 1996; Simm, 1998).

In the short term, the greater the genetic variability, intensity and accuracy and the shorter the generation interval, the greater the rate of improvement per year. However, high intensity of selection and high accuracy can lead to high rates of inbreeding and therefore to substantial reductions in the genetic variability, limiting the scope for future improvement. Thus, in programme design, an acceptable balance must be struck between short- and long-term gain. How this is achieved will be dictated to a great extent by the selection method used.

12.6.1.1 Mass selection

Mass selection is based on an individual's performance and has been a common strategy in fish breeding. It is the simplest and least costly selection method as there is no need to record pedigrees for making selection decisions and families can be reared together through the whole life cycle. Rapid genetic improvement can be realised by mass selection when the heritability (h^2) of the selected trait is high. However, a high h^2 is also expected to incur a high level of inbreeding as the probability of selecting related individuals increases as h^2 increases. Inbreeding can be reduced by increasing the number of breeders selected beyond the minimum number required to produce the numerical requirements for the next generation. Changes in actual levels of inbreeding can be monitored using molecular marker data. Furthermore, molecular markers can be used to assess the relatedness of individuals selected for broodstock and mating controlled to minimise the relatedness of individuals in specific crosses.

12.6.1.2 Family selection

Selection can be carried out by selecting or rejecting whole families based on their average performance. A variant of family selection commonly used in salmon breeding programmes is 'sib selection' where the average family performance is ascertained from a subset of siblings not destined for use as broodstock. This is useful in selecting for traits, such as disease resistance or meat quality, that can not been measured in potential parents. This approach requires that individual family groups be identifiable and incurs an additional cost. This is associated with construction and maintenance of multiple tanks for the rearing of isolated families and the maintenance of equivalent environmental conditions in each tank (to control for environmental influences on performance variation). Alternatively, this can be used in combination with a programme of discriminatory physical tagging once fish are large enough to allow families to be reared together. Using molecular markers for parental assignment, some of this cost can be avoided (Verspoor, 1998). However, practicalities of cost and time delays in molecular typing, and the need for typing each time a fish is measured, may constrain its application and mean that it is most effectively used in conjunction with physical tagging.

12.6.1.3 Within-family selection

Improvement can also be achieved by the selection of individuals based on their deviations from their family means in one of two ways (Hill *et al.*, 1996). The first is to select only the best male and the best female from each family. The second is to select individuals across families based on the magnitude of their deviation from their family means (i.e., more than one male and one female can be selected from a given family and some families may not contribute any selected offspring). Dempfle (1975) showed that long-term gains could be greater with selection within families than with mass selection. This is mostly due to the maintenance of genetic variability with within-family selection. The advantage of within-family selection increases when the heritability is high and with large families. As for family selection, within-family selection requires that individuals can be assigned to family groups. Levels of inbreeding can be calculated from pedigrees and reduced by increasing the number of families used.

12.6.1.4 Index selection

Within- and between-family selection can be combined with information on the candidate and its relatives in an optimal way to obtain the highest possible genetic progress in one generation of selection. This is referred to as index selection. As with all the selection methods already mentioned, index selection assumes that performance differences observed among individuals have been corrected for all sources of environmental bias. This correction may itself lead to bias in selection, if there is a confounding between genetic merit and non-genetic factors. To deal with this, a sophisticated variant of index selection called best linear unbiased prediction (BLUP; see Simm, 1998) can be used simultaneously to estimate environmental effects and predict breeding values. BLUP uses all information on relatives, increasing the accuracy of estimating the breeding value. Since being developed, BLUP has come to be accepted as the optimum procedure for genetic evaluation in most terrestrial livestock species and is currently employed in farmed Atlantic salmon selection programmes in Norway (H.M. Gjøen, pers comm). However, in common with all methods using information on performance of relatives, BLUP can result in higher rates of inbreeding as the probability of selecting related animals is increased.

12.6.1.5 Walk-back selection

A novel approach based on the use of molecular markers, referred to as 'walk-back' selection, was proposed by Doyle and Herbinger (1994). With this approach fish are reared in mixed family groups in the same tank. At the time of selection, the 'best' individual in the population is identified and typed for molecular markers which can distinguish families (Verspoor, 1998). Then the 'second best' individual is identified, genotyped, its family membership determined, and a decision made whether it is to be selected. This continues down the list of ranked individuals until the desired number of families and individuals from each family have been selected.

When individuals are selected solely according to their own performance (i.e., information on relatives is ignored) 'walk-back' selection is intermediate between standard within-family selection and mass selection. It is equivalent to standard within-family selection if only one male and one female is chosen from each family and equivalent to mass selection if there are no restrictions on the number of fish selected from each family. However, selection may also be based on independent evaluations of family performance in which the decision to select or reject a typed individual depends on the performance of siblings (see Section 12.6.1.2). The walk-back approach eliminates the need for isolated rearing or physical tagging of family groups, something which can be costly in terms of facilities and labour if large numbers of families are used in a selection programme. The use of large numbers of families is often desirable to increase the intensity of family selection and reduce the risk of inbreeding and general loss of genetic variability.

12.6.1.6 Marker-assisted selection

Heritable performance variation will most often be due to multiple genes. Most will have a small effect. However, some genes may account for a relatively large proportion of variation for a given trait and, if molecular markers linked to variants at these genes can be identified, this variation could, in principle, be selected for directly. The approach will be particularly valuable for production traits which are difficult or expensive to measure routinely (e.g., flesh quality and disease resistance). This approach, referred to as marker-assisted selection (MAS) is currently being explored and could also potentially be used for marker-assisted introgression (MAI), to introduce a given gene of favourable effect from one stock to another stock as part of a crossbreeding programme.

The potential for MAS is considerable (Poompuang and Hallerman, 1997) and research to identify useful molecular markers for economically important performance traits (QTL) is under way in Atlantic salmon and other species. However, to date the only markers reported for fish species are in rainbow trout, in relation to temperature tolerance (Jackson *et al.*, 1998) and in rainbow/cutthroat trout hybrids for IHN virus resistance (Palti *et al.*, 1999). At the same time, while applying MAS may be easy in principle, their development and their integration with traditional selective breeding approaches will also present a major research challenge. However, the future should see increasing use of both MAS and MAI in the genetic management of Atlantic salmon stocks.

12.6.1.7 Optimal selection with constrained inbreeding

In the last few years, research to find the optimal selection approaches for breeding programmes have focussed on methods that not only give the highest possible genetic progress but also restrict the accumulation of inbreeding. The restriction on the rate of inbreeding ensures the long-term response to selection is maintained by limiting the reduction in genetic variance and in inbreeding depression. What is an acceptable rate of inbreeding will vary among stocks, depending among other things on current inbreeding levels and the magnitude of the reduction in genetic variability and the depression in production traits inbreeding can be expected to cause. In salmon breeding the use of more accurate methods of evaluation (e.g., BLUP, see Section 12.6.1.4) and the high reproductive capacity (which allows only a few parents to produce the next generation) could greatly increase this loss of genetic variation. In general, safe limits to the rates of inbreeding are not known and general practice in breeding is to aim for a maximum rate of inbreeding of 1% per generation.

Procedures for finding the optimum number of parents to be selected, to maximise genetic gain while restricting the rate of inbreeding, in mass selection programmes have been developed and applied in fish breeding schemes (Gjerde *et al.*, 1996; Villanueva *et al.*, 1996). These methods have been extended to index selection (Villanueva and Woolliams, 1997), for optimising the emphasis given to family information in the selection criteria, and to BLUP selection (Meuwissen, 1997; Grundy *et al.*, 1998). In the latter, estimates of breeding values from evaluation using BLUP and pedigrees are used to give recommended contributions for candidates to future generations. The methods developed give guidance on how many parents should be selected, and how many offspring each selected parent should have for obtaining the highest possible progress under restricted inbreeding. Selected fish resulting from the optimisation selection algorithms can be mated under the most efficient mating system to further increase gains (Sonesson and Meuwissen, 2000).

12.6.1.8 Advantages and disadvantages of different methods

In theory, mass selection has the advantage over other methods in that it does not require that fish are distinguishable at the family or individual level. For other methods, families need to be reared separately until physical tagging is possible, or distinguished using molecular markers. Thus mass selection avoids the cost of tanks, constraints on numbers of families used and avoids performance variation associated with families being reared under different conditions. While this problem can in principle be overcome by the application of molecular markers, the advantages and possibilities for their exploitation will be highly dependent on the specific design of a breeding programme, which will determine the numbers needing to be screened, and on the screening costs. The latter currently stand at in the order of £10 per individual for typing for up to six microsatellite loci.

In recent years, assessments of the optimal selection approach has focused on identifying those that give the highest genetic progress for a specified rate of inbreeding. Tables 12.3 and 12.4 show the expected gains per generation, obtained with different selection methods (excluding MAS) when restricting the rate of inbreeding to 1% and optimising:

1 the numbers of parents to be selected;

Table 12.3. Genetic gains (in phenotypic standard deviation units) obtained with different selection methods and heritabilities (h^2) when the rate of inbreeding is restricted to 1% and the number of sires (N_S) and dams (N_D) are optimised. The common environmental variance was zero because all families are reared in the same environment in one tank. The numbers of candidates for selection were 500 males and 500 females.

Method	$h^2 = 0.1$		$h^2 = 0.4$		
	Gain	$N_S = N_D$	Gain	N_S	N_D
mass	0.17	36	0.56	33	66
within-family	0.10	21	0.44	21	21
index	0.19	65	0.56	36	72
BLUP	0.20	56	0.63	40	40

Table 12.4. Genetic gains (in phenotypic standard deviation units) obtained with different selection methods and heritabilities (h^2) when the rate of inbreeding is restricted to 1% and the number of sires (N_S) and dams (N_D) are optimised. The common environmental variance was 0.2 with all families reared separately in different tanks. The numbers of candidates for selection were 500 males and 500 females.

Method	$h^2 = 0.1$			$h^2 = 0.4$		
	Gain	N_S	N_D	Gain	N_S	N_D
mass	0.16	34	68	0.53	40	80
Within family	0.11	21	21	0.51	21	21
index	0.16	32	96	0.56	31	31
BLUP	0.18	53	53	0.61	38	38

2 the relative weighting given to within- and between-family information in the selection criteria (with index and BLUP selection); and
3 the contributions of parents to the next generation (with BLUP selection).

When an environmental effect common to members of the same family is simulated then gain is reduced if families have been reared in separate tanks (Table 12.4) compared to being reared in a common environment (Table 12.3). In a common environment, interfamily variation is ascribable entirely to genes, whereas when family environments differ variation will have both an environmental and genetic component. The latter makes successful identification of genetically-superior individuals less likely, reducing the rate of genetic gain. The advantages of a common environment can be gained by using molecular markers to distinguish family groups.

When methods are compared at a fixed rate of inbreeding, then the method giving the highest gains in all cases was the optimisation using BLUP breeding values; the method giving the lowest gains was within-family selection. When families are reared in a common environment, both index and BLUP selection require the genotyping of all the selection candidates to obtain the maximum gains. The 'walk-back' alternative of within-family selection requires from 7% ($h^2 = 0.1$) to 13% ($h^2 = 0.4$) of the fish to be genotyped. Comparing mass selection, the cheapest and simplest approach, and BLUP when families were reared together, the approach giving the greatest gain (Table 12.2), the advantage of BLUP over mass selection was between 13% ($h^2 = 0.4$) and 18% ($h^2 = 0.1$). Comparing mass selection and BLUP selection with families reared separately, the advantage of BLUP was reduced to 6% ($h^2 = 0.1$) from 9% ($h^2 = 0.4$). Thus the advantage of BLUP is about doubled by using a common rearing environment, something which is facilitated by using molecular marker-based discrimination. Which approach is to be preferred will depend on the relative economic gain realised from the genetic gain compared to the additional cost incurred by using BLUP. Clearly, the economic gain will be greater the more genetically-improved animals are reared.

These comparisons between the methods have assumed that environmental effects affecting performance, such as farm where the measurement is made (i.e., environment), sex, age of dam (female), etc., and referred as to fixed effects, are known and that data have been corrected for them. However, in practice these effects need to be estimated and BLUP is the only method that allows simultaneous estimation of genetic and environmental fixed effects. Therefore, in practice, the advantage of BLUP will be greater than that indicated by the simulations.

12.7 GENETIC ENGINEERING

The improvement philosophy driving genetic engineering differs. Rather than improving by selecting the best that nature can generate, genetic engineering improves by trying to build an artificial genetic construct specifically suited to a particular production objective. It does this by manipulating the numbers, types, or organisation of genes in the fish in a stock. Currently, two classes of engineering are being explored: chromosomal manipulation (including sex reversal) and transgenics.

12.7.1 Chromosomal manipulation (including sex reversal)

The main objective of sex-reversal techniques is to produce monosex stocks where sexes differ significantly in their production characteristics. In Atlantic salmon, a major difference relates to the timing of maturation, with many stocks having a significant proportion of males maturing during the freshwater stage and, once in saltwater, males tend to mature earlier than females. This could be avoided by producing all-female fish using hormonal treatments to produce sex-reversed females as a source of sperm to fertilise eggs (Purdom, 1993). Sexual differentiation in Atlantic salmon is poorly understood and is likely to have a genetic basis, and appears to be based on males being the heterogametic sex (i.e., XY; Johnstone *et al.* 1979), though sex specific chromosomes have yet to be identified. Monosex stocks of

Atlantic salmon have been produced (Johnstone, pers. comm.) but, unlike rainbow trout (Purdom, 1993), have yet to be exploited in a commercial context.

Sex reversal has been considered for use in Atlantic salmon in conjunction with triploidy, for the production of all-female triploids (Johnstone, 1992). Triploidy, the genetic state where an individual is induced by a temperature or pressure shock to have three rather than two sets of chromosomes, normally causes sterility (Maclean, 1998). For this reason production of triploids continues to be considered as a way of preventing genetic mixing of escaped farm fish with wild stocks. However, the widespread utilisation of triploids in Atlantic salmon has not occurred due to concerns that triploids show inferior production performance in relation to traits such as disease resistance and growth. This has been confirmed by recently-completed research, though the differences in performance, while significant, are small (R. Johnstone, pers. comm.).

Other chromosomal manipulations of Atlantic salmon which have been explored include gynogenesis or androgenesis. Gynogenesis is the process where individuals are created in which both sets of chromosomes are derived from the female parent; androgenesis is the complementary process for males (Maclean, 1998). However, the applications of these methods are confined largely to research programmes and involve the production of isogenic lines, i.e., lines where all individuals are genetically the same. These lines are useful in studying the genetic structure of the chromosomes as regards gene locations and in studying environmental control of performance variation. However, there is potential scope for using the method to produce inbred lines for outcrossing where outcrossing can be shown to give rise to economically-significant levels of heterosis for production traits. This is, of course, conditional on being able to control fitness reductions in the inbred lines, caused by inbreeding depression, to an acceptable level.

12.7.2 Transgenics

Transgenesis involves the artificial introductionof DNA into an organism, usually by micro injection, so as to generate permanent changes to its genetic make-up. The DNA transferred is most commonly a gene coding for a particular protein which affects cellular metabolism plus attached sections of DNA which ensure that the gene is expressed. The general methodology used to do this is reviewed by Maclean (1998).

In principle transgenic methods can be used to introduce any type of gene. However, what is both possible and desirable is constrained by the identification of genes known to be important to performance. Two potentially useful genes on which transgenic research has been carried out on the species are growth hormone (GH) (Du *et al.*, 1992) and antifreeze protein (Fletcher *et al.*, 1992). GH transgenics have achieved considerable success with claimed enhancement of growth rates of up to 400% and no effect on product quality (Dunham and Devlin, 1999; Aqua Bounty Farms: webhost.avint.net/afprotein.com). While these transgenic fish are now available to the industry, there is considerable resistance to their use due to a lack of consumer acceptance of GM salmon products, and due to concerns for the effects of escaped transgenic fish on wild populations (Kapuscinski and Hallerman, 1991).

12.8 FUTURE DEVELOPMENTS

In the future, improvements in the productive efficiency of salmon farming will become increasingly dependent on better genetic management of farm stocks and, in particular, on their genetic improvement. Compared to traditional farming sectors focused on dairy cattle, pigs or poultry, salmon farming has to date seen little attention paid to genetic management. This is partly because traditional approaches to genetic management, used for terrestrial livestock, rely heavily on the ability to physically track the pedigrees of individual animals across generations. Tracking of Atlantic salmon with physical tags alone is difficult given their small size at birth. Also, in the past, the cost of purchasing and applying physical tags to large numbers of small fish presented a major constraint. However, this constraint has been considerably alleviated in recent years by developments in fish tagging methods such as miniaturised electronic transponders (i.e., PIT tags).

In the past, the obstacles to traditional methods of genetic management could only be overcome at considerable expense and inconvenience. It required the building and running of specialised facilities that provided for the isolation of family groups in effectively identical environmental conditions until the fish were large enough to be physically tagged. However, this situation has now changed with the advent of molecular marker technology. Using molecular markers, the requirements for isolated rearing can be removed. Furthermore, used alone, or in combination with new physical methods of tagging fish that allow individual identification, molecular marker technology can increase the numbers of individuals and families which can be tracked. By using more families in breeding programmes problems of inbreeding can be reduced and the rate and scope of genetic improvement within a stock can be increased.

What constitutes an optimal breeding programme for a salmon stock will depend on the stock involved and on the specific circumstances prevailing in the farming operation in which it is kept. Considerable effort is now being directed at developing operational methodologies for optimising breeding programme design based on using the added information from molecular markers. The availability of cost-effective markers will also facilitate the adoption of comprehensive genetic evaluation schemes such as BLUP which will allow more rapid genetic improvement of farm stocks. In contrast, the use of genetic engineering is likely to be constrained by consumer concerns regarding the safety of GM organisms.

The development of optimal genetic management programmes represents a major challenge for salmon farmers. It cannot happen overnight given that the production cycle takes 3–4 years and must be based on a long term (10+ year) management perspective. It will first require an increased awareness and understanding of genetic issues among farm managers. Furthermore, the complexity of genetic issues, and the stock-specific nature of such programmes, means that consultation with experts, or taking on staff with genetic expertise, is essential to success. How an individual farmer approaches genetic management will depend to some extent on whether a farm maintains and improves its own stocks, as is the case for dairy farming, or stock improvement is left to specialised breeders, as is currently the practice in the poultry farming industry. Where genetic management has been carried out in the industry so far, it has been associated overwhelmingly with selective breeding programmes heavily supported by public funding. However, molecular marker technology now makes it possible to carry out genetic management on a farm-by-farm basis.

How increased levels of genetic management are achieved within the salmon farming industry will depend to some extent on whether farm broodstock is held by a few companies, which sell eggs or juveniles to market producers, or is distributed amongst a large number of independent farming operations, each with their own stock lines. A comparison with terrestrial farming sectors suggests that selective breeding in salmon farming is more likely to be addressed using the model followed by the poultry industry. In the latter, the majority of production will be derived from breeding stocks established, maintained and improved by specialist firms which supply improved fish to farmers for on-growing. Under such a system, a basic understanding of genetic management issues by individual producers will still be essential for them to make informed choices on which stocks will best meet their needs.

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13

Integrated management of salmon farming areas

13.1 INTRODUCTION

This chapter presents important challenges faced by the salmon farming industry internationally and illustrates the need for an integrated approach to management in order for the industry to achieve its full growth potential in a sustainable way. The main aim is to provide an overview of the various factors linked to management that influence how salmon are farmed, including the economic, environmental, legal, political, regulatory, scientific, social and sustainable aspects. A second aim is to show that it is only by consideration of all these factors in an Integrated Management Strategy for Salmon Farming Areas (IMSSFA) that the industry can operate in a responsible and sustainable manner in harmony with the environment. At the same time, the industry must coexist with other resource users that share the same land and water, and fulfil the requirements for production as well as address the views of other stakeholders and interested parties.

A brief summary of the main points important to managing the salmon farming industry is presented. This chapter provides a guide to the key issues confronted by a sector that has seen rapid changes, resulting in often complex and abundant literature scattered in government reports and conference proceedings where text can be difficult to find as well as to understand. The 1990s saw an improvement in available information; for example, focussed reviews now exist on policy (Fluharty, 1991) and regulation (Schwindt and Bjørndal, 1993) in relation to salmon farming. Such texts help to improve our understanding of these important topics which are needed for developing effective management. Furthermore, Sutherland and Clayton (Chapter 7, this volume) give a more detailed account of the main economic and business issues whilst Thomson and Side (Chapter 9, this volume) describe some of the main legislative dimensions using the Scottish salmon farming industry as an illustration.

The following sections outline existing and emerging management strategies. Although the management details will vary within and between the various

Table 13.1. 1997 EU Aquaculture Production. (After MacAlister Elliott and Partners Ltd., 1999)

	Salmon		Trout		Carp		Eel		Sea bass/bream	
Member State	Volume (tonnes)	Value (€,000)	Volume (tonnes)	Value (€,000)	Volume (tonnes)	Value (€,000)	Volume (tonnes)	Value (€,000)	Volume (tonnes)	Value (€,000)
Austria	0	0	3,400	10,700	800	1,680	0	0	0	0
Belgium	0	0	820	2,360	300	567	150	946	0	0
Denmark	0	0	36,550	74,366	0	0	1,700	13,860	0	0
Finland	9	20	16,315	37,311	0	0	0	0	0	0
France	0	0	51,660	101,954	5,500	11,550	160	1,696	3,485	27,138
Germany	0	0	25,000	63,655	11,514	23,030	150	1,290	0	0
Greece	2	16	2,322	5,805	50	120	312	2,761	25,500	154,687
Ireland	15,441	50,734	1,799	4,628	0	0	0	0	0	0
Italy	0	0	51,000	105,940	100	264	3,100	29,446	8,500	59,931
Netherlands	0	0	200	618	0	0	1,800	14,670	0	0
Portugal	0	0	1,500	4,504	0	0	200	1,678	2,611	20,884
Spain	1,100	3,289	25,000	41,358	0	0	266	2,036	6,040	38,419
Sweden	0	0	4,875	11,382	0	0	215	1,625	0	0
UK	99,197	339,469	15,100	33,574	0	0	0	0	0	0
Total	115,749	393,528	235,541	498,157	18,264	37,211	8,053	70,007	46,136	301,059

salmon farming countries, this chapter highlights the trends, common issues and challenges faced by an internationally successful industry. Case studies are cited where appropriate.

Salmon farming has grown to become an important and valuable industry around the world, providing both economic and social benefits to many nations. Decisions regarding policy and management for farming of salmon are largely driven by economic factors to ensure that this industry remains competitive in a global market. The largest producers of farmed salmon are Norway, Chile, the UK and Canada, in that order. In 2000, production figures for salmon in these countries were approximately 474,000, 302,000, 114,000 and 70,000 million tonnes respectively– these values also include figures for sea trout (Egan, 2001). Atlantic salmon, *Salmo salar* L. is the species most commonly farmed worldwide, due to market preferences and cost advantages. Table 13.1 illustrates the volume and value of farmed salmon produced compared with other aquaculture products across the EU in 1997.

The development of the industry has been influenced by government policies, regulation and legislative frameworks that reflect the changes in the size and value of this dynamic sector. There has been a progressive move from small, privately-owned businesses to ownership by larger and often multinational companies. In addition, operations are generally now centred on larger sites. The increased production reflects farmed salmon retaining its popularity as an internationally-recognised consumption good, although its earlier perceived image as a luxury product has been replaced by that of a commodity item. In economic terms, salmon aquaculture is often welcomed as a significant source of employment and income, especially in rural locations where employment opportunities can be few. However, this is changing as the industry matures and increasingly adapts to more automated technology.

1999.)

Turbot		Mussels		Oysters		Clams		Others		EU Totals	
Volume (tonnes)	Value (€,000)	Volume (tonnes)	Value (€,000)	Volume (tonnes)	Value (€,000)	Volume (tonnes)	Value (€,000)	Volume (tonnes)	Value (€,000)	Volume (tonnes)	Value (€,000)
0	0	0	0	0	0	0	0	74	267	4,274	12,647
0	0	0	0	0	0	0	0	201	819	1,471	4,692
0	0	0	0	0	0	0	0	0	0	38,250	88,226
0	0	0	0	0	0	0	0	41	91	16,365	37,422
980	7,448	53,604	66,444	87,103	138,952	618	4,215	8,095	27,668	211,205	387,065
0	0	22,330	10,819	75	662	0	0	0	0	59,069	99,456
0	0	25,434	8,006	0	0	0	0	1,327	6,659	54,947	178,054
5	39	13,285	6,563	4,406	7,209	165	1,291	0	0	35,101	70,464
0	0	103,000	53,631	0	0	40,000	83,310	6,219	24,509	211,919	357,030
0	0	93,200	55,908	1,234	1,981	0	0	1,206	2,663	97,640	75,840
105	840	445	432	618	1,200	3,260	23,897	42	286	8,781	53,722
2,055	16,440	188,793	59,528	3,387	7,893	5,591	36,071	1,461	6,955	233,693	211,989
0	0	1,425	629	0	0	0	0	8	176	6,523	13,812
75	591	12,991	7,711	1,053	2,801	36	115	73	262	128,525	384,522
3,220	25,358	514,507	269,672	97,876	160,699	49,670	148,899	18,747	70,354	1,107,763	1,974,944

In addition to being a means to produce a food commodity, salmon farming—sometimes referred to as salmon aquaculture or salmon culture—exists in each of the world's major geographic areas where the fish's wild counterparts can be found. Farming salmon is also considered to have an important role in 'gene banking' of endangered stocks and in the restocking of rivers, mainly through the introduction of individuals that have previously been reared in freshwater hatcheries. The success of culture as a method for restocking attracts opposing views, however; its use has led to the introduction of non-indigenous species to countries such as Chile that have gone on to develop a successful salmon farming industry. Atlantic salmon is generally the preferred species for cultivation as it is relatively easy to rear successfully under artificial conditions compared to other salmonid species.

The scale on which salmon is farmed has led to increasing importance being placed on how this industry is managed. There is often confusion by what is meant by 'management', and why it is important to adopt a holistic approach that integrates economic, environmental, legislative, political, regulatory, social and scientific factors among others. Only by gaining a combined understanding of all these factors in planning and management can a full picture of the needs and requirements for the industry be assessed and acted upon so that it grows to its full potential. Section 13.2 explains these key factors before moving on to discuss the main management issues and challenges that face the salmon farming industry.

13.2 MANAGEMENT

What is management? Management can be described as a system based on regulations and rules permitting the controlled exploitation of resources such as salmon

(Van Tilbeurgh, 1994 cited in Barnabé and Barnabé-Quet, 2000). Management can mean many different things to different people: confusion can arise over the distinction between administration and management. The former involves the orderly arrangement of resources in accordance with a defined set of rules and regulations, whereas management generally involves the use of resources to achieve a set of objectives. In reality, most managers are involved in both so the distinction between administration and management does not exist and is generally a matter of language.

Management exists at different levels and in order to have successful multilevel management systems it is necessary to have a clearly defined set-up where goals and objectives are agreed and understood by all involved. Identification of management or managers at the local level, for example the farm manager, is relatively easy; however, it can be difficult to identify who is responsible for the overall management of salmon aquaculture at a national and regional level. This can be frustrating where conflict resolution is required at a national level. The difficulty can partly be explained in that a large number of bodies can be linked to the management of salmon production; for instance in Scotland, the salmon farming industry is regulated by at least ten different statutory bodies and is covered by approximately 63 pieces of legislation. Perhaps if for each salmon farming location an IMSSFA existed that contained easy-to-digest information on regional, national and local issues and priorities then management could be simplified. In Scotland, voluntary management schemes along these lines have been proposed, although largely to address the control of lice. Plans for area management agreements (AMA) are recommended (see Section 9.2.5.1). Similar management schemes are being developed in other salmon farming nations, largely addressing the marine on-growing phase in the context of integrated coastal management recommendations.

Clearly, a successful manager must have knowledge in all or most of the following: strategic planning, project management, budgeting, marketing, personnel management, performance management, quality procedures and environmental resource management. Larger salmon farm companies often have managers who specialise in one or more of these areas. Employees with these skills therefore play an important role in profitable businesses. Before attempting to explain IMSSFA as a way forward for the industry it is helpful to understand the various factors important for a successful management strategy and collectively what information is needed. The following sections explain the main factors, starting with economics.

13.2.1 Economics

Economics is concerned with the way in which wealth is produced and distributed. The rationale behind farming species such as salmon is to supply the demands of consumers, which can not be met through wild salmon fisheries alone. Chapter 7 of this volume deals with the economic and business issues of salmon farming in more detail under the headings: demand, supply, analysis, planning and control. This section gives a short summary of some important issues related to the economic analysis of salmon farming and managerial/business economics. As a point of reference, some texts confuse the terms financial analysis and economic analysis. The former deals with factors that regulate the costs of production, marketing and profits from the sale of salmon associated with the fish farm. Economic analysis is based on a broader accounting framework that includes factors not necessarily directly related to the producer but refers to those that may influence other activities and/or have associated costs in a social or environmental context. One example of the latter is pollution from a farming unit which has an impact on other activities sharing the same environment; however, the polluter does not have to pay if there is no mechanism in place to ensure this happens.

The discipline of economics is conventionally divided into two branches: microeconomics and macroeconomics. Microeconomics concentrates on the working of markets and the price mechanism. Questions that might be addressed include: Why are some salmon products expensive and others cheap? What determines the profitability and success of a salmon farming operation? How do companies behave and what determines their policies and strategies? A microeconomist might also be interested in market failure, monopoly power which can lead to government intervention, privatisation, and the control of utilities such as gas, electricity and water. Macroeconomics focuses on the functioning of the economy as a whole and the factors that affect it, for example, growth rate of the salmon industry and the existence and severity of inflation and unemployment. Policy issues are an important part of macroeconomics because part of a government's obligation to its people is to deliver satisfactory economic performance.

Economic influences that need to be taken in to consideration by the industry as part of a management strategy include:

- *Profitability*: for the salmon farming industry to continue to be profitable there needs to be a balance between demand expansion and supply growth. The farmed salmon market has suffered from periodic excess supply and demonstrates the dangers associated with rapid supply growth. In the context of diminishing barriers to trade under multilateral and bilateral trade agreements the supply situation is important on both a domestic and an international scale.
- *Demand*: according to MacAlister Elliott and Partners Ltd (1999) in relation to salmon, continuing strong demand growth is likely to be able to absorb plausible increases in domestic production. These authors also predict that salmon, along with other farmed species such as seabass, sea bream, turbot and trout, have the most potential for product development in order to meet growing demands for processed and convenience products. Salmon prices are expected to remain sensitive to supply increases, including imports. Generic promotion is one approach to expanding demand and as salmon production is being increasingly exposed to international competition as trade liberalisation proceeds then salmon farming must remain competitive.

To summarise the influence of economic factors in management, a case study based on the economic analysis of salmon production in the EU conducted by MacAlister Elliott and Partners Ltd (1999) is presented and illustrates the expected growth for this sector in Europe. Although the example given is based on produce figures for Europe, this example serves to highlight similar trends for expected growth in other salmon producing countries:

- Consumption of salmon in the 1990s has been variable although some years have seen an increase by 10% or more. This positive trend is thought to reflect increased concerns about healthy eating and the greater availability of salmon products through multiple retailers.
- Expected growth of the salmon production sector is estimated to approximate 4% per year. The main constraints to growth potential include: tightening of environmental policy; a shortage of new sites; prohibitive costs associated with offshore technology; and continuing Infectious Salmon Anaemia Virus (ISAV) problems or parasite infestations such as sea lice.
- Production costs are likely to decline slightly with further growth, mostly due to increases in efficiency in labour. Costs associated with feed are assumed to remain stable at 1996 levels. Capital expenditure per unit output is expected to fall and be neutralised by more expensive engineering solutions. Unit cost of eggs and smolts should be reduced through increased stock performance. Fish health regimes will be facilitated as licensing of new sea-lice compounds improve overall productivity in the short term, and by sea-lice vaccines possibly having more influence in the longer term.
- Salmon exports to the EU are predicted to increase by 6% per year. This calculation is based on Norway and Chile achieving success in export diversification and the current volume limitations on Norway remaining.

This section links well into a more general discussion on environmental and sustainability considerations, the subject for the next part of this chapter.

13.3.2 Environmental and sustainability issues

The impacts of salmon farming on its surrounding environment is well understood in most areas of research, with increasing information being gathered on issues that are not yet fully understood such as sea lice and ISAV. Details on these and other environmental impacts are discussed in Chapter 9. In summarising Chapter 9 of this volume, which concludes that salmon farming need not have serious negative impacts on the environment if salmon are farmed in a sustainable and responsible manner.

Sustainable development (SD) has become an overused term for which many definitions exist. The most commonly-used definition is that of the World Commission on Environment and Development (The Bruntland Report; WCED, 1987) which defines SD as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. An obvious question then follows: is aquaculture and, more specifically salmon farming, sustainable? Although some may have some ready-made answers to this question there is no one straight answer. Recent debates on whether or not salmon farming is sustainable have raised some interesting challenges to this field of investigation and any debates on this issue should consider the complex interrelationships between salmon farming and environmental and human factors (see Chapter 9 of this volume for details). One area in which reliable information is scarce or lacking is on the carrying capacity of an aquatic environment supporting salmon production. Compounded with the uncertainty surrounding the likely impact of climate change on the physical properties of an ecosystem it is difficult in reality to determine how sustainable salmon farming is and will be in the future. The theory developed behind sustainability can be argued more easily from a moral standpoint than from a practical and readily implemented one. An example that has received a lot of attention questions how salmon farming, along with other cultured finfish species, can be sustainable when it relies on wild fisheries for key dietary components. This is debated further below.

13.2.3 Salmon farming and its effect on world fish supplies

The publication of a review on the 'effect of aquaculture on world fish supplies' by Naylor *et al.* (2000) raised many views opposing the authors' claims. The main issue raised by Naylor *et al.* (2000) was that the expansion of the global aquaculture industry posed a threat to both ocean fisheries and to itself. The authors argued that farming carnivorous fish such as salmon requires large inputs of wild fish—the main source of fishmeal and fish oil—for feed. They also stated that if the growing aquaculture industry is to sustain its contribution to world fish supplies then it must reduce wild fish inputs into aquaculture diets and adopt more ecologically-sound management practices. This argument was contested by Roth *et al.* (unpublished) who pointed out that fishmeal constitutes only 4% of the total fish-oil market demand (Asche and Tveterås, 2000), and that fishmeal for use in aquaculture can vary between 20% (Gérin, 1999) and 35% (Chamberlain and Barlow, 2000). Roth *et al.* (unpublished) concluded that terrestrial live stock production is the most influential factor with respect to the demand for fishmeal and not aquaculture.

The related arguments about the use of wild fish from capture fisheries as sources of fishmeal and fish oil for feed production are an important part of the debate on sustainability of salmon farming. This issue, in the opinion of the author, has not yet been resolved in any convincing way and particularly in a way that communicates to the wider public. It is acknowledged that the complexity of the subject does not allow for definite and easy answers. Trying to answer what kind of aquaculture is desirable can then lead to having to answer what kind of capture fisheries, and eventually what kind of agriculture is ideal. Although all the answers may not be available at present, it is important that the issues are debated and understood. It would be unacceptable to reject the challenge of solving many of the outstanding sustainability and environmental issues related to salmon farming or to ignore or downplay their importance. Instead, it is better to explicitly acknowledge the uncertainty that exists and promote flexible and adaptable management and policies. Salmon farming has been portrayed as an activity which has a negative impact on the environment, and rather than counteracting the arguments against its practices at times the industry has been seen to have its 'head stuck in the sand'. Although some environmental awareness groups have been accused of presenting only one side of the argument, many have encouraged the wider and more open debates on issues related to this activity. There was a welcome change in the 1990s when the salmon farming and aquaculture industries were on the whole more prepared to defend and discuss openly the benefits that they can bring to society. This has been achieved by initiatives from, for example, growers' associations and representatives who have organised proactive and transparent campaigns with a focus on wider dissemination of factual and interesting information. Also, salmon farming, along with other aquaculture industries, has actively been involved in promoting and increasing public and consumer awareness to ensure that a positive and representative image is presented to all.

Further encouraging signs include an increase in applied research that addresses some of the issues already mentioned, such as rearing carnivorous fish like salmon and cod on herbivorous diets. The main aim of this work is to reduce the reliance placed on artificial diets composed of fishmeal and instead use feed composed of alternative sources of protein of plant origin, such as cereals like corn. It is especially important to find alternative sources of protein to those of wild fish origin, not just for salmon but also for the newer species being farmed such as cod, haddock and sole that will also make increasing demands on supplies of fishmeal.

Other research projects are focussing on technological advances to allow production of marine species onshore and thus alleviate the increasing demands made on coastal resources. Section 13.2.4 discusses new species and new technologies and presents an example of such work by Krom *et al.* (2001) in more detail. A further example of research under investigation is on the effects of salmon farming and other forms of aquaculture on local economies, employment, capture fishery performance and coastal biodiversity. This work aims to address concerns about salmon farming and the effects it has on local fishing activities in terms of pollution, the spread of fish diseases, and tourism.

Given the arguments of over-exploitation of natural resources as discussed, then the question arises: should some limits of growth be placed on the salmon farming industry? Increased regulation already appears to be having an impact on the growth of the industry in some countries, yet few studies have fully addressed the carrying capacity of aquatic environments with regard to salmon farming and other forms of aquaculture in the longer term, as mentioned earlier. Yet without this knowledge it remains a challenge to have meaningful discussions on the sustainability issues of salmon farming. It is a challenge to explain all the relationships that exist, especially when there are uncertainties, such as the effect of global warming on climate change when patterns of ocean currents are changing, and in particular the effect it could have on changing water temperatures and fish farm production. Knowledge on this topic could have implications on the future development of rearing systems for salmon and new species, for example in response to the supply and regulation of water. It is sometimes difficult to forecast events accurately well into the future. Nonetheless, it is important to plan ahead and be prepared for potential changes and the possible action that can be taken—this can be best prepared for by knowing how to deal with various scenarios if they occur.

Some researchers are addressing the uncertainties surrounding the environmental carrying capacity for aquaculture in developing rearing systems that minimise their reliance on natural resources—could this be the way forward? This is discussed next.

13.2.4 New species and new technologies

In the last decade, the aquaculture industry has seen the introduction of many new species and new technologies, partly in response to increasing demand and the search for diversity in food choice in affluent societies. Diversification in aquaculture production has increased both in the number of species farmed and the tonnage harvested, as illustrated by Table 13.2. The latest pilot production trials in temperate parts of Europe are for halibut, *Hippoglossus hippoglossus*, and haddock, *Melanogrammus aeglefinus*. Other species more recently identified as potential candidates for European aquaculture and currently under investigation include the sole (reproduction and hatchery rearing of *Solea solea* and *S. senegalensis* is possible although culture has not yet been optimised) and cod (*Gadus morhua*). Some argue that we should concentrate more on improving production of existing species and develop new technologies to meet increasing demands, especially in view of reducing environmental impacts of aquaculture, rather than on developing new farmed species. On the other hand, can diversification strengthen the aquaculture industry on the whole? One promising development in finfish production technology is that by Krom *et al.* (2001) who have designed the first marine finfish production system that can grow commercial quantities of fish successfully away from the shoreline. This raises immediate questions regarding the potential for rearing salmon during the marine on-growing phase further inland, thus removing the increasing difficulties of finding suitable sites for marine cage farming in coastal areas. Is this the way forward for salmon farming? Krom *et al.* (2001) plan to investigate the costs and benefits of their system in the next phase of development of this research. Most alternative systems still require large amounts of high-quality water, which can be expensive to pump and also limits the location to close to the shoreline. Systems such as those designed by Krom *et al.* (2001) could significantly reduce the environmental impacts of fish farming in inshore areas.

Table 13.2. Diversification in aquaculture production. (After Wurmann, 2001)

5-year periods	Number of species farmed	Annual harvest (Tonnes, in 1000)	Average harvest/species (Tonnes, in 1000)
1970/74	140	4.240	30.3
1980/84	191	8.538	44.7
1995/99	325	36.639	117.7

Technological advances in rearing systems may increase the potential for diversification into farming more new species of marine finfish, which traditionally have only been available from the capture fisheries). Diversification is one way to address demanding markets and product proliferation. However, some of the same issues arise that were raised earlier such as: Will new species increase the demand for fishmeal and fish oil from wild fishery resources? Can new species stimulate more fishing down and farming up on the food chain? Could new species partly utilise feed from agricultural overproduction? Will new species introduce new disease problems? Related issues also include the possible effects of farming new species on biodiversity and how escapees could influence the gene pool of wild stocks. Perhaps these questions will be addressed in the next edition of this book in 2012 or beyond. At this time, examples of wise management in dealing with some of these situations should be applied and adopted by farmers of new and emerging finfish species when and where appropriate. Advances made in biotechnology could hold some of the answers to these issues.

13.2.5 Biotechnology

Much discussion has taken place on the relative merits of biotechnology and its role in salmon farming and other forms of aquaculture. Food scares now appear more frequently in the press with some articles labelling salmon as 'Frankenstein fish'. Confusing messages have been sent out to the public, largely reflecting disagreements among experts on the pros and cons of biotechnology and the uncertainties associated with its use. It is not surprising then that some misunderstanding exists over the various terms used to describe the different types of biotechnology, such as genetically modified organisms (GMOs), triploidy and transgenic salmon. The following describes what is meant by each of these terms before moving on to discuss the broader issues.

One reason why uncertainty may exist about GMOs is that a number of definitions exist. According to the Food and Agriculture Organisation of the United Nations there is no universally accepted definition of a GMO, although several international organisations and countries have adopted the following definition: that a GMO is an organism in which the genetic material has been altered anthropogenically by means of gene or cell technologies. These technologies according to ICES (1995) refer primarily to gene transfer and 'include the isolation, characterisation, and modification of genes and their introduction into living cells or viruses of DNA as well as techniques for the production of living cells with new combination of genetic material by the fusion of two or more cells'.

In the EU a GMO is defined as 'an organism in which the genetic material has been altered in a way that does not occur naturally by mating and/or natural recombination'. The EU has excluded the products of selective breeding and organisms that have had their chromosome-set altered (polyploidy) (European Commission, 1990). In contrast, the US Department of Agriculture includes chromosome manipulation and interspecific hybridisation in their definition of techniques applied to organisms that are subject to performance standards for GM fish and shellfish (ABRAC, 1995). Perhaps the broadest definition of GMO that exists is that used by the Fisheries Department of the FAO and the International Center for Living Aquatic Resources Management which includes any genetic manipulation, for example selective breeding, hybridisation, sex reversal and chromosome set manipulation as well as the modern biotechnologies of gene transfer (Pullin 1994; Pullin and Bartley 1996).

To conclude, and to avoid confusion when referring to GMOs, it is best to define what technologies and classes of organisms are being discussed when referring to organisms that are being modified or manipulated. When discussing salmon, for example, other commonly-used terms are 'transgenic salmon': this refers to salmon into which genes from another species have been deliberately introduced by genetic engineering. 'Triploid salmon' are salmon that have been treated (heat or pressure shocks administered to recently fertilised ova) to produce three sets of chromosomes per nucleus compared to the normal two sets of chromosomes (diploid) and the salmon are functionally sterile. Triploid salmon have been suggested as a possible solution for the problem of escapees, with the argument being that triploid fish are sterile and hence can not compete with their wild counterparts. However, research has shown that it is not always possible to obtain 100% success rate in sterility by the use of triploidy.

At the time of writing, the European aquaculture industry has not used transgenic salmon for production although transgenic fish, including salmon and also tilapia, rainbow trout and zebra fish, have been produced in research projects throughout Europe. Additionally, other countries, including Canada, USA and Cuba, are currently developing transgenic fish for increased growth or cold water tolerance. Some countries have now endorsed a moratorium on the rearing of GM fish in marine cages and some support the use of GM animals, including fish, in medical research, stating that they may play a crucial role in the battle against diseases such as cancer, muscular dystrophy, cystic fibrosis and foot-and-mouth. In view of this application, it has been suggested that GM fish could be produced commercially for medical research in land-locked facilities only. The advantages of using GM fish in research is that species such as salmon have demonstrated threefold increases in growth rates over non-GM fish and a potential to exploit colder waters. Although there remains the possibility that GM escapees could compete successfully in the wild, having an impact on native stocks, it is thought that GM technology may actually provide fewer welfare problems over existing methods in terms of conducting research. This is because to obtain a GM fish involves the transfer of specific genes whose primary functions are known, whereas projects relying on selective breeding can be unpredictable as results in many genes of unknown function are being changed. Furthermore, GM technology requires fewer generations for the full effects to be observed so results can be obtained more quickly when compared to conventional methods used.

If biotechnology can be used to affect traits that currently seem to stand in the way of sustainable development then should it not be used, especially in developing countries, to aid supplies of protein from a fish source? Taking a moral viewpoint, is it appropriate to sustain the salmon farming industry that largely serves the needs of the richer societies without balancing considerations concerning the food needs of the growing world population in the poorer countries? In terms of the sustainability issues surrounding the demand of fishmeal and fish oil (from wild capture fisheries) in salmon feed then one application of biotechnology might be to use molecular genetics to produce salmon with a reduced need for fishmeal and fish oil without compensating growth performance.

So in order to fully debate sustainability issues seriously there is a need to challenge existing attitudes taken by consumers and other interested parties and to seek out a constructive dialogue on the strengths, weaknesses, opportunities and threats (SWOT analysis) of biotechnological development. Similar considerations apply to the introduction of sterile fish that could minimise the biological impacts of escapees. Given that many consumers are confused about the issues then it is clear that the public needs to be given advice that is easy to understand so that they can make an informed decision about the choice of salmon and other products produced by aquaculture. It can be difficult to communicate a clear factual message, especially when experts have strong opposing views that are often reported widely by the media, which can enhance uncertainty about the issues at hand.

13.2.6 Legislative, political and regulative dimensions

The rapid expansion of salmon farming and other forms of aquaculture, especially in terms of economic importance, has led to the increased need for tools that can protect and sustainably enhance development of this industry. Until recently the legal system has been slow to respond to aquaculture and its development in comparison to its terrestrial counterpart, agriculture. In part this can be explained by the abundant and complex laws and regulations that exist which are relevant to aquaculture although do not mention aquaculture per se. In addition, in some countries' difficulties arose initially owing to a lack of a legal definition of aquaculture or fish culture. During the 1990s, legislation pertaining to aquaculture has developed and passed into law at an accelerated rate, so much so that some consider regulation (a set of rules or restrictions that control activities) to be a hindrance rather than facilitator to the development of the industry.

Simply put, laws that may affect the salmon farming industry can be divided into common, international (for example, those set by the EU), federal (such as Australia, Canada and USA), national (for instance, Scotland and Norway), and local laws. There is much variation between various countries' legal systems and some countries, such as the United Kingdom, do not have a common legal system. In the UK, some laws are unique to only one of the nations, which can have its own procedures, legal professions and courts. For example, in Britain, Westminster legislation is applied largely across the different nations although in Scotland, where most Atlantic salmon is farmed, the Scottish Parliament legislates on devolved matters, which include some environmental considerations specific to salmon farming. Common laws generally refer to water rights and the culture of organisms in public waters. International laws relate largely to exclusive economic zones and fishing agreements between nations: in respect to salmon these have implications largely for salmon ranching. Federal and national laws are mainly concerned with trade of salmon products and associated technology, pollution of waterways, food safety, health of consumers, development of areas that support salmon farming and marketing. Local laws are more directly related to the salmon farmer and include regulations, planning permission and building consents. Public or regulatory bodies usually act on behalf of federal and national governance systems and may be responsible for monitoring discharges from the salmon farm, water quality and environmental impacts.

Law has an important role to play in ensuring that salmon farming is developed sustainably. It is vital that legislation considers the balance between meeting recognised needs, for example salmon as a source of protein for people and farming practices that minimise the consequent environmental losses. Law is a flexible mechanism which allows the use of a range of regulatory approaches related to the undesirability of the activities that need to be addressed in order to achieve a desired outcome. Legal controls are diverse and can range from absolute prohibition, through licensing and authorisation requirements to less mandatory measures, for example self regulation, codes of practice and educational provision. In terms of salmon farming and aquaculture in general, legal mechanisms need to ensure that the least environmentally desirable practices are subject to the highest degree of legal stringency. Howarth (2000) recommends that beyond appropriate regulatory instruments, enforcement is central to securing best practice for aquaculture activities. Furthermore, this author explains that extremes of unacceptable behaviour need to be identified and prevented by punishment where necessary. In reality, enforcement can be difficult to implement and has associated costs for resources and time, which are usually not readily available. It is perhaps better to encourage good practice through the offer of incentives rather than opting for punishment as a deterrent. Incentives have already been addressed by the salmon farming industry in some countries in that salmon reared in good-quality water by environmentally-sensitive methods are rewarded with selective product labelling issued through quality assurance schemes. This then ensures that the consumer is buying a product that meets their demands in terms of quality expected. Regulation can be used to encourage good practice in salmon farming by the imposition of regulatory standards for salmon products at national and international levels which again can aid marketing (see Chapter 6 of this volume).

Increased awareness about salmon farming and its environmental consequences, in addition to product supply and safety, has led to increased pressure being exerted on political figures to introduce policies supporting appropriate legislation and tighter product control procedures. Given the number of recent food safety-related scares that have raised concerns in consumers—such as bovine spongiform encephalytis (BSE) and dioxin contamination—it is important that the salmon farming industry maintains public credibility. One good example of action taken to address this very issue is that by the Federation of European Aquaculture Producers (FEAP), which supports the need for strong self-regulation by the food production sector. (This is in light of the uncertainty that exists as to whether or not state or regional control is likely to be effective.) FEAP has prepared a Code of Conduct for European aquaculture where the prime goal is to establish a common base, through effective self-regulation, for sectoral responsibility within society. An additional aim is to demonstrate the considerations of the production sector towards the fish it rears, the environment and the consumer (Hough, 2000). This code is a voluntary and non-binding document also called soft law that was drawn up in response to self-regulated sector development (Hough, 2000) and includes all species, types and scale of fish farming. The topics addressed include the following:

- guiding principles of the Code (describes the expected conduct and attitudes by all those involved in aquaculture in Europe);
- fish husbandry;
- environmental issues;
- consumer issues; and
- social and economic considerations.

FEAP have continued to promote further proactive actions within the fish farming sector such as the development of Codes of Practice by Associations, Best Management Practices by Producer Groups and Cooperatives, recognised quality schemes such as Scottish Quality Salmon and approved labelling schemes, for example, 'organic'. As stressed by Hough (2000), it is important that salmon farmers contribute actively towards the balanced and sustainable development of its industry and make their best efforts to assure the transparent development of salmon farming to the benefit of the consumer and society. Although increased visibility can lead to more frequent conflicts between the public and private sectors and other interested bodies, especially those with regulatory powers, it is only by adopting transparent discussions that the industry can move forward towards improved sustainable farming of salmon. FEAP launched a new initiative in 2001 called 'Aqua-media' that has been designed to counter negative reports of the aquaculture industry, including salmon, in the media. The project is funded by the private sector and it will prepare and release relevant information, using the Internet, multimedia CDs, newsletters and brochures (Hough, 2001). The target audience includes the general public, people in education (schools, colleges and universities), government and related institutions, the press, consumer and special interest groups. Aqua-media aims to provide information on all areas of the aquaculture sector and will not avoid sensitive areas where criticism is raised. In order to reach wider audiences, information will be developed in multilingual formats. This initiative, along with others, will aid the development of legislation and regulation for the farming of salmon through the availability of reliable and interesting information based on proven facts.

The next section focuses on the key scientific issues that need to be addressed in the management of salmon farming.

13.2.7 The role of science in integrated management

To date, management of aquatic resources such as salmon has largely been based on scientific information, with little consideration given to the views of stakeholders. This is changing in recognition of the benefits associated with adopting a holistic approach to management that integrates knowledge from the natural (sometimes referred to as physical, pure or life), applied and social sciences (including social and cultural dimensions). In Canada, the Department of Fisheries (DFO) and Oceans has recently started a new initiative to encourage and extend citizen engagement through the development of academic partnerships where knowledge in all the different branches of science can be collected and used alongside local knowledge in developing good management and policy for activities such as salmon production (Coastal Zone Canada Association, 2001).

So why do scientists sometimes attract negative press? Partly because some are unskilled in communicating to wider audiences, others are suspicious of the press and many do not know how to use the media to their best advantage. Scientists have also been observed to be preoccupied with aquaculture and accused of not being in accord with producers' problems (Van Tilbeurgh, 1994, cited in Barnabé and Barnabé-Quet, 2000). Among common criticisms directed at scientists is that they 'sit on the fence' when asked for a definitive answer and/or are unable to give their own opinion on an issue. Why? One explanation is that natural scientists are taught to base their investigations on a thesis to be tested and then present results in a stylised way, e.g., 'there is not sufficient evidence to suggest that salmon farming has a long-term negative impact on its environment'. Similarly, scientists are also trained to be 'objective' and to minimise personal opinions and are therefore not generally comfortable with including the views of other actors.

Scientific research on salmon production deals with complex subject matter and this is made more challenging when socio-economic considerations are included alongside scientific and technological advances. Integrated management strategies often contain uncertainty that can lead to high value stakes. Values can be built on traditions and beliefs on the one hand, and on actual knowledge on the other. Given that an individual's views and values on issues are subjective and will vary according to their background, knowledge, perceptions, priorities and experiences, it is important that scientists are in touch with social debate, especially when making recommendations to policymakers. Integrated management strategies must include information from the stakeholders. At a local government level there is a move towards planners playing key roles in integrated management through being given the responsibility to gather, validate and incorporate local and traditional ecological knowledge into the knowledge base. That way, communities which support activities such as salmon farming are empowered and develop a sense of ownership of the management and policy which supports production and related activities in their local area. However, this will only prove successful if resources are made available to allow this work to be done.

The European Aquaculture Society (EAS) promotes integrated management of salmon farming and organises events that especially target the dissemination and exchange of information between scientists and stakeholders, particularly the producers. In 2001, the EAS organised a workshop at the Aqua Nor Exhibition in Trondheim, Norway on the better use of water, nutrients and space, which brought together producers, industrialists, researchers, buyers and members of the public. Discussions arising from such meetings can then act as a forum for debate and act as recommendations which can be discussed with policy advisors and makers. There is increasing interest about scientific information and its role in policy and decision making (governance) and many scientists admit they find it difficult to deal with high system uncertainties, especially when the value stakes are high, as mentioned before (Funtowicz and Ravetz, 1993, 1999; Ziman 1996). This has led to more scientists addressing the criticism that science must be in touch with real situations and societal needs. Many scientific experts working on policy-related aquaculture research are now more in tune with social debate on particular issues. This has largely been achieved by natural scientists embracing techniques used more frequently by social scientists, such as stakeholder involvement, participant observation and consensus building methods. Funding opportunities for scientists, which state that due consideration must be given to the economic and social dimensions of the research project alongside the scientific and technical components, have aided advances in this area. Other initiatives include those taken by the DFO in Canada which has adopted a 'low tech' approach to management by combining DFO resources with the knowledge of local stakeholders (fishers in this case), to produce a series of resource inventory maps that can be used by fishers and which would be accepted by resource managers and researchers (Coastal Zone Canada Association, 2001). Similar methods could be applied to help the salmon farming industry in cases of conflict resolution where salmon farmers need to expand into new temporary or permanent sites, as in the Bay of Fundy in Canada. Here, there is conflict in New Brunswick between the aquaculture industry—which wants to expand to avoid cage overcrowding and to control the spread of diseases while at the same time continuing economic growth in a sustainable manner—and fishers, who have expressed concern that they will lose access to new aquaculture sites and that habitat alteration or loss will occur (Coastal Zone Canada Association, 2001). In Canada until recently, fish farming sites were chosen and licensed with little public consideration or indigenous knowledge; however, when temporary fish cages were placed next to a lobster fishery, having been granted approval from the New Brunswick government amid objections from fishers, the community and scientists, this issue went to the courts (Coastal Zone Canada Association, 2001). The outcome is that the cages are to stay but that the New Brunswick government is committed to monitoring the site. Court action could have been avoided had the views of all those with an interest in the area been discussed and debated to develop a management plan that was accepted by all.

Those readers interested in finding out more about the debates surrounding the relationships between science and society should refer to the summary and conclusions section in the proceedings of the conference entitled Science and Governance in a Knowledge Society—The Challenge for Europe. This event took place on 16 and 17 October 2000 in Brussels, Belgium and information is well written and can be easily downloaded from the following website: http://www.jrc.es/sci-gov/

13.2.8 Social considerations

Although the importance of integrating social and cultural considerations into management is frequently mentioned, little information exists on the socio-cultural and socio-economic dimensions related to the salmon farming industry and its associated communities. This section describes some of these factors in the light of their influences on salmon production areas.

In most countries the development of salmon farming activities has been largely concentrated in less populated localities. Management of the salmon farming industry has improved as both environmental and economic performance of production has increased through, for example, improved feed conversion efficiencies, reduced feed, chemical and nutrient wastages, site rotation of cages, fallowing of sites, improved health and safety for salmon and employees, and enhanced rearing technologies. Environmental and economic advances have gone hand in hand, although some issues remain to be resolved such as interactions of salmon and human resources with wildlife, and escapees. Less attention has been directed towards the assessment of the socio-cultural and socio-economic costs and benefits, especially the negative implications.

The social impacts of salmon farming will vary according to the location, stage of economic development and the different actors involved in the community and local government interests. In general, salmon farming—albeit to varying degrees—depends on local manpower (unless brought in from further afield), ancillary services and transport links. On the one hand it can be argued that salmon farming has helped to reduce emigration from rural communities and provides security for remotely located communities where other opportunities are limited. Linked to increased productivity of the salmon production sector is the possibility for individuals to earn higher wages and thus improve their standard of living and quality of life on the whole. On the downside, as salmon farming becomes more efficient and automated there is less of a need for human resources and increased likelihood of unemployment, especially following disease outbreaks such as ISAV. In addition, concentration of ownership within the industry has led to a change in the distribution of income where benefits to local populations and the work force has decreased (Burbridge *et al.*, 2001).

Many coastal rural communities that support salmon farming are also involved in the capture fisheries. This has led to initiatives which have focussed on the possible diversification of fishers into salmon farming and other forms of aquaculture. This can be difficult because there appears to be limited overlap of skills between those involved in fishing (fishers) and fish farmers. The cultural differences (hunter versus gatherer) in these two activities are often overlooked. Fishers view salmon aquaculture as farming rather than fishing and the investment in terms of time, labour and other inputs varies greatly between fish farming and the wild capture fisheries. Hence this needs to be understood when examining issues involving fishing and aquaculture.

When integrating social considerations into management it helps to understand how people become what they are and about their interests, which in turn can help towards explaining their behaviour and perceptions of issues and how best to develop policy which is acceptable to those it is primarily targeted at. Social scientists achieve this by studying the relationship between an individual's biography and the influences existing in the historical period in which that person lives. Social influences investigated might include the community, culture, family, perceptions of risk and personal objectives. Knowledge about social and cultural issues can provide useful information on, for example: the location and suitability of a salmon production unit to minimise resource user conflicts; availability of human resources locally; marketing and demand of salmon products; consumer preferences; increasing public awareness about a positive image of salmon farming; and the support and adoption of salmon production. Understanding the cultures of a community and individuals is essential for effective communication and can sometimes influence the success or failure of a salmon farm in terms of local support. The importance of taboos and magico-religious factors should be considered and catered for, especially in countries where salmon farming is relatively new. Unfortunately, some of the earlier sitings of salmon farms were not always undertaken with local backing and resulted in the sabotage, where vandalism of nets in cages resulted in farmed salmon escapees. At the initial stages of potential development for a production unit the salmon farmer and/or owner should take into account how it will adapt the system to the particularities of an area and its people and not just the environmental and infrastructure considerations.

Understanding social issues facilitates the development of effective policy and is often lacking in management systems at regional, national and international levels. This is partly due to the difficulty in obtaining reliable and meaningful information. Also, it can take considerable time to conduct investigations that involve some form of surveying, whether through interviews or participant observation. Nonetheless, policy makers need to consider and integrate the social and cultural issues of all those who could be affected by salmon farming. It may not be possible to satisfy all views from interested individuals; however, it is important to take these into consideration and to manage salmon farming in a way that minimises conflict between interested parties yet maximises benefits for both the developer and the community as a whole. It is far worse to ignore people's views, which can lead to undesirable consequences. Although the ecological, political, economic, technological, cultural and social systems may differ between countries it can be helpful to examine examples of good and bad practice related to social considerations and salmon farming. There are usually common lessons that can be learned and applied to existing and future scenarios. Common social issues to be considered include: cultural norms and values; community control mechanisms; attitudes to risk; adoption of farming systems; land and water resources (such as availability, access, aesthetic and environmental impacts); and the employment of local versus importing outside individuals. The salmon farming industry is moving in the right direction in that it has shown increased sensitivity to constraints, and new developments focus not only on the technological and environmental issues but also on some of the before mentioned social and cultural factors.

The future of the salmon industry is difficult to predict. Nonetheless, given equal opportunities to those that are enjoyed by other forms of development, such as tourism, its growth potential will be influenced by (a) increased diversification of other species cultured; (b) further development of polyculture and integrated culture systems; and (c) improved productivity (lower unit cost of production) (Burbridge *et* *al.*, 2001). Potential conflicts between salmon farming, other types of aquaculture and tourism are expected to increase. Although fish farming can be seen as a hindrance to some types of tourism and leisure activities (for example, aesthetic detriment to coastal views from holiday residences; cages becoming loose from their moorings to be a danger to boats), measures should be directed towards opportunities which offer beneficial collaboration with other economic activities such as tourism and fisheries. Already some salmon production units have facilities for visitors and schools.

The next section goes some way to explain why delays in integrating social and cultural considerations have occurred and how the way forward for the salmon industry might be in the form of developing an IMSSFA.

13.3 CAN AN IMSSFA WORK?

Salmon farming traditionally was classed as part of aquaculture, which was categorised under the capture fisheries in terms of its management administration. Also scientific advice, policy and legislation matters related to aquaculture were dealt with by centralised administration systems, e.g., Ministries for Fisheries and Agriculture. Therefore, aquaculture has not always been treated in isolation to fisheries or given due consideration, hence discussions on relevant issues have on occasion not been privatised and have led to delays in action needed in the aquaculture industries. It is noteworthy that in 2001, the Food and Agriculture Organisation of the United Nations (FAO) has set up a COFI (Committee on Fisheries) Sub-committee on Aquaculture to reflect the growing importance of this industry. This is an encouraging step in the right direction, although there still remains some missing links before an IMSSFA can be developed as a useful tool for managers.

The necessity for a specific management system to address the unique problems of salmon farming arises from the need to integrate the management process of the land and water resources that support this activity. In most countries, legislation for these two environments have been treated separately from each other, causing problems for planning, development and management of aquaculture. An integrated management system is one approach that can be used to ensure that legislation pertaining to salmon farming is considered both from a landward and seaward perspective.

In recent times, two major policy lines of thinking have come to the fore. Firstly, environmental objectives must be systematically integrated into economic development. Secondly, territorial and regional planning aspects must be taken into account at the European level in a spirit of subsidiarity and cooperation (this is discussed further in Section 13.4). Furthermore, there has been increasing recognition that, in order for environmental resource management to be successful, there should be a shift from sectoral management to management strategies that have a greater degree of accountability for 'natural systems' (Mitchell, 1997; Bellamy *et al.*, 1999). This should include recognition of the salmon farming activities that are both land and water based. The main concerns raised—which will be familiar to many involved in salmon farming—have been summarised by Margerum and Born (1995), who reported that decision makers at all levels have become dissatisfied with the outcomes resulting from narrowly focused, incremental, and disjointed environmental management plans. These authors also found that many traditional approaches to environmental management have usually failed to deal with interconnections, complexities, multiple perspectives, multiple uses and the resulting cross cutting externalities. Action from these concerns have taken the form of a series of integrated environmental management (IEM) approaches which have emerged to achieve multiple objectives via the harmonisation of resource sectors (Mitchell, 1990). Whilst IEM approaches take many forms (including, *inter alia*, catchment area management, ecosystem management, watershed management, integrated resource management and integrated coastal management), they contain a series of common elements. Usually, these approaches operate at the regional rather than macro scale, recognise the need for coordinated management approaches, involve a wide range of stakeholders and work in accordance with an agreed set of environmental and social objectives (Hooper *et al.*, 1999). An IMSSFA should adopt similar approaches: a common complaint at the different levels of management (local, national, regional and international) is that there is a lack of information on projects and activities related to salmon farming. This is especially frustrating when similar projects are undertaken at the same time and project managers are not aware of this. Effective communication through a coordinating mechanism that disseminates information quickly, easily and widely is therefore important. Experience to date clearly shows that for some geographical areas sustainable development is being implemented too slowly in relation to the gravity and complexity of the problems of many natural resources, for example in coastal zones around the world. Specific action is urgently required by all players perhaps through IMSSFA, in order to improve the future of salmon farming and the aquaculture industry. Effective communication should be fundamental to any sort of integrated management strategy.

In looking at the relationship between policy and legislation, Howarth (1995) explains that, 'The task of the policy maker and legislator is to reconcile the needs of the environment with the facilitation of an efficient aquaculture industry which functions in the common interest of all'. This is a good point and an essential prerequisite for any IMSSFA. However, it is the linking of all management levels (international, regional, national, local and farm) that often is still missing from management strategies and policy can only be useful if supported by an effective multilevel management system. A further gap in management is the inadequate consideration of social and cultural factors, as outlined in Section 13.2.8. Collecting meaningful information on social and cultural considerations can prove to be labour intensive, time consuming and expensive. The subsequent analysis of the qualitative data can then be difficult to analyse in context with quantifiable data with which some scientists are more familiar. In spite of this there is an increasing trend for integrated management approaches that incorporate, among others, scientific, economic and social factors at the same time.

There is a need for the development of IMSSFA that can be adopted and used by resource managers. It is important to remember when considering such management strategies that the geographical area, local communities, political and social systems, and experiences of salmon farming are understood. IMSSFA need to be adjusted for local or regional needs and constraints if they are to prove effective. A successful IMSSFA can only be developed through a multidisciplinary approach combined with stakeholder participation and consensus building. Salmon farming is an international activity and it is essential that individual farming countries share experiences of good and bad practice. This could then help to develop IMSSFA as a framework in which international audiences could communicate experiences in a standardised format which takes account of local and national differences and similarities. With increased efficiency of computers and the Internet it is relatively easy to disseminate information widely and quickly. So in response to the question given in the title to this section—can an IMSSFA work—then the answer is yes if developed in a user-friendly manner that communicates its messages clearly, effectively and in different languages. One good example is to learn from the experiences of the European Commission's initiative on integrated coastal zone management (ICZM), which adopted a holistic and interdisciplinary approach to its work. The next section goes on to describe ICZM and its role in salmon farming.

13.4 ICZM AND SALMON FARMING

Coastal zones are important habitats for both society and resource users such as salmon farmers. In 1994, Goldberg estimated that 50% of the population of the industrial world lived within 1 km of the coast and that this was likely to increase at a rate of 1% per annum over the next decade. Coastal ecosystems also tend to have high biological productivity. The reproduction and nursery grounds of most finfish and shellfish species of economic value are in the coastal strip and a significant proportion of the catch of these species comes from this area, which also accounts for almost half of the jobs in the fisheries sector. Conflict often arises between fishers and finfish (and shellfish) farmers in inshore waters over the use of the same water and space. Further disagreements over exploitation of coastal resources can take place between farmers and fishers with recreational users (divers, surfers, swimmers, water skiers, jet skiers), sailors, marine mining operators, property and business developers and those who support tourism interests. Integrated planning and management of coastal resources that build in due consideration for all users needs to be developed in a way that achieves consensus through stakeholder and community involvement. One such mechanism that promotes this approach is ICZM.

ICZM is a framework which received a lot of attention in Europe in the 1990s. In 2001 it was adopted by the European Commission as a basis for recommendations on the management of coastal resource use including demands from aquaculture development. In the context of salmon, this would largely have implications for the on-growing stages in sea cages. The remainder of this section discusses how the marine salmon farming industry can build a solid foundation for its future management needs based on examples of best practice in ICZM.

The UN Conference on Environment and Development (UNCED), held in Rio de Janeiro in 1992, proved an important turning point to the shaping of IEM in that it took account of development which is not only economically and socially but also environmentally sustainable. The ensuing Rio Declaration and Agenda 21 endorsed the need for collective and concerted action to protect the commons and included marine resources. Chapter 17 of Agenda 21 makes special reference to the importance of coastal zones which are vital to the salmon farming industry in that they sustain the main growth phase of the salmon's lifecycle. Following on from Agenda 21, interest in ICZM arose from the European Council of Environment Ministers and resulted in a call for its promotion through a proposed development in the form of a European Community strategy. ICZM was then incorporated into the 5th Environmental Programme published in 1993. This led to the European Commission's announcement of a Demonstration Programme on ICZM, which was conducted between 1996 and 1999 (European Commission, 1999) and was operated by the Directorates General for Environment, Fisheries and Regional Policy. The initiative was set up to examine the fate of coastal zones for the following reasons:

- problems are of a European dimension and cannot be solved by the Member States separately (e.g., common, natural and cultural heritage);
- the influence of the European Union's policies and action on the development of the coastal zones (e.g., regional, aquaculture and fisheries policy);
- the need for an exchange of experience and know-how in a field where successes are still rare and where there is substantial public and political demand for the conservation of the coastal zones and their sustainable development.

The findings of the ICZM Demonstration Programme strongly supported the idea that sustainable development of coastal zones requires the application of the principles of integration[1] and subsidiarity[2]. This can be achieved only with the active participation of all players (political authorities, administrations, economic operators, scientists, researchers, stakeholders and the general public). For sustainable development of salmon farming to be accomplished and maintained in coastal zones then according to ICZM plans it is necessary to:

1 The Principle of Integration is set out in Article 130 R of the Maastricht treaty and stipulates that environmental protection requirements must be integrated into the definition and implementation of other Community policies (http://europa.eu.int/comm/environment/ iczm/overview.htm).

2 The Subsidiarity Principle states that the Community takes action only if and in so far as the objectives of the proposed action cannot be adequately met at national, regional or local level and be better achieved by the Community. The environment programme links this concept with shared responsibility, complementarity of projects and the need for cooperation between the different levels of authority (http://europa.eu.int/comm/ environment/iczm/overview.htm).

- test cooperation[3] models for the integrated management of salmon production in coastal zones and to provide the technical results needed to set up such models;
- establish structured dialogue between all the players with a stake in the sustainable development of salmon farming in coastal areas (this can equally be applied to freshwater areas).

The recommendations from the Demonstration Programme on ICZM formed the basis of a proposed European Strategy (European Commission, 2000) that recommends the following actions:

- promote ICZM activity within Member States and at the 'Regional Seas' level;
- make EU sectoral legislation and policies compatible with ICZM;
- promote dialogue between European coastal stakeholders;
- develop best practice in ICZM;
- support the generation of factual information and knowledge about the coastal zone;
- diffuse information and raise public awareness.

This document (European Commission, 2000) highlighted that insufficient participation and consultation with relevant stakeholders and members of the public can lead to degradation and mismanagement of resources. This has already been observed for some salmon farming areas. In the author's opinion, salmon farming in coastal areas could benefit from being managed using ICZM recommendations, which could aid the development of IMSSFA. The management system must be desired by the community and population of a particular area combined with an understanding of the associated specific conditions of that region. Although some regard the recommendations of ICZM to be too general, important lessons have been observed through the 35 individual demonstration projects, for which more detailed information is available (European Commission, 1999). Policy makers responsible for coastal management and salmon farming have relied too long on natural scientists to identify and estimate risks to the marine environment, living resources and human health. A gap in management at the time of writing, and especially in the area of policy development, is the obvious dearth of social scientists working with the scientists in the decision-making process that includes examination of both scientific

[3] Improved cooperation between all concerned is the basis for sustainable development. It helps identify synergies or contradictions between actions resulting from the various policies and facilitates the acceptance of arbitration. In short, it develops a general sense of responsibility; such cooperation can develop only from full, comprehensible information on the state of the environment, the origin of the changes affecting it, the implications of policies and measures at the various levels, and the options; cooperation has to be organised and maintained. There is a need for procedures and working methods to ensure dialogue between those involved in the various sectors of activity and at the various levels of territorial authority, and an ongoing exchange of information, from the local level up to Community level and vice versa (http://europa.eu.int/comm/ environment/iczm/overview.htm).

and social issues related to salmon farming. This is a failing of existing systems since social scientists have valuable expertise in participatory mechanisms, an important part of ICZM. It is reassuring to note that this is changing and literature on this topic is slowly emerging. Section 13.5 follows this theme and looks at the role of participation and consensus building as part of the management strategy.

13.5 ROLE OF PARTICIPATORY MECHANISMS AND CONSENSUS BUILDING IN MANAGEMENT

As discussed meaningful participation is a central feature of ICZM and should also be so for any IMSSFA. It is also important that all players participate from the start and are involved throughout the development stages of any project or enterprise based on managing the farming of salmon. Participation can be viewed as a means of confidence building and is an efficient way of making recommendations reached through consensus. It is also seen as an integral part of the planning process and an essential part of creating a common vision or focus for developing long-term sustainable management strategies for salmon farming. The approach to participation ought to be gradual: building trust, understanding, confidence and a common language. Participation is essential for consensus building. On a cautionary note, it is necessary to take time constraints into account and to anticipate and address early on the disappointment that can come with building too-high expectations of results from this approach. To help avoid disappointment, it is important to ensure that the participatory methods used are appropriate for the target audience and are not too cumbersome or onerous, as this may lead to the alienation of some interests and the goals being lost sight of. At the same time, there can be some urgency in obtaining meaningful results in order to strengthen and keep the stakeholders' belief in the participatory process and therefore a balance is needed. The focus on immediate stakeholders such as salmon farmers in specific development projects may not be sufficient to build the kind of trust and mutual understanding between industry and society that is needed for long-term stability. Hence, the salmon farming industry should always aim to involve the general public. Further information on participatory management tools in relation to aquaculture is given in Kaiser and Stead (2001).

One promising mechanism that is rapidly gaining momentum and support for its adoption is consensus conferences with (lay) citizen-panels. The structure of these conferences was originally developed in Denmark by the Danish Board of Technology (Joss and Durant, 1995; Fixdal, 1998; Kaiser, 2000; Kluver *et al.*, 2000). The way in which they work is that lay people choose the experts with whom they want to debate issues on a particular subject (e.g., salmon farming) and then the experts are asked questions that the lay people decide are most relevant for making recommendations. One of the expected outcomes is that the lay panel will develop recommendations for policy makers based on consensus. Experience has shown that the lay panel usually attaches significant weight to existing uncertainties, similar to that observed in public debate, and they also address the underlying value issues explicitly. The results of these conferences communicate very easily to the broader public, they usually get large press and TV coverage, and their communication triggers trust. Sometimes the panel reaches surprising conclusions that seemingly go against pre-existing attitudes of the public. Typical goals for a conference on salmon farming may include:

- to elaborate a consensus on specific policy recommendations for farming salmon in coastal areas;
- to create a forum for open dialogue between experts and lay public, bridging the gaps between the public, stakeholders, scientists and policy makers;
- to contribute to a broader societal debate about the issues at hand such as the public image of salmon farming, food health and safety, environmentally-sound farming practices, environmental impacts of salmon farming and the use of biotechnology in salmon production.

Some critics question the value of these conferences and ask why considerable resources are made for a panel of some 15–16 people when they are statistically unrepresentative of the whole society, not recognised as opinion leaders in the media, or constituted by the conflicting parties, by the decision-makers, or the powerful organisations and non-governmental organisations (NGOs) (Kaiser and Stead, 2001). Sceptics have also queried why lay panels should make recommendations on particular matters and suggest they can be easily manipulated. To date there are too few systematic studies that can counter these arguments convincingly, but the ongoing experiences and experiments are, at least, promising. It is agreed that the recommendations formulated may not be the most useful results when viewed in the larger policy contexts; however, these events can trigger substantial social debate, and often it is the ensuing debate in the media that provides the platform for political decisions. Lay panels communicate more easily with the proverbial man or woman on the street than experts or sectors, partly because they openly address value-issues and existing uncertainties, to which some individual experts typically contribute little or find difficult to give views on. Furthermore, these panels can act as a mechanism for addressing disagreement among experts, which can be a major factor of uncertainty. Expert disagreement can significantly influence the progress of decision making and formulating recommendations for policy makers when brought into the discussion by the press. Another positive aspect to this approach is that the panel cannot be suspected of having hidden agendas, which is a common criticism when a collection of experts works closely on issues, for example a task force. The use of conferences with lay panels is likely to increase and this approach could certainly benefit the process of developing IMSSFA through consensus. The main conclusion from all of this is that there are four key criteria for the development of any successful management strategy such as is proposed for IMSSFA, that is: openness; participation; transparency; efficient dissemination of the discussions and debates that take place. One method to ensure that this happens is to have professional organisers and facilitators who are independent of the outcome and the different sectors involved. It is too early to predict if such participatory mechanisms can be sufficient as proactive measures to avoid the kind of withdrawal of trust that the agriculture and fishing industries has witnessed. However, until they are tried and tested it is not possible to evaluate their use and potential for promoting farmed salmon.

13.6 SUMMARY

Management strategies and their various components are complex, especially when applied to a dynamic activity such as salmon farming. Understanding the various factors that play important roles, such as the economic, environmental, legal, political, regulatory, scientific, social and sustainable aspects, is an essential prerequisite for any successful IMSSFA.

Given the increasing awareness of the general public about the issues surrounding salmon farming, it is essential that the industry addresses any negative press and uncertainty without delay. In terms of long-term planning for the industry then it is useful to have information on consumer reactions and market changes. Positive responses to salmon farming by consumers and the public can only be created through trust. The current discussions about agriculture and food safety should act as a warning to the salmon farming industry. Rather than being a reactive sector, the industry needs to take a more proactive stance, especially to reduce any existing or emerging uncertainties in salmon products or on the issues surrounding their production, as this is crucial for further development. In addition, the incorporation of factors relating to social and cultural conditions can add significant information to management plans and aid the adoption and development of the salmon farming industry.

There is a clear need for the salmon farming sector to address existing and anticipated uncertainties and value conflicts in a more explicit manner and in new fora. Existing concerns for future development of the industry relate largely to the general issues on sustainability and food safety. Management systems should include elements for consensus building through community and stakeholder involvement in addition to active participation from other players at an early stage. Lay panels are one such mechanism that may prove useful. Social scientists have valuable expertise to contribute and their knowledge should be used more widely.

The formulation of any legislation should be developed from a 'bottom up' approach. Unless a significant level of cooperation can be established between the legislative measures and the local people then any management strategy, including an IMSSFA, will be unlikely to be a great success. The keystone to this process is the development of partnerships that will provide a direct link between the legislators, implementers and all resource users, including salmon farmers.

In relation to the question 'can an IMSSFA work?' the adoption of the recommendations of the ICZM strategy could be one step in the right direction to ensure that they do work. Given that uncertainty can arise from poor and fragmentary information it is important that a holistic approach to management is adopted through the development of multidisciplinary frameworks such as is proposed for IMSSFA.

Although ICZM promotes increased participation as a necessary prerequisite for successful management, the participatory measures required need to take into consideration that the overall development of the salmon farming industry may not be sufficient through ICZM alone. It is recommended that effective participatory mechanisms based on the characteristics of an area, its people and associated industry are researched, tried and tested. Principally, whatever management process is adopted it should be fluid, transparent and facilitate open and honest discussions between all interested parties. Experiments with lay panel consensus conferences and other innovative participatory mechanisms will take discussions an important step further, and in the long run may have the greatest impact on the development of salmon farming.

Future salmon management systems such as IMSSFA will necessitate an integration of existing knowledge and research, together with the harmonisation of regulations, legislation and human interest, in order to provide a cohesive and well-structured framework. The challenges to salmon farming managers during the next few years will be to develop and adopt new frameworks and methodologies that will allow the human interests to be harmonised with those of the environment and nature.

It is beyond the scope of this chapter to give details on all components important to integrated management strategies; however, it provides an overview of the main points and those interested in this area of work can refer to the various references for more detailed information and/or contact the author for further discussion.

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