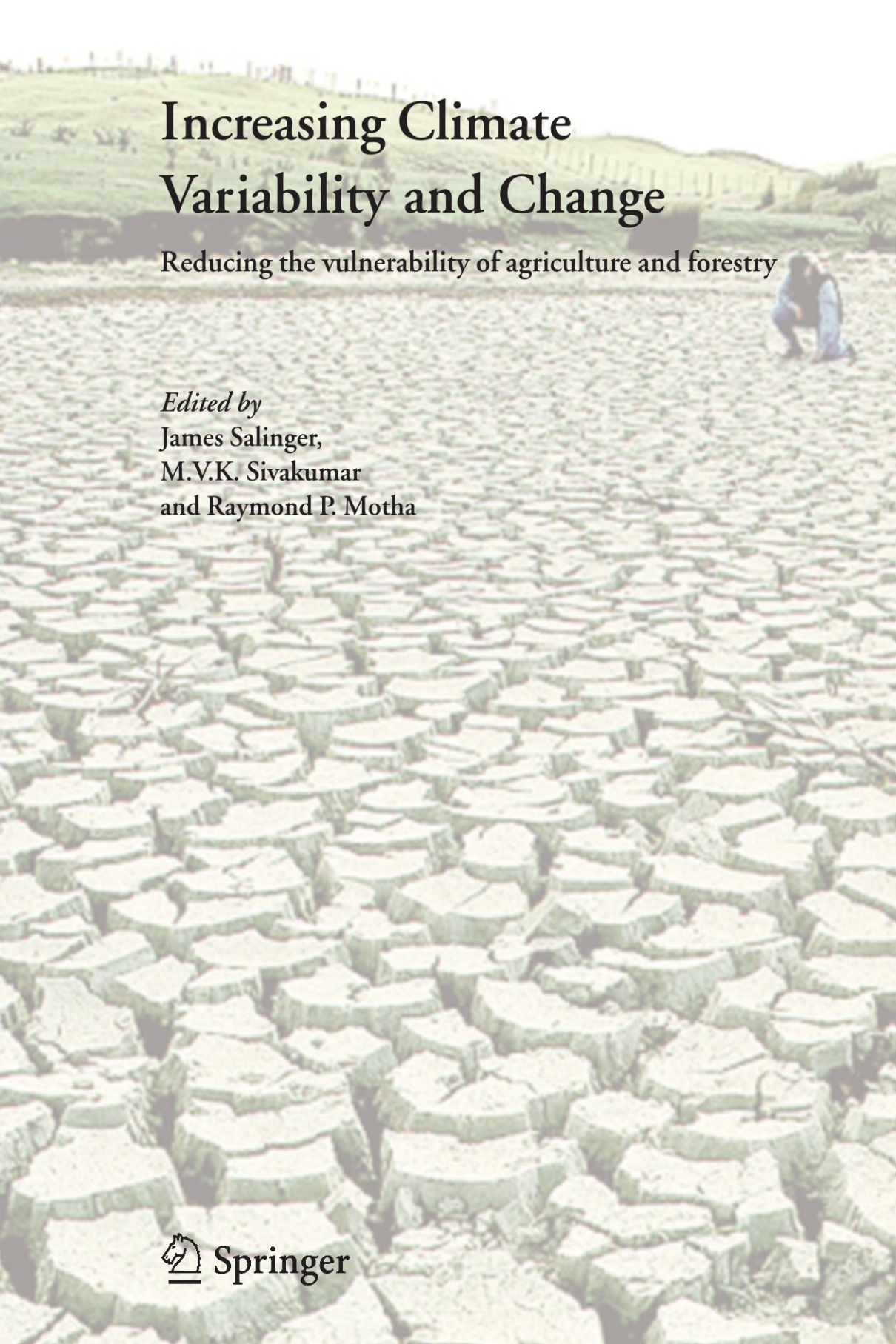


The background of the cover is a photograph of a severely dry, cracked field. The ground is composed of numerous irregular, raised polygonal blocks of parched earth, creating a mosaic-like pattern of cracks. In the upper right, a person is crouching in the distance, providing a sense of scale to the vast, cracked landscape. The sky is bright and hazy.

Increasing Climate Variability and Change

Reducing the vulnerability of agriculture and forestry

Edited by
James Salinger,
M.V.K. Sivakumar
and Raymond P. Motha



Springer

INCREASING CLIMATE VARIABILITY AND CHANGE

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Edited by

James Salinger

*National Institute of Water and Atmospheric Research,
Auckland, New Zealand*

M.V.K. Sivakumar

*World Meteorological Organization (WMO),
Geneva, Switzerland*

Raymond P. Motha

*United States Department of Agriculture,
Washington, DC, USA*

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INCREASING CLIMATE VARIABILITY AND CHANGE: REDUCING THE VULNERABILITY

Guest Editorial

Since time immemorial, climate variability and change have triggered natural disasters and climate extremes causing heavy losses of life and property, forcing civil society to “learn to live” with these calamities. Floods, droughts, hurricanes, storm surges, heat waves precipitating wild fires and such other natural calamities have claimed more than 2.8 million lives all over the world in the past 25 years, adversely affecting 828 million people. Damage caused by these climate extremes during the same period was estimated at 25–100 billion dollars, dramatically affecting agriculture and forestry systems in regions where these have occurred.

Agricultural and forestry production is highly dependent on climate, and is adversely affected by increasing climate variability and anthropogenic climate change leading to increases in climate extremes. There is strong evidence that global warming over the last millennium has already resulted in increased global average annual temperature and changes in rainfall, with the 1990s being likely the warmest decade in the Northern Hemisphere at least. During the past century, changes in temperature patterns have, for example, had a direct impact on the number of frost days and the length of growing seasons with significant implications for agriculture and forestry. Land cover changes, changes in global ocean circulation and sea surface temperature patterns, and changes in the composition of the global atmosphere are leading to changes in rainfall. These changes may be more pronounced in the Tropics.

During the course of the 21st century, scientific evidence points to global-average surface temperatures are likely increasing by 2–4.5 °C as greenhouse gas concentrations in the atmosphere increase. At the same time there will be changes in precipitation, and climate extremes such as hot days, heavy rainfall and drought are expected to increase in many areas. The combination of global warming will be superimposed on decadal climate variability, such as that caused by the Interdecadal or Pacific Decadal Oscillation, and interannual fluctuations caused by the El Niño/Southern Oscillation and the North Atlantic Oscillation. All these may lead to a century of increasing climate variability and change that are expected to be unprecedented in the history of human settlement and agrarian activities.

The main purpose of the United Nations Framework Convention on Climate Change (UNFCCC, 1992) is to reduce the growth of greenhouse gases. Article 2 of the Convention states that its ultimate objective is “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”

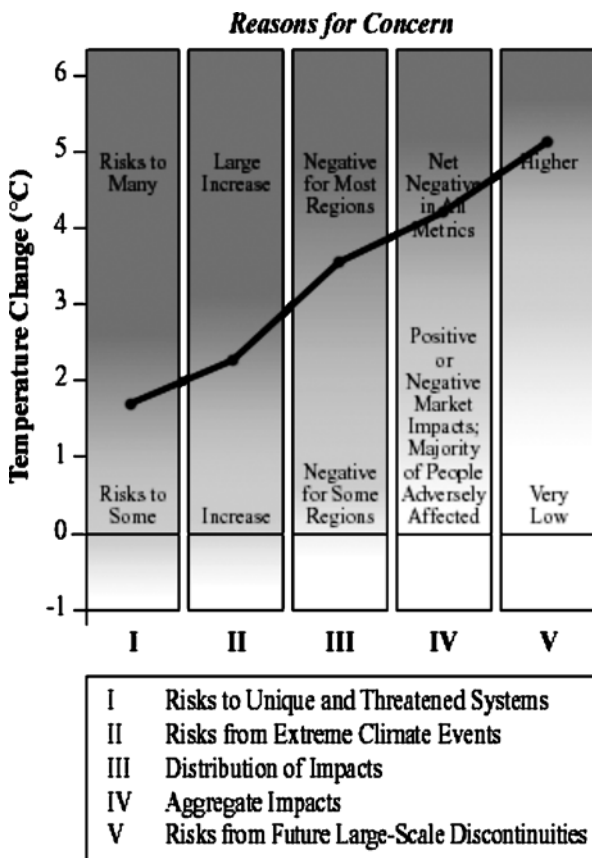


Figure 1. The risk of adverse impacts increase with the magnitude of climate change. Global mean annual temperature is used as a proxy for the magnitude of climate change (IPCC WG2, as modified by Mastrandrea and Schneider, 2004).

The natural greenhouse effect keeps the planet and biosphere at an equable temperature for planetary processes to operate. The current rate of global warming is 2 °C per century, and this rate is projected as a lower range for the remainder of the 21st century. Thus, increases in greenhouse gases released by human activities are creating a potential situation where the stability of agriculture and forestry systems is threatened by dangerous climate change (Figure 1).

Adapting to increasing climate variability then provides tools to reduce the vulnerability of agriculture and forestry. Some farming systems with an inherent resilience may adapt more readily to climate pressures, making long-term adjustments to varying and changing conditions. Other systems will need interventions for adaptation. Traditional knowledge and indigenous technologies should not be ignored. Age-old technologies such as planting calendars, intercropping and mulching reduce the vulnerability to climate extremes.

However, the path of increasing variability and change will require the introduction of much more sophisticated technologies. Seasonal to interannual climate forecasting is a relatively new branch of climate science, and it promises reducing vulnerability. Improved seasonal forecasts are now being linked to decision making for cropping, developing climate risk practices to improve the application of climate information for the management of grazing practices, and developing climate risk practices to enhance the productivity and performance of forests. The application of climate knowledge to the improvement of risk management will increase the resilience of farming systems.

Consequently, the occurrence of seasonal to interannual climate variability and their extremes can be forecast with a greater degree of accuracy. Availability of such crucial information in advance can greatly assist in taking effective measures for prevention and mitigation of losses by agricultural and forestry. Thus, the resultant disastrous effect can be reduced considerably through proper planning and more effective preparedness. Vulnerability associated with climate can be controlled to some extent by accurate and timely prediction and by taking counter-measures to reduce their impacts on various sectors of agriculture.

One fact is for certain though – the historical record shows that our climate has changed in the past, and will continue to vary and change during the coming seasons and decades. The underlying theme of global warming is likely to cause increases in temperature and their extremes of heat waves, with climate scenarios of changing rainfall patterns as the 21st century progresses, with increasing extremes of floods and droughts. These will provide a challenge unparalleled in the history of civil society to agriculture and forestry: the papers in this issue of *Climatic Change* assess the likely impacts of change and examine the adaptation and capacity building options to reduce vulnerability and increase resilience.

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National Institute of Water and Atmospheric Research
P.O. Box 109-695
Newmarket, Auckland
New Zealand
E-mail: j.salinger@niwa.co.nz

M. JAMES SALINGER

FOREWORD

One of the major challenges facing humankind is to provide an equitable standard of living for the current and future generations: adequate food, water and energy, safety, shelter and a healthy environment. Human-induced climate change, and increasing climate variability, as well as other global environmental issues such as land degradation, loss of biological diversity, increasing pollution of the atmosphere and fresh water and stratospheric ozone depletion, threaten our ability to meet these basic human needs. Considerable efforts have been deployed in monitoring and projecting the changes and in evolving possible options for managed systems including agriculture and forestry.

Today, there is certainty from the surface temperature data, collected by WMO's Global Observing System, that the globally averaged surface temperatures are rising. According to records maintained by members of WMO, the global surface temperature has increased since the beginning of instrumental records in 1861. Over the 20th century that increase was about 0.6 °C. The rate of change for the period since 1976 is roughly three times that of the past 100 years. Analyses of proxy data for the Northern Hemisphere indicate that the late 20th century warmth is unprecedented for at least the past millennium. Over the same period, the 1990s were the warmest decade, the year 1998 was the warmest year and the years 2002 and 2003 the second and third warmest, respectively. The projected temperature rise by the end of the century is between 1.4 and 5.8 °C.

Scientific assessments have shown that over the past several decades, human activities, especially burning of fossil fuels for energy production and transportation, are changing the natural composition of the atmosphere. Proxy records indicate that for over at least the last 400,000 years, up to about 1800 AD, the atmospheric concentration of carbon dioxide (CO₂) varied only by 1–3 per cent. Since then, it has increased by more than 33 per cent, and reached 376 parts per million by volume (ppmv) at the end of 2003. WMO's Global Atmosphere Watch observing network monitoring atmospheric chemistry show that today's atmospheric CO₂ concentration has not been exceeded during the past 420,000 years. More than half of that increase in CO₂ concentration has occurred since 1950.

It is also possible, even likely in some cases, that human-induced climate change will affect naturally occurring climate variability such as the frequency or intensity of El Niño/Southern Oscillation (ENSO) events. A growing number of extreme weather and climate events, some of which have been of unprecedented intensity, continue to be observed with associated degradation of the environment. This requires the global community to give urgent attention and high priority to addressing key issues related to climate change through appropriate measures and policies at national and regional levels.

Climate variability affects all economic sectors, but agricultural and forestry sectors are perhaps two of the most vulnerable and sensitive activities to such climate fluctuations. Climate change and variability, drought and other climate-related extremes have a direct influence on the quantity and quality of agricultural production and in many cases, adversely affect it, especially in developing countries, where the pace of technology generation, innovation and adoption does not allow them to counteract the adverse effects of varying environmental conditions. For example, inappropriate management of agroecosystems, compounded by severe climatic events such as recurrent droughts in many parts of the world, have tended to make the drylands increasingly vulnerable and prone to rapid degradation and hence desertification. Even in the high rainfall areas, increased probability of extreme events can aggravate nutrient losses due to excessive runoff water logging. Projected climate change can influence pest and disease dynamics with subsequent crop losses. Improved adaptation of food production, particularly in areas where climate variability is large, holds the key to improving food security for the global population.

The range of adaptation options for managed systems such as agriculture and forestry is generally increasing because of technological advances, thus opening the way for reducing the vulnerability of these systems to climate change. However, some regions of the world, particularly developing countries, have limited access to these technologies and appropriate information on how to implement them. Here successful traditional technologies used over the centuries should be maintained. Incorporation of climate change concerns into resource-use and development decisions and plans for regularly scheduled investments in infrastructure will facilitate adaptation.

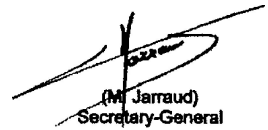
Agriculture and forestry are currently not optimally managed with respect to today's natural climate variability because of the nature of policies, practices and technologies currently in vogue. Decreasing the vulnerability of agriculture and forestry to natural climate variability through a more informed choice of policies, practices and technologies will, in many cases, reduce the long-term vulnerability of these systems to climate change. For example, the introduction of seasonal climate forecasts into management decisions can reduce the vulnerability of the agriculture to floods and droughts caused by the ENSO phenomena.

It is with this background that WMO had organized the International Workshop on Reducing Vulnerability of Agriculture and Forestry to Climate Variability and Climate Change in conjunction with the 13th session of the Commission for Agricultural Meteorology of WMO held in October 2002 in Ljubljana, Slovenia. The workshop was co-sponsored by the Asia-Pacific Network for Global Change Research (APN), the Canadian International Development Agency (CIDA), the Centre Technique de Coopération Agricole et Rurale – Technical Centre for Agricultural and Rural Co-operation (CTA), the Environmental Agency of the Republic of Slovenia, the Ministry of Agriculture, Forestry and Food of the Republic of Slovenia, the Ministry of Environment, Spatial Planning and Energy of the Republic

of Slovenia, the Food and Agriculture Organization of the United Nations (FAO), the Fondazione per la Meteorologia Applicata and the Laboratory for Meteorology & Climatology (F.M.A.-La.M.M.A.), Météo-France, the International START Secretariat (START), the Ufficio Centrale di Ecologia Agraria (UCEA), the United Nations Environment Programme (UNEP) and the United States Department of Agriculture (USDA).

The workshop reviewed the latest assessments of the science of climate variability and climate change, and their likely impacts on agriculture and forestry in different agroecological regions during the 21st century. It also surveyed and presented a range of adaptation options for agriculture and forestry and recommended appropriate adaptation strategies required to reduce vulnerability of agriculture and forestry to the observed and projected climate variability and climate change highlighted earlier. I hope that the papers presented in this special issue will serve as a major source of information to all services, agencies and organizations at national, regional and global levels involved with designing and implementing appropriate programmes in using agrometeorological techniques to reduce vulnerability to climate variability and climate change through the course of the 21st century.

World Meteorological Organization
Geneva, Switzerland
E-mail: mjarraud@wmo.int



(M. Jarraud)
Secretary-General

CLIMATE VARIABILITY AND CHANGE: PAST, PRESENT AND FUTURE – AN OVERVIEW

M. JAMES SALINGER

*National Institute of Water and Atmospheric Research, P. O. Box 109-695, Newmarket,
Auckland, New Zealand
E-mail: j.salinger@niwa.co.nz*

Abstract. Prior to the 20th century Northern Hemisphere average surface air temperatures have varied in the order of 0.5°C back to AD 1000. Various climate reconstructions indicate that slow cooling took place until the beginning of the 20th century. Subsequently, global-average surface air temperature increased by about 0.6°C with the 1990s being the warmest decade on record. The pattern of warming has been greatest over mid-latitude northern continents in the latter part of the century. At the same time the frequency of air frosts has decreased over many land areas, and there has been a drying in the tropics and sub-tropics. The late 20th century changes have been attributed to global warming because of increases in atmospheric greenhouse gas concentrations due to human activities. Underneath these trends is that of decadal scale variability in the Pacific basin at least induced by the Interdecadal Pacific Oscillation (IPO), which causes decadal changes in climate averages. On interannual timescales El Niño/Southern Oscillation (ENSO) causes much variability throughout many tropical and subtropical regions and some mid-latitude areas. The North Atlantic Oscillation (NAO) provides climate perturbations over Europe and northern Africa. During the course of the 21st century global-average surface temperatures are very likely to increase by 2 to 4.5°C as greenhouse gas concentrations in the atmosphere increase. At the same time there will be changes in precipitation, and climate extremes such as hot days, heavy rainfall and drought are expected to increase in many areas. The combination of global warming, superimposed on decadal climate variability (IPO) and interannual fluctuations (ENSO, NAO) are expected lead to a century of increasing climate variability and change that will be unprecedented in the history of human settlement. Although the changes of the past and present have stressed food and fibre production at times, the 21st century changes will be extremely challenging to agriculture and forestry.

1. Introduction

In the course of climate history over the last millennium, there has been intense interest on the cooling documented to the 19th century for the Northern Hemisphere (NH) at least, the cooler period of climate in the 19th century and rapid global warming during the late 20th century. Over the last millennium climate has varied by as much as 1°C globally (IPCC, 2001a). Key questions of any future impacts of global warming are the effects on human society and economics, and in particular, on agriculture and forestry. History can provide very valuable lessons on effects of climatic variability on the human dimensions. The multidecadal cooling of the late 16th century in Europe resulted in one of the peak cooling excursions of the so called Little Ice Age epoch of Europe. This example of climate variability provides impacts of a mere 0.5°C cooling in annual mean temperature on society.

Increases were observed in surface global temperatures during the 20th century, and interannual climate variability has been observed in many regions of the globe (Salinger, 1994; Salinger et al., 1997). The 1982/83 and 1997/98 El Niños and the 1991 Mt. Pinatubo volcanic eruption (Salinger et al., 2000) caused considerable variability in the interannual climate of tropical regions in the late 20th century. Recently IPCC (2001a) reported on warming trends, confirmation of continuing climate change based on observations from Arctic and Antarctic sea ice, from later ice appearance days and earlier ice breakup days particularly in European Russia, the Ukraine and Baltic countries. Observations of shrinking mountain glaciers during the 20th century and the increase of permafrost temperatures in many areas occurring provides additional confirmation.

Perhaps of more importance are the implications on agriculture that arise from the multidecadal climate fluctuations. If climatic variability in the order of 0.5°C can cause such dramatic effects on glaciers, flood events and storm surges, agricultural commodity prices, wine yields and other societal effects as documented for the 16th century, then this poses questions of what are the impacts of the projected increasing climatic variability and change during the 21st century. There is now better understanding of the climate system, and the natural and anthropogenic factors that have caused climate variability and change over the past century, and likely changes in climate and its variability during the 21st century (Salinger, 1994; Salinger et al., 1997, 1999; IPCC, 1996, 2001a). The latest IPCC projections (IPCC, 2001a) from the entire range of 35 IPCC scenarios place temperature increases in the range of 1.4 to 5.8°C by the end of the 21st century, with likely increases in heavy rainfall events. The 90% range is 2 to 4.5°C .

Although agrometeorology provides methods and technologies to allow adaptation of food and fibre production to cope with increasing climate variability and climate change (Salinger et al., 2000) lessons from the past are that the consequences can only be dramatic. An overview of past climate trends over the last millennium is provided as a context to view current climate variability and future trends for providing increasing preparedness of agriculture and forestry to future variability and change. Climate trends during the 21st century from scenarios of human activities are described, together with broadscale implications for agriculture and forestry. The United Nations Framework Convention on Climate Change has clauses on 'Dangerous Climate Change'. This concept will be examined in terms of the ability of agriculture and forestry to adapt to anthropogenic climate change this century.

2. Past Climate

2.1. THE LAST THOUSAND YEARS

The course of annual average temperature change for the Northern Hemisphere over the past 1,000 yr is shown in Figure 1. This is a particularly important time frame

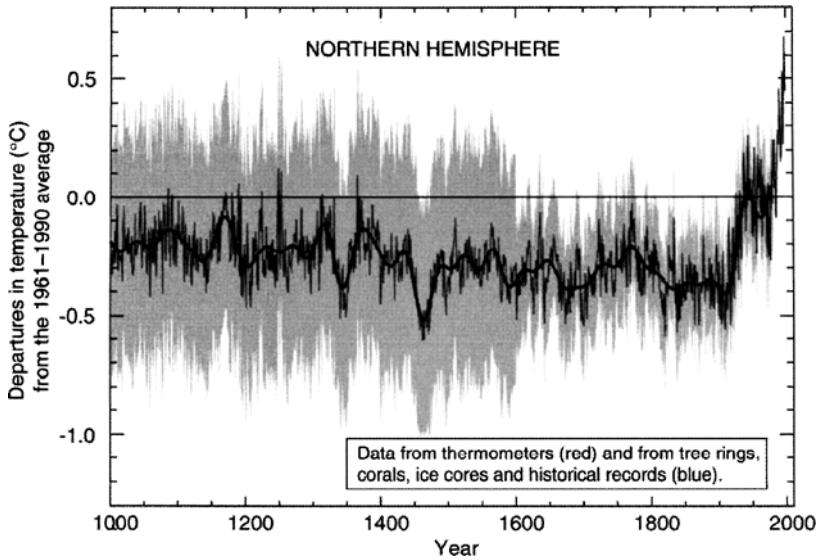


Figure 1. Northern Hemisphere average annual surface air temperature variations over the last millennium from proxy, historical and instrumental observations (IPCC, 2001a). Temperature reconstruction and instrumental data from AD 1000–1999. Smoother version of NH series and two standard error limits (gray shaded) are shown.

for assessing the background natural variability of climate, to place 21st century changes in context of which both modern and traditional agricultural and forestry systems developed over the past millennium.

Palaeoclimate proxy indicators (Folland et al., 2001) include tree rings, which provide precisely dated annual information, corals that provide information on past variability of the tropical and sub-tropical oceans and ice cores from polar regions of Greenland and Antarctica, which can have annual resolution. Other information can be gleaned from borehole measurements, which provide broadscale temperature trends, historical documentary evidence particularly from Europe and China, and mountain glacier moraines providing evidence of past glacial advances.

From these sources there is enough evidence to reconstruct temperature patterns over the Northern Hemisphere back to AD 1000 (Folland et al., 2001). These reconstructions show a slow cooling peaking around AD 1450 and 1880 over the last 1,000 yr, with the most recent cool period being around the end of the 19th century. Lamb (1982) has documented the downturn of climate in the North Atlantic/European region commencing with the storminess and cooling and wetness of 14th century Europe. Desertion of farms and village settlements are noted all over northern and central Europe. The prevailing wetness led to more prevalent disease. During the late 1500 s many years of general death and famine occurred in Scotland. For Norway extremely stormy years are noted in the 1600 s with changes in fisheries around Scandinavia.

Documentary evidence by Pfister et al. (1999) illustrates the impacts of climate excursions of similar magnitude (of the order of 0.2°C) that occurred in late 16th century Europe on agricultural commodity prices and wine production. A clear link is made with grain price fluctuations. Wine yields and prices show a more dramatic response. The interannual deterioration from 1586 to 1587 decimated yields, with wine prices jumping and beer sales tripling in the 1590s. It is interesting to note though that for the Northern Hemisphere the coldest period occurred in the late 15th century when temperatures were 0.5°C below the 1961–1990 average.

Evidence for Southern Hemisphere temperature trends in past centuries is quite sparse. There is evidence of some large-scale hydrological changes, which are best documented by lake levels in Africa (Nicholson, 1989).

2.2. THE OBSERVED RECORD

2.2.1. *Temperature*

Measurements of global-average air temperature of the land surface are available from thousands of station records distributed over the land surfaces of the globe. Marine temperature series have been derived from sea surface temperature (SST) and night marine air temperature records from ships. These have been blended and area averaged to produce anomalies of globally averaged surface air temperatures shown in Figure 2.

The global average of the surface air temperature has increased by about 0.6°C since about 1860, the earliest date for which sufficient data for global estimates are available to present. New analyses indicate that the warming in the 20th century is likely to be the largest of any century during the past 1,000 yr for the Northern Hemisphere, as indicated by Figure 1. Further, on a global basis, the 1990s were the warmest decade and 1998 was the warmest year since 1860. Two periods of temperature rise occur: one between 1910–1945, where the global temperature increase was 0.14°C , and the other from 1976–1999 when temperatures increased by 0.17°C .

The distribution of temperature increase is shown in Figure 3. The warming observed in the period 1910–1945 was greatest in Northern Hemisphere latitudes. In contrast the period 1946–1975 shows cooling in the Northern Hemisphere relative to much of the Southern Hemisphere. For the most recent period (1976–1999) increases in average temperature have been greatest over the mid-latitude of the Northern Hemisphere continents, particularly in winter. There has been relatively faster warming of land-surface temperature than of the ocean surface temperature in the last 25 yr of the 20th century (Figure 3).

On average, night-time daily minimum temperatures over land have increased at about the twice the rate of daytime daily maximum temperatures since about 1950 (approximately 0.2°C , compared to 0.1°C per decade). This trend has lengthened

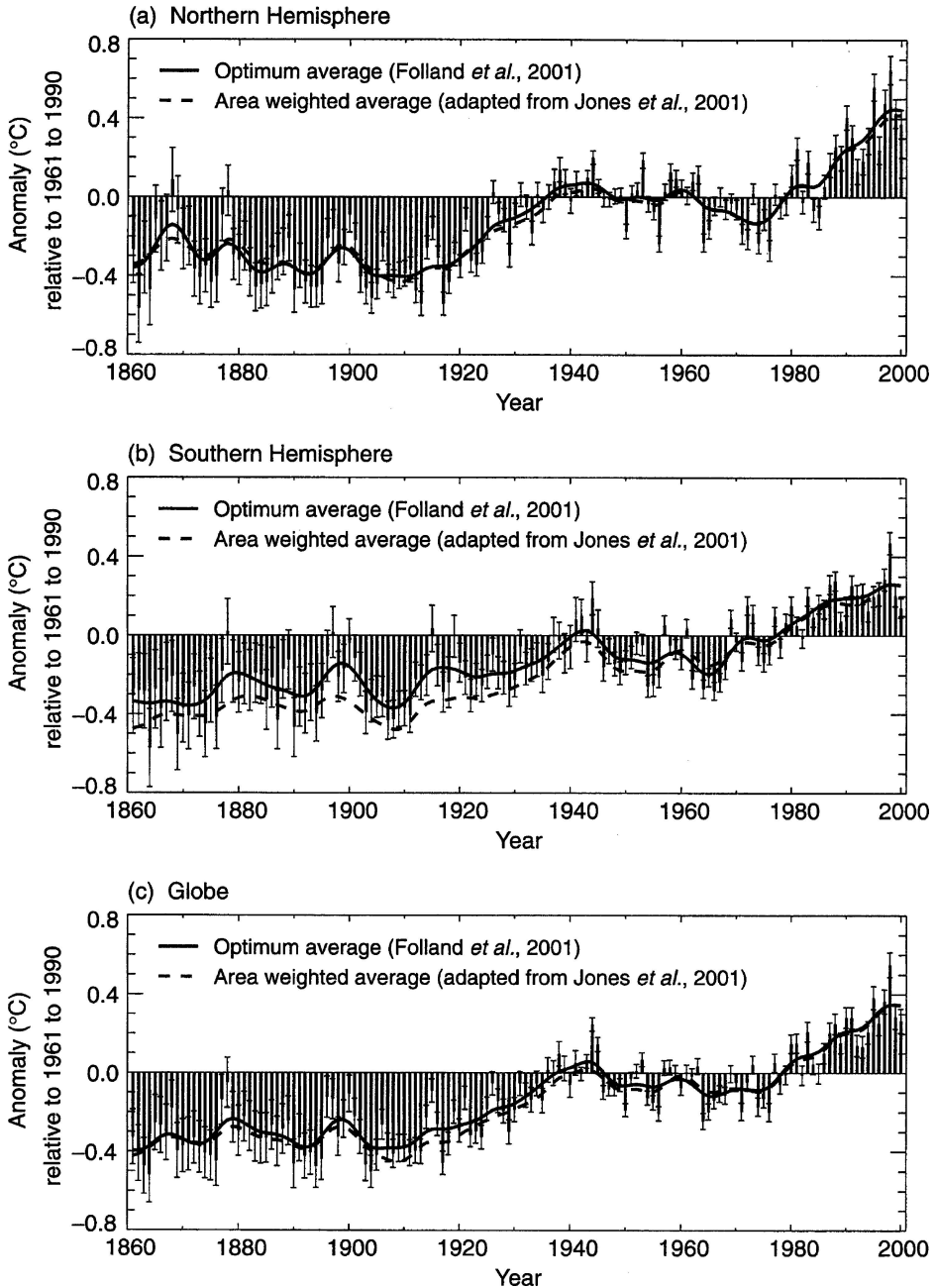


Figure 2. (a) to (c). Combined annual land-surface air and sea surface temperature (SST) anomalies relative to 1961 to 1990 ($^{\circ}\text{C}$) 1861 to 1999, calculated using optimum averages of United Kingdom Meteorological Office ship and buoy and Climatic Research Unit land surface air temperature data (bars and solid smoothed curves) taken from Folland *et al.* (2001): (a) Northern Hemisphere; (b) Southern Hemisphere; (c) Globe. The dashed smoothed curves are corresponding area weighted averages, updated from Jones *et al.* (2001).

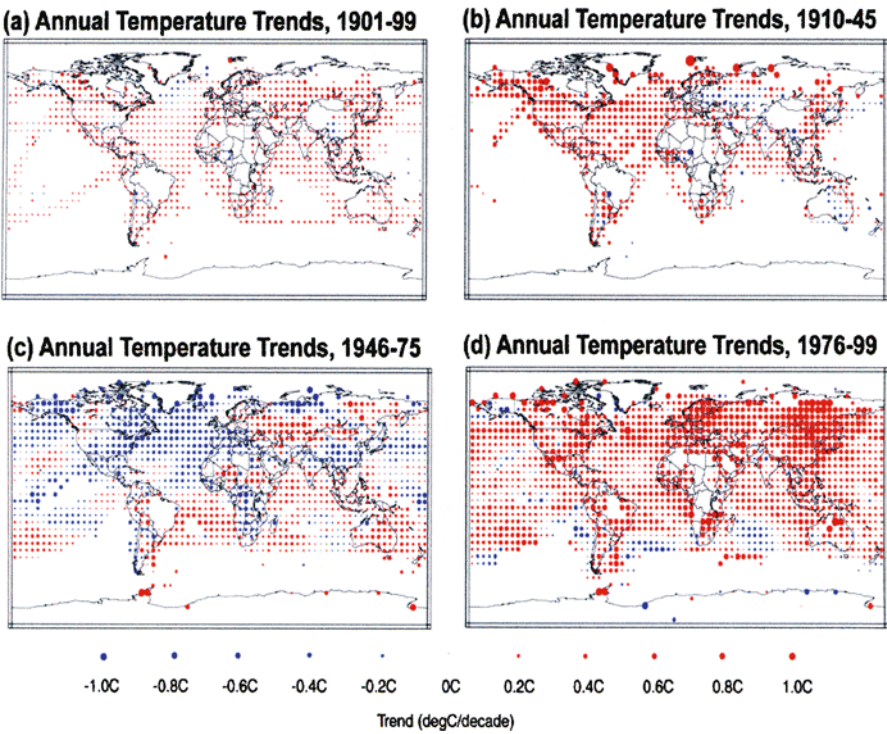


Figure 3.

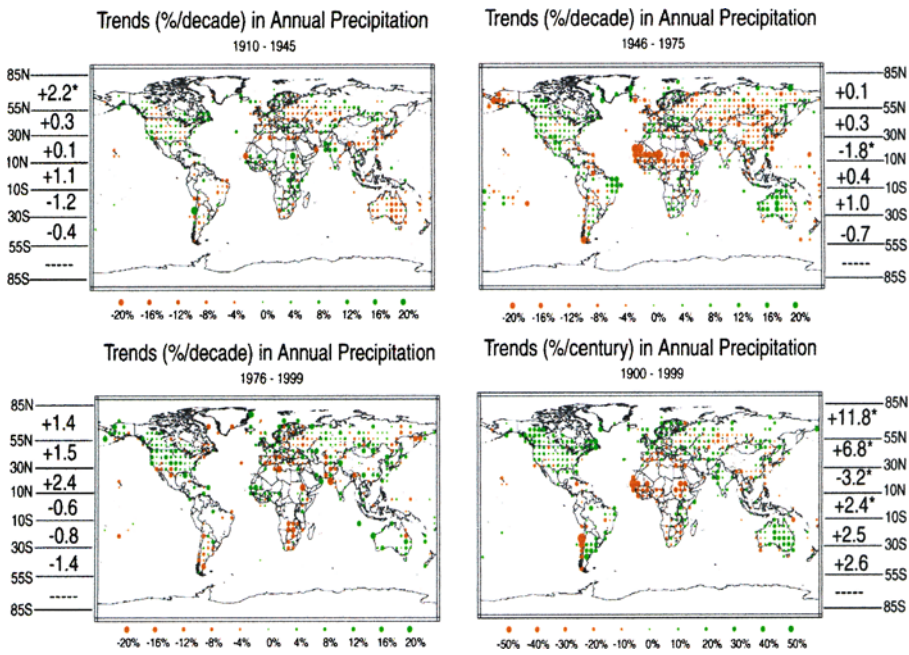


Figure 4.

the frost-free season in many mid- and high-latitude regions (Figure 5). Analysis of numbers of days with air frost (days with minimum temperature below 0°C) across much of the globe (Frich et al., 2000) shows a reduction in the order of 10%.

2.2.2. Precipitation

Overall, global land precipitation has increased by about 2 percent over the 20th century (Hulme et al., 1998). This increase is neither spatially nor temporally uniform (Figure 4). Over the mid- and high-latitudes of the Northern Hemisphere precipitation increased by between 7 and 12 percent between 30 and 85°N , especially during the boreal autumn and winter, but these increases vary both in space and time. Over North America precipitation has increased in the order of 10%, a 5% increase in western Russia and a slight decrease in eastern Russia and China. This general increase contrasts with decreases in the northern sub-tropics. Record low precipitation has been observed in equatorial regions in the 1990s. Small increases are observed in the southern sub-tropical landmasses.

Figure 3. (a) to (d): Annual temperature trends for the periods 1901–1999, 1910–1945, 1946–1975 and 1976–1999 respectively. Data from Jones et al. (2001). Trends are represented by the area of the circle with red representing increases, blue representing decreases. Trends were calculated from annually averaged gridded anomalies with the requirement that the calculation of annual anomalies include a minimum of 10 months of data. For the period 1901–1999, trends were calculated only for those grid boxes containing annual anomalies in at least 66 of the 100 yr. The minimum number of yr required for the shorter time periods (1910–1945, 1946–1975, and 1976–1999) was 24, 20, and 16 yr respectively.

Figure 4. Annual trends for the three periods of changing rates of global temperature of figure 3 and the full period, 1900–1999. During the 100 yr period, calculation of grid cell trends required at least 66% of the ys without missing data and at least 3 yr of data within each decade except the first and last. During the shorter periods, calculation of grid cell trends required at least 75% of the years without missing data. Stations with more than 1/6 of their data missing during the normal period and grid cells with more than one season or year without any measurable precipitation during the normals period were excluded from consideration. Precipitation trends are represented by the area of the circle with green representing increases and brown representing decreases. Annual trends were calculated using the following method. Precipitation anomalies in physical units were calculated for each station based on 1961–1990 normals and averaged into $5^{\circ} \times 5^{\circ}$ grid cells on a monthly basis. The 1961–1990 monthly mean precipitation for each grid cell was added to the monthly anomalies and the resulting grid cell values summed into annual totals. This series was converted into percentages of normal precipitation, and trends calculated from the percentages. Average trends within six latitude bands are shown in the legend of each map. The 1961–1990 monthly mean precipitation for the latitude band was added to the anomaly time series and the resulting values totaled across all months within the year. The significance of each trend (based on a 0.5 level) was determined using a *t*-test and a non-parametric test statistic. Trends found to be significant under both tests are indicated with a “*”.

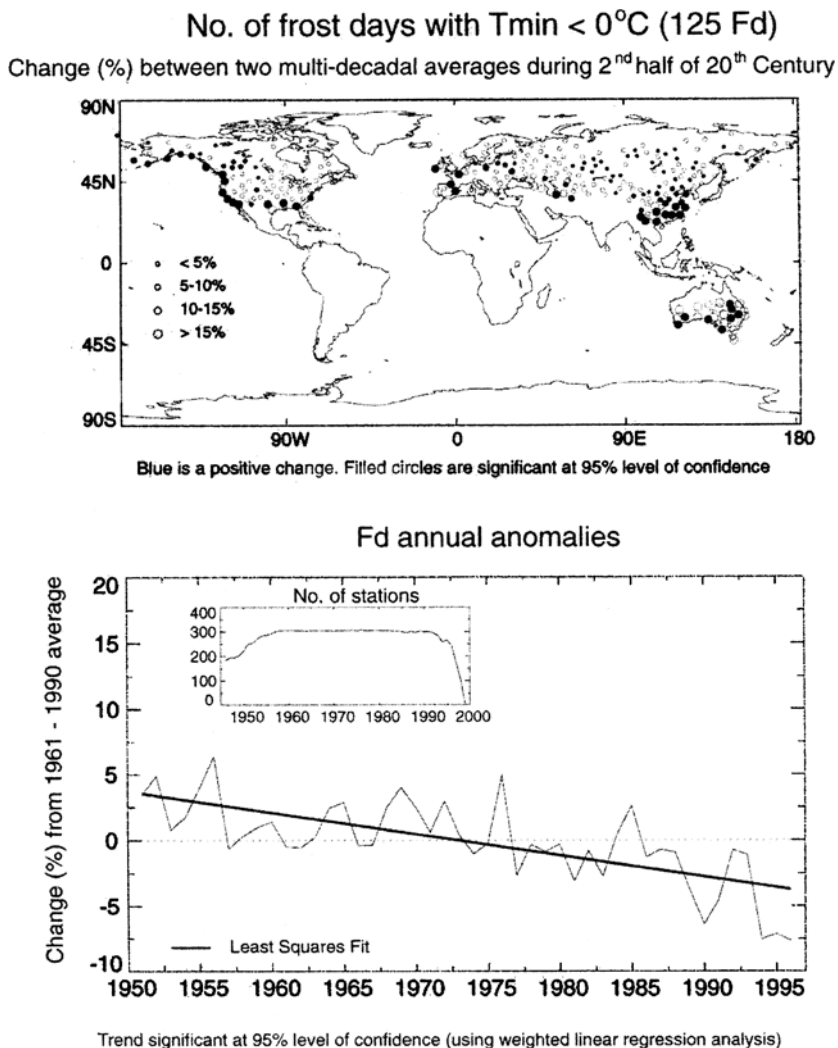


Figure 5. Changes in the number of frost days during the second half of the 20th century. The upper panel shows percentage changes in the total number of frost days, days with a minimum temperature of less than 0°C , between the first and second half of the period 1946–1999. The size of each circle reflects the size of the change it represents. The lower panel shows the average annual numbers of frost days as percentage differences from the 1961–1990 average value. The trend shown is statistically significant at the 5% level. The analysis shown is from Frich et al. 2000.

3. Present Climate

Beneath the earlier mentioned trends, current climate shows significant variability, on timescales of seasons to decades, which are of importance to agriculture and forestry. Those that are most important interannually are the El Niño/Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO), and decadal the

recently described Interdecadal Pacific Oscillation (IPO). These quasi-periodic variations are superimposed on the general trend of global warming, but their frequencies may be influenced by global warming.

3.1. INTERANNUAL VARIABILITY

3.1.1. *El Niño/Southern Oscillation (ENSO)*

ENSO is the primary global mode of natural climate variability in the 2–7 year time band defined by sea surface temperature SST anomalies in the eastern tropical Pacific. The Southern Oscillation is a measure of the atmospheric pressure across the Pacific-Indian Ocean region. Atmospheric and oceanic conditions in the tropical Pacific vary considerably during ENSO, fluctuating somewhat irregularly between the El Niño phase and the opposite La Niña phase. In the former, warm waters from the western tropical Pacific migrate eastwards, and in the latter cooling of the tropical Pacific occurs.

As the El Niño develops, the trade winds weaken and warmer waters in the central and eastern Pacific occur, shifting the pattern of tropical rainstorms eastward. Higher than normal air pressures develop over northern Australia and Indonesia with drier conditions or drought. At the same time lower than normal air pressures develop in the central and eastern Pacific with excessive rains in these areas, and along the west coast of South America. Approximately reverse patterns occur during the La Niña phase of the phenomenon.

The ENSO phenomenon's trigger is in the tropical Pacific Ocean. The observed global influences occur as teleconnections as the atmosphere transmits the anomalous heating in the tropics to large-scale convection and thus to anomalous winds in the atmosphere. The main global impacts are that El Niño events cause above average global temperature anomalies above the trend. Since the mid-1970s El Niño events have been more frequent, and in each subsequent event global temperature anomalies have been higher (Trenberth and Hoar, 1997). Figure 6 shows the Southern Oscillation Index since 1930; the Tahiti minus Darwin normalized pressure

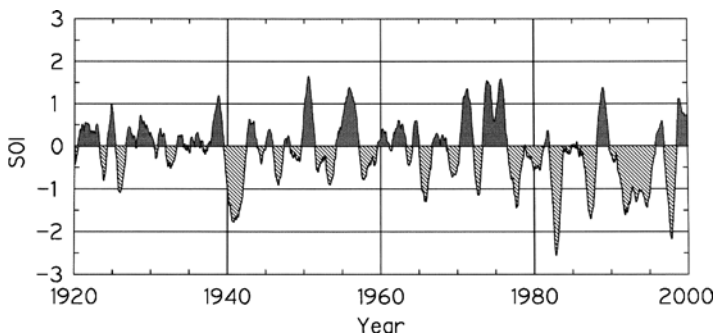


Figure 6. The Southern Oscillation Index 1930–2000. Negative values represent El Niño and positive values of this index La Niña conditions.

index, which measures whether the climate system is in the El Niño or La Niña state. A negative index indicates the El Niño state, and a positive index the La Niña state.

Reconstructions of ENSO from proxy climate indicators (Stahle et al., 1998; Mann et al., 2000) show that ENSO fluctuations have prevailed since at least 1700, but also suggest that the 1982–83 and 1997–98 very large warm events could be outside the range of variability of the past few centuries. Instrumental records show both the activity and periodicity of ENSO have varied considerably since 1871 with considerable irregularity in time. There was an apparent “shift” in the temperature of the tropical Pacific around 1976 to warmer conditions (Salinger et al., 1996), which appeared to continue until at least 1998 (Figure 6). It is unclear whether this warm state continues now as the current moderate but increasingly long La Niña, that began in late 1998 finally subsided during early 2001. The 1990s have received considerable attention, as the recent behaviour of ENSO has seemed unusual relative to that of previous decades. A protracted period of low SOI occurred from 1990–1995, during which several weak to moderate El Niño events occurred with no intervening La Niña events, which is extreme rare (Trenberth and Hoar, 1997) statistically.

3.1.2. *North Atlantic Oscillation (NAO)*

This large-scale alternation of atmospheric pressure between the North Atlantic regions of the sub-tropical high (near the Azores) and sub-polar low pressure (extending south and east of Greenland) determines the strength and orientation of the poleward pressure gradient over the North Atlantic, and the mid-latitude westerlies in this area. This is measured by the NAO (Figure 7). One extreme of the NAO occurs in winter when the westerlies are stronger than normal, bringing cold winters in western Greenland and warm winters to northern Europe. In the other phase the westerlies are weaker than normal which reverses the temperature anomalies. In addition, European precipitation is related to the NAO (Hurrell, 1995). When this index is positive, as it has been for winters in the last decade, drier than normal conditions occur over southern Europe and the Mediterranean, with above normal precipitation from Iceland to Scandinavia. The NAO also affects conditions in North Africa and possibly the Sahel.

There is a seesaw of atmospheric mass between the polar cap and mid-latitudes in both the Atlantic and Pacific Ocean basins, which has been named the Arctic Oscillation (AO). The time series of the AO and NAO (Figure 7) are quite similar (Thompson and Wallace, 2000) and the NAO is regarded by some as the regional expression of the AO.

3.2. INTERDECADAL VARIABILITY

Recently shifts in climate have been detected in the Pacific basin, driven by a newly described climate feature, the IPO, which shifts climate every one to three decades (Power et al., 1999; Salinger et al., 2001). This is an ‘ENSO-like’ feature of the climate system that operates on time scales of several decades. There is a

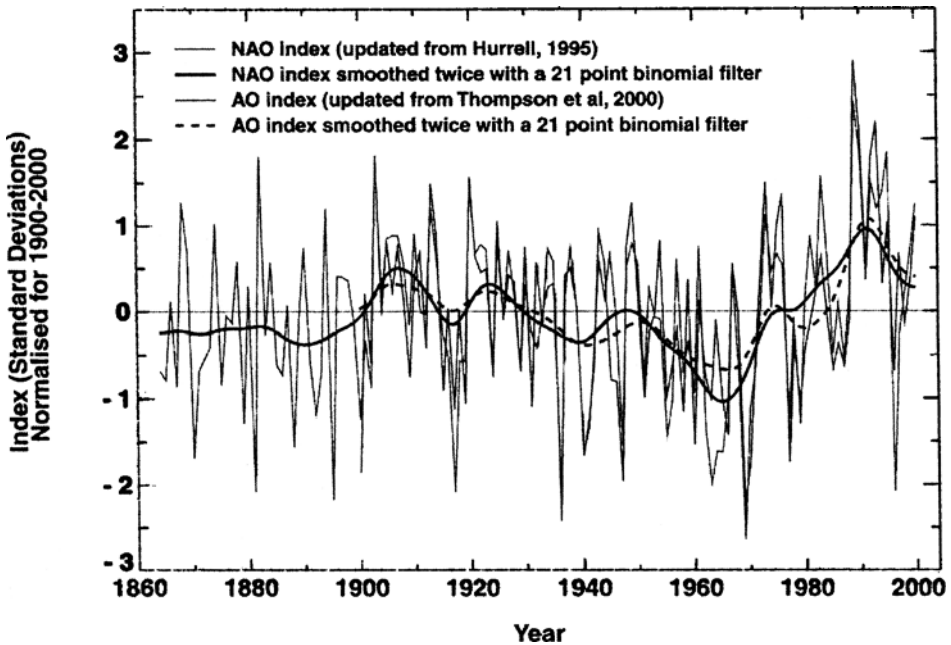


Figure 7. December to March North Atlantic Oscillation (NAO) indices, 1864–2000, and Arctic Oscillation (AO) indices, 1900–2000, updated from Hurrell (1995) and updated from Thompson and Wallace (2000) and Thompson et al. (2000) respectively. The indices were normalised using the means and standard deviations from their common period, 1900–2000, smoothed twice using a 21 point binomial filter where indicated and then plotted according to the years of their Januarys.

tight coupling between the ocean and atmosphere. The main centre of action in SST is in the north Pacific centred near the Date-Line at 40°N , with an opposing weaker centre just south of the equator in the eastern Pacific, north of Easter Island at 10°S . There is also another weaker centre of action, in the southwest Pacific centred near the Cook Islands at 20°S , which is in the same phase as the north Pacific centre. The matching atmospheric sea level pressure pattern is one of an east/west seesaw at all latitudes, but again centred over the north Pacific, with the centre of action over the Aleutian Islands. The IPO has been shown to be a significant source of decadal climate variation throughout the South Pacific and Australia, and also the North Pacific. Future research may determine whether this feature could contribute to decadal climate variability throughout Pacific-rim countries.

Three phases of the IPO have identified during the 20th century: a positive phase (1922–1946), a negative phase (1947–1976) and the most recent positive phase (1977–1998). There is now evidence that the recent positive phase has ended (Figure 8). Prior to the end of the 19th century there is not enough information to derive an IPO index. Power et al. (1999) show that the two phases of the IPO appear to modulate year-to-year ENSO precipitation variability over Australia. The IPO is

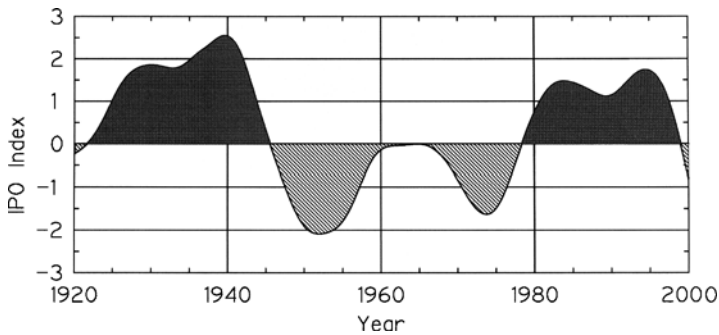


Figure 8. Smoothed index denoting the phases of the Interdecadal Pacific Oscillation (IPO).

a significant source of decadal climate variation throughout the South Pacific, and modulates ENSO climate variability in this region (Salinger et al., 2001). It may also play a key role in modulating ENSO teleconnections across North America on interdecadal time scales (Livezey and Smith, 1999). The results demonstrate that the IPO is a significant source of climate variation on decadal time scales throughout the South West Pacific region. The IPO also modulates interannual ENSO climate variability over the region.

3.3. GLOBAL WARMING

The three features, ENSO, NAO and the IPO all impinge on aspects of global climate, and two are dominant features of the tropical Pacific and oceanic Southern Hemisphere which effect climate variability of the three southern continents of Southern Africa, Australasia, and South America, as well as the Pacific basin. It is on this background of internal climate variability that external mechanisms such as volcanism and the increase of greenhouse gases from anthropogenic activities have acted (Salinger et al., 2000). Modelling studies are best able to identify the importance of these external factors in the period of current climate.

A climate model can be used to simulate the temperature changes that occur both from natural and anthropogenic causes. Figure 9 shows the results of global mean surface temperature anomalies relative to the 1880–1920 instrumental record compared with ensembles of four simulations with a coupled ocean-atmosphere climate model (Stott et al., 2000; Tett et al., 2000; IPCC, 2001a).

From these simulations IPCC (2001a) concluded that climate forcing from changes in solar radiation and volcanism is likely to have caused fluctuations in global and hemispheric mean temperatures in the first part of the 20th century. However, these have been too small to produce the mean temperature increases in the latter part of the 20th century. Well-mixed greenhouse gases (carbon dioxide, methane, chlorofluorocarbons, etc) must have made the largest contribution in radiative forcing to warm the climate in the late 20th century, as now validated by the above mentioned climate model simulations of global-average surface temperature.

Simulated annual global mean surface temperatures

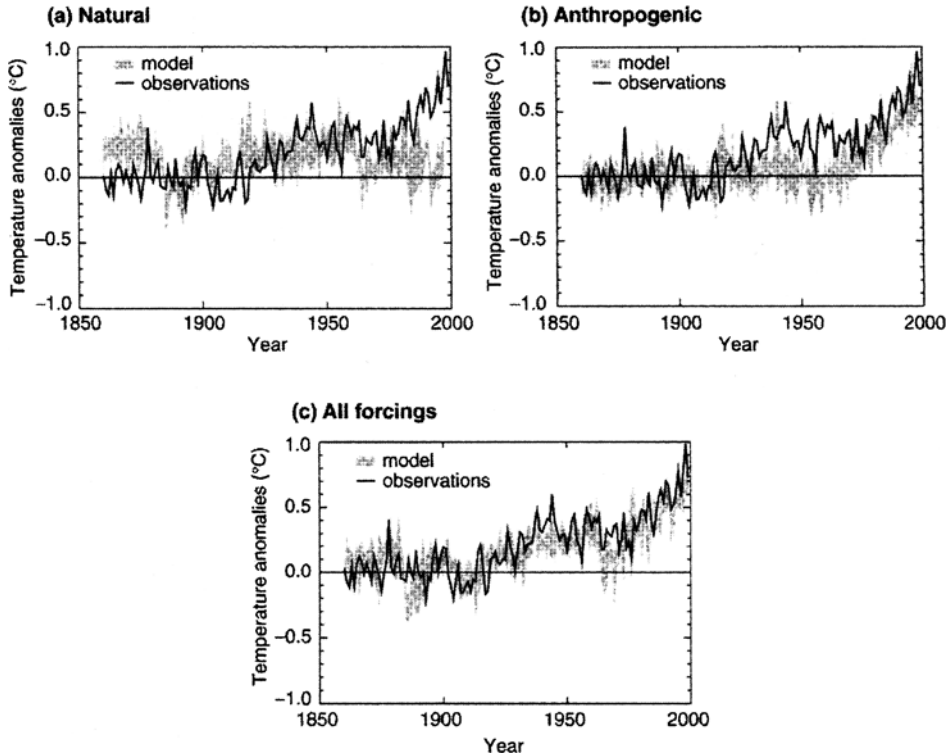


Figure 9. The simulations represented by the band in (a) were done with natural forcings: solar variation and volcanic activity. Those encompassed by the band in (b) were done with anthropogenic forcings: greenhouse gases and an estimate of sulphate aerosols and those encompassed by the band in (c) were done with both natural and anthropogenic forcings included.

4. Future Climate in the 21st Century

The growth in greenhouse gases in the atmosphere because of anthropogenic activities is also expected to be the most important factor forcing climate to change during the 21st century. Within the atmosphere there are naturally occurring greenhouse gases, which trap some of the outgoing infrared radiation emitted by the earth and the atmosphere. The principal greenhouse gas is water vapour, but also carbon dioxide (CO_2), ozone (O_3), methane (CH_4) and nitrous oxides (N_2O), together with clouds, keeps the Earth's surface and troposphere 33°C warmer than it would otherwise be. This is the *natural greenhouse effect*. Changes in the concentrations of these greenhouse gases will change the efficiency with which the Earth cools to space. The atmosphere absorbs more of the outgoing terrestrial radiation from the surface when concentrations of greenhouse gases increase. This is emitted at higher altitudes and colder temperatures and results in a positive radiative forcing which tends to warm the lower atmosphere and Earth's surface. This is the *enhanced*

greenhouse effect – an enhancement of an effect that has operated in the Earth's atmosphere for billions of years due to naturally occurring greenhouse gases e.g. Salinger et al., (2000) IPCC, (2001a). The natural concentration ranged from about 190 to 280 parts per million (ppm). When CO₂ concentrations were low, so too were temperatures, and when CO₂ concentrations were high, it was warmer. Greenhouse gases in the atmosphere are expected effectively double or quadruple by 2100.

In order to make projections of future climate, models incorporate past, as well as future emissions of greenhouse gases and aerosols. The IPCC has modeled climate using seven main scenarios of greenhouse gas and other human-related emissions, based on the IPCC Special Report on Emissions Scenarios (SRES) (IPCC, 2000). From these a full range of 42 SRES scenarios have been produced, based on a number of climate models. The pattern of temperature increase from these is shown in Figure 10.

The model results show that globally averaged surface temperature is projected to increase by 1.4 to 5.8 °C over the period 1990–2100 (IPCC, 2001a) for the full range of SRES scenarios. This projected rate of warming is much larger than the observed changes during the 20th century and is without precedent during at least

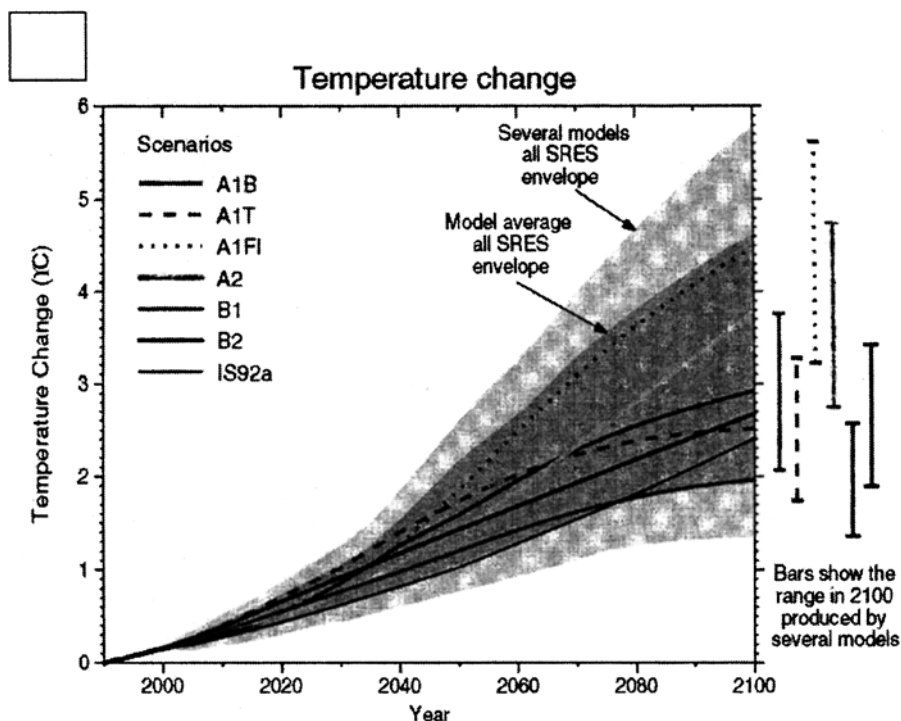


Figure 10. Estimated anthropogenic global temperature change for 1990–2100 for the seven illustrative SRES scenarios using a simple climate model tuned to seven atmosphere-ocean general climate models. The dark shading represents the full envelope of the full set of 42 SRES scenarios. The bars show the range of model results in 2,100 for the six climate model tunings.

the last 10,000 yr – and certainly during the period of settled agriculture and forestry. The global model simulations indicate that nearly all land areas will warm more rapidly than the global average, especially those located at northern high latitudes (IPCC, 2001a). Most notable of these is the warming in the northern regions of North America, and northern and central Asia. In contrast, the projected warming is less than the global mean change in southeast Asia in summer and in southern South America in winter.

More crucial to agriculture and forestry, especially in areas at low latitudes where activities are rainfed, are the likely changes in precipitation. Global model simulations (IPCC, 2001a) indicate that by the second half of the 21st century, it is likely that precipitation will have increased over northern mid- to high-latitudes. At low latitudes both increases and decreases have been projected over land areas. Trends in these regions will be critical.

TABLE I

Estimates of confidence in observed and projected changes in extreme weather and climate events. (IPCC, 2001a)

Confidence in observed changes (latter half of the 20th century)	Changes in phenomenon	Confidence in projected changes (during the 21st century)
Likely	Higher maximum temperatures and more hot days over nearly all land areas	Very likely
Very likely	Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely
Very likely	Reduced diurnal temperature range over most land areas	Very likely
Likely, over many areas	Increase of heat index (Footnote 12) over land areas	Very likely, over most areas
Likely, over many Northern Hemisphere mid-to high-latitude land areas	More intense precipitation events*	Very likely, over many areas
Likely, in a few areas	Increased summer continental drying and associated risk of drought	Likely, over most mid-latitude continental interiors. (Lack of consistent projection in other areas)
Not observed in the few analyses available	Increase in tropical cyclone peak wind intensities**	Likely, over some areas
Insufficient data for assessment	Increase in tropical cyclone mean and peak precipitation intensities**	Likely, over some areas

*For other areas, there are either insufficient data or conflicting analyses.

**Past and future changes in tropical cyclone location and frequency are uncertain. For more details see IPCC (2001a).

Extreme events have important impacts on agriculture and forestry. Currently climate models lack the spatial detail required to make confident projections. However, broadscale assessments of observed changes in extremes for the 20th century and projected changes for the 21st century have been made (IPCC, 2001a) and are given in Table I. Similar tabulations at broad regional levels are also available in the IPCC 2001 synthesis report (IPCC, 2001c). The theory of changes in extremes, as a result of changes in both means and variability is illustrated in Figure 11. This

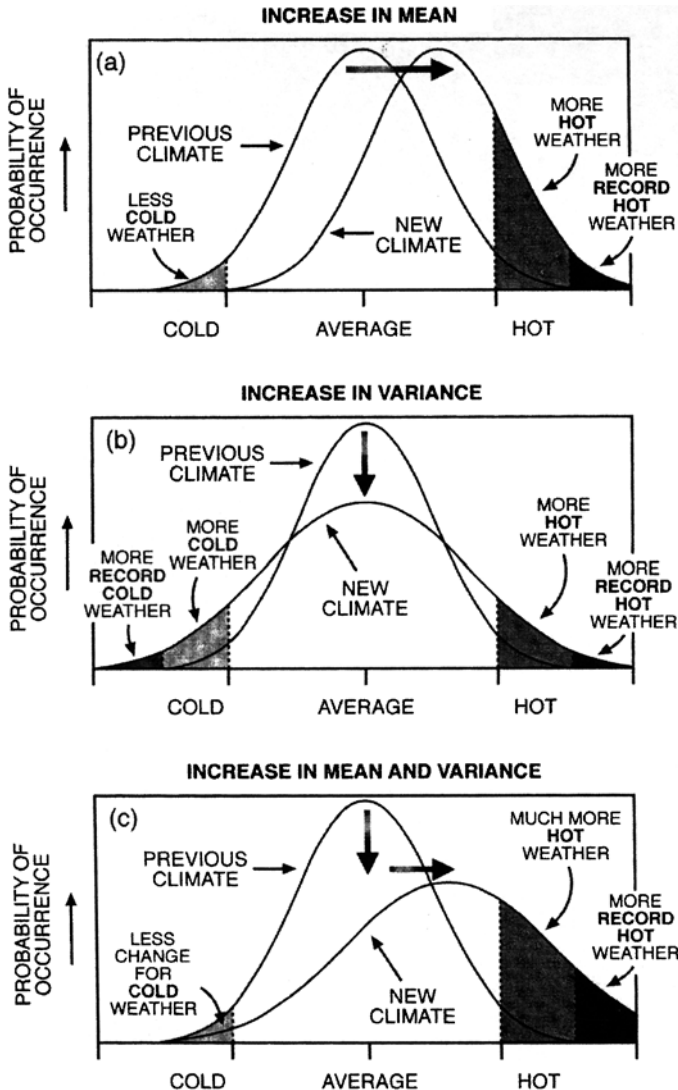


Figure 11. Schematic theory showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature.

shows that shifts in both means and variance can have a profound effect on the frequency of extremes.

5. Implications for Agriculture and Forestry

5.1. IMPLICATIONS

The implications of both past and present climate variability and change on agriculture and forestry are the subject of impact studies, some of which have been summarized in the IPCC Third Assessment Report (IPCC, 2001b). Broad scale future impacts have already been identified. From the most well understood trends in climate during the 21st century the key trends that have been identified are

1. The continued rapid temperature increase in high latitudes of the Northern Hemisphere;
2. Further drying in Mediterranean areas, and some tropical and sub-tropical latitudes;
3. The accentuation of climate extremes as a consequence of increasing climate variability especially in sub-tropical and tropical latitudes.

All these aspects will be considered in later papers in this volume. The purpose of this contribution is to identify the underlying trends in climate change and variability during the 21st century. This will be a blend of the centennial scale trends induced by anthropogenic climate warming, on which will be superimposed decadal scale variability from the IPO and interannual variability imposed by ENSO and the NAO, of which the frequencies may be influenced by global warming.

5.2. DANGEROUS CLIMATE CHANGE

Throughout historical time, and agrarian settlement, climate has varied. Both natural climate change and variability has occurred, which past and current agricultural and forestry systems have adapted to. Where systems in the recent geological past, such as those in the Indus valley, in this case to changing soil conditions, have not adapted, they have not survived. The record of observed climate, by instruments and proxy indicators, suggest that the rate and magnitude of change and variability has been quite modest, with centennial temperature changes globally in the order of 0.5 °C, and locally 1 °C. Natural variability because of ENSO has been a factor throughout recorded history.

However, the magnitude and rates of change that are projected for the 21st century fall outside that range. The 90% confidence range of global warming is in the range of 2 to 4.5 °C (Wigley and Raper, 2001). Although agriculture and forestry might adapt given a modest rate of climate change, the rapidity of projected change

is unprecedented in the last 10,000 yr. The current rate of global warming since the mid-1970s has been at 0.2°C per decade, which is consistent with the lower projected warming rates for the 21st century.

The United Nations Framework Convention on Climate Change (United Nations, 1992) main purpose is to reduce the growth of greenhouse gases in the atmosphere and stabilize climate.

“the ultimate aim of this Convention... is to achieve... Stabilisation of greenhouse gas concentrations in the atmosphere..to prevent dangerous climate change¹”

The natural greenhouse effect keeps the planet and biosphere at an equable temperature for planetary processes to operate (e.g. Salinger et al., 2000).

Climate, agriculture and forestry are thus inextricably linked. The mean surface air temperature of the earth can be used as a measure of the stability of the climate system. It responds to energy inputs, and cycling processes such as the hydrological (water) cycle. Temperature is part of the process of life systems. Over the last 420,000 yr climate has varied by 6°C between glacial and interglacial periods, with the most rapid change being about 1°C per century. Temperature increases or decreases outside these ranges will create an unstable climate, as parts attempt to adjust to rapidly changing temperatures. Native forests take centuries to adjust their range, and agriculture would face almost impossible adjustments.

The current rate of global warming is 2°C per century, and this rate is projected as a lower range for the remainder of the 21st century. Thus increases in greenhouse gases released by human activities are creating a potential situation of dangerous climate change where the stability of agriculture and forestry systems is threatened. Greenhouse gases are likely to double during this century. This could bring with it unknown climate surprises and their impacts, such as flooding from unmanageable catchments and inundation of land areas due to storm surges and sea level rise.

Adaptation strategies are going to be of crucial importance. These can range from traditional to new technologies. Traditional management practices such as intercropping, mulching and agroforestry will be important. Changes in agronomic practices such as earlier planting or cultivar switching are simple adaptive strategies for the tropics. Earlier planting and sowing, shorter rotations and larger spacing in areas undergoing drying and use of shelterbelts can be used in temperate regions. Understanding of impacts, modeling and improved spatial measurement of agriculture and forestry will provide new methods of adaptation. The improvement of seasonal climate forecasting will increase preparedness and risk management on seasonal to interannual time-scales for increasing climate variability. All these strategies and others discussed in later papers in this volume will be of critical importance to cope with the increasing climate variability and change of the 21st century to prevent these variations being dangerous to agriculture and forestry.

6. Conclusions

Climate variability and change have gone on throughout time, and on geological time scales of millions of years the climate system has undergone large changes as the earth has evolved. During the last glacial maximum, approximately 20,000 yr ago global temperatures were 5 to 6 °C less than those at the beginning of the 21st century (IPCC, 2001a). Even though temperatures have increased by this amount, the rise occurred over thousands of years, and stabilized into the modern climate regime about 10,000 yr ago.

In the perspective of human settlement and agriculture and forestry activities over the last 10,000 yr at least climate changes have been quite small, and certainly in the documented record for the last 1,000 yr small variations in global temperature have occurred compared with the glacial/interglacial changes. Hydrological variations may have been larger though. The projected global mean temperature trends for the 21st century are without precedent, with rates expected of between 2 and 4.5 °C for the century.

Underneath the strands of 21st century climate warming due to anthropogenic activities, interdecadal and interannual climate variability will continue and possibly increase. Decadal climate variability, as induced by the IPO, will continue throughout the Pacific basin. Both will impact on regional and global climate and hence temperature and rainfall.

Interannual climate variabilities, particularly that caused by ENSO and NAO are expected to continue and possibly increase throughout this century. In fact global warming has been identified to lead to greater extremes of drying and heavy rainfall and increases the risk of droughts and floods that occur with ENSO events in many different regions, thus increasing climate variability from these sources.

As well, extremes are expected to increase (Table I). More hot days are expected over nearly all land areas and more intense precipitation events over many Northern Hemisphere mid- to high-latitude land areas. Increased summer continental drying and associated drought risk is likely in a few areas and peak wind and precipitation intensities in tropical cyclones are assessed to increase in some areas.

Climates of the globe have always varied over the last millennium, because of natural phenomena such as ENSO and the IPO. However, as the century progresses the interannual and decadal phenomenon will be superimposed on an unprecedented global warming trend. Together these will produce rapid climate change, increasing climate variability and climate extremes. Thus agriculture and forestry will face unprecedented challenges in the 21st century.

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IMPACTS OF PRESENT AND FUTURE CLIMATE VARIABILITY AND CHANGE ON AGRICULTURE AND FORESTRY IN THE ARID AND SEMI-ARID TROPICS

M. V. K. SIVAKUMAR¹, H. P. DAS² and O. BRUNINI³

¹*World Meteorological Organization, 7bis Avenue de la Paix, 1211 Geneva 2, Switzerland*

E-mail: msivakumar@wmo.int

²*India Meteorological Department, Shivaji Nagar, Pune 411005, India*

³*Center for Ecology and Biophysics, 13.020-430-Campinas, Sao Paulo, Brazil*

Abstract. The arid and semi-arid regions account for approximately 30% of the world total area and are inhabited by approximately 20% of the total world population. Issues of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics of the world were examined and discussion under each of these issues had been presented separately for Asia, Africa and Latin America.

Several countries in tropical Asia have reported increasing surface temperature trends in recent decades. Although, there is no definite trend discernible in the long-term mean for precipitation for the tropical Asian region, many countries have shown a decreasing trend in rainfall in the past three decades. African rainfall has changed substantially over the last 60 yr and a number of theoretical, modelling and empirical analyses have suggested that noticeable changes in the frequency and intensity of extreme events, including floods may occur when there are only small changes in climate. Climate in Latin America is affected by the El Niño-southern oscillation (ENSO) phases and there is a close relationship between the increase and decrease of rainfall depending upon the warm or cold phases of the phenomenon.

Over land regions of Asia, the projected area-averaged annual mean warming is likely to be $1.6 \pm 0.2^\circ\text{C}$ in the 2020s, $3.1 \pm 0.3^\circ\text{C}$ in the 2050s, and $4.6 \pm 0.4^\circ\text{C}$ in the 2080s and the models show high uncertainty in projections of future winter and summer precipitation. Future annual warming across Africa is projected to range from 0.2°C per decade to more than 0.5°C per decade, while future changes in mean seasonal rainfall in Africa are less well defined. In Latin America, projections indicate a slight increase in temperature and changes in precipitation.

Impacts of climate variability and changes are discussed with suitable examples. Agricultural productivity in tropical Asia is sensitive not only to temperature increases, but also to changes in the nature and characteristics of monsoon. Simulations of the impacts of climate change using crop simulation models show that crop yield decreases due to climate change could have serious impacts on food security in tropical Asia. Climate change is likely to cause environmental and social stress in many of Asia's rangelands and drylands. In the arid and semi-arid tropics of Africa, which are already having difficulty coping with environmental stress, climate change resulting in increased frequencies of drought poses the greatest risk to agriculture. Impacts were described as those related to projected temperature increases, the possible consequences to water balance of the combination of enhanced temperatures and changes in precipitation and sensitivity of different crops/cropping systems to projected changes. In Latin America, agriculture and water resources are most affected through the impact of extreme temperatures (excessive heat, frost) and the changes in rainfall (droughts, flooding). Adaptation potential in the arid and semi-arid tropics of Asia, Africa and Latin America was described using suitable examples. It is emphasized that approaches need to be prescriptive and dynamic, rather than descriptive and static.

1. Introduction

The World Atlas of Desertification (UNEP, 1992) defines arid regions as the areas where the ratio of mean annual rainfall (R) to mean annual potential evapotranspiration (PET) varies between 0.05 and 0.20 and the semi-arid regions as those where the ratio ranges between 0.2 and 0.5. In an assessment of population levels in the world's drylands, the Office to Combat Desertification and Drought (UNSO) of the United Nations Development Programme (UNDP) showed that the arid and semi-arid regions account for approximately 30% of the world total area and are inhabited by 1.10 billion people or approximately 20% of the total world population. The arid and semi-arid regions are home to about 24% of the total population in Africa, 17% in the Americas and the Caribbean, 23% in Asia, 6% in Australia and Oceania, and 11% in Europe (UNSO, 1997).

Climate variability has been, and continues to be, the principal source of fluctuations in global food production in the arid and semi-arid tropical countries of the developing world. Throughout history, extremes of heat and cold, droughts and floods, and various forms of violent weather have wreaked havoc on the agricultural systems in these regions. In conjunction with other physical, social and political-economic factors, climate variability and change contribute to vulnerability to economic loss, hunger, famine and dislocation. Hence, it is imperative that these aspects are well understood in order to formulate more sustainable policies and strategies to promote food production in the arid and semi-arid tropics.

Increasing greenhouse gas accumulation in the global atmosphere and increasing regional concentrations of aerosol particulates are now understood to have detectable effects on the global climate system (Santer et al., 1996) and global average temperatures and sea level are projected to rise under all the scenarios from the Special Report on Emission Scenarios (IPCC, 2000). According to IPCC (2001a), the global average surface temperature increased over the 20th century by about 0.6°C and temperatures have risen in the past four decades in the lowest eight kilometers of the atmosphere. New analyses of data for the northern hemisphere indicate that the increase in temperature in the 20th century is likely to have been the largest during any century since 1000 AD.

In this paper, we examine the issues of present and future climate variability and change on agriculture and forestry in the arid and semi-arid tropics of the world. For the sake of convenience, the discussion under each of these issues had been presented separately for Asia, Africa and Latin America. In view of the relatively smaller proportion of area, no attempt has been made to cover the arid and semi-arid tropics in the developed world.

2. Present Climate Variability and Change in the Arid and Semi-Arid Tropics

2.1. ASIA

Tropical Asia, including arid and semi-arid tropics, has a unique climatological distinction because of the pervasive influence of the monsoons. The summer southwest monsoon influences the climate of the region from May to September, and the winter northeast monsoon controls the climate from November to February. The monsoon brings most of the region's precipitation and is the most critical climatic factor in the provision of drinking water and water for rain-fed and irrigated agriculture. The El Niño-Southern Oscillation (ENSO) phenomenon, which is geographically very extensive, has an especially important influence on the weather and inter-annual variability of climate and sea level, particularly in the western Pacific Ocean, South China Sea, Celebes Sea, and the northern Indian Ocean. Suppiah (1997) has found a strong correlation between the southern oscillation index (SOI) and seasonal rainfall in the dry zone of Sri Lanka; Clarke and Liu (1994) relate recent variations in south Asian sea-level records to zonal ENSO wind stress in the equatorial Pacific. The influence of Indian Ocean sea-surface temperature on the large-scale Asian summer monsoon and hydrological cycle and the relationship between Eurasian snow cover and the Asian summer-monsoon also has been substantiated (Zhu and Houghton, 1996).

Several countries in this region have reported increasing surface temperature trends in recent decades. The warming trend over India has been reported to be about 0.57°C per 100 yr (Rupakumar et al., 1994). In Pakistan, annual mean surface temperature has a consistent rising trend since the beginning of 20th century (Chaudhari, 1994). In most of the Middle East, the long-time series of surface air temperature show a warming trend. In Vietnam, annual mean surface temperature has increased over the period 1895–1996, with mean warming estimated at 0.32°C over the past three decades. Annual mean surface air temperature anomalies over Sri Lanka during the period 1869–1993 suggest a conspicuous and gradually increasing trend of about 0.30°C per 100 yr (Rupakumar and Patil, 1996).

In general, an increasing trend in temperature has been observed in southern and central India in recent decades in all seasons and over all of India in the post-monsoon seasons. This warming has generally been accompanied by increases in diurnality except over northern India in the winter, pre-monsoon and post-monsoon seasons. Srivastava et al. (1992) observed increase in trends of annual mean, maximum and minimum temperatures south of 23°N and cooling trends north of 23°N . The diurnal temperature range (DTR) shows an increasing trend in all the seasons over most of peninsular India. This is in contrast to many other land regions of the northern hemisphere (Nicholls et al., 1996).

Mean annual rainfall is considerably low in most parts of the arid and semi-arid region of tropical Asia, and temporal variability quite high. In some places in the region, as much as 90% of the annual total is recorded in just two months of the year. Although, there is no definite trend discernible in the long-term mean for precipitation for the region or in individual countries during this time period, many countries have shown a decreasing trend in rainfall in the past three decades. In India, long-term time series of summer monsoon rainfall have no discernible trends, but decadal departures are found above and below the long-time averages alternatively for three consecutive decades (Kothyari and Singh, 1996). Recent decades have exhibited an increase in extreme rainfall events over northwest India during the summer monsoon (Singh and Sontakke, 2001). Moreover, the number of rainy days during the monsoon along east coastal stations has declined in the past decade. A long-term decreasing trend in rainfall in Thailand is reported (OEPP, 1996). In Pakistan, seven of 10 stations have shown a tendency toward increasing rainfall during monsoon season (Chaudhari, 1994).

Chattopadhyaya and Hulme (1997) analyzed the trends in potential evapotranspiration (PE) for 10 stations in India including stations in arid and semi-arid tropics. In the monsoon and post-monsoon seasons, PE was found to have decreased over the last 15 yr over the whole country, whereas in the winter and pre-monsoon seasons the trends are less consistent. The decreasing trend in PE is up to a maximum of about $0.3 \text{ mm day}^{-1} \text{ decade}^{-1}$ over west-central India in the monsoon and post-monsoon seasons (Figure 1). These trends are generally lower than for surface evapotranspiration (E_p) and represent a reduction in PE of less than 3% per decade. Changes in PE were most strongly associated with changes in relative humidity, particularly in the winter and pre-monsoon seasons. In the monsoon season, radiation was the dominant variable for regulating the PE variation at nearly all stations. Changes in both radiation and relative humidity are associated with decreases in PE in the post-monsoon season.

No identifiable variability in the number, frequency, or intensity of tropical cyclones or depressions has been observed in the northern Indian Ocean cyclone region (Bay of Bengal and Arabian Sea) over the past 100 yr, though Gadgil (1995) has shown decadal-scale variations with a rising trend during 1950–1975 and a declining trend since that time. No conclusive increasing or decreasing trends in time series data of flooded areas has been noticed in various river basins of India and Bangladesh (Mirza et al., 2001). Drought can reach devastating proportions in tropical Asia, though the incidence is variable in time and space. Drought or near-drought conditions occur in parts of Nepal, Papua New Guinea, and Indonesia, especially during El Niño years. In India, Laos, the Philippines, and Vietnam drought disasters are more frequent during years following ENSO events. At least half of the severe failures of the Indian summer monsoon since 1871 have occurred during El Niño years (Webster et al., 1998). When several decades were combined to provide an understanding of the decadal scale variability of drought occurrence in India, it is found that the 1891–1920 and 1961–80 periods witnessed frequent droughts

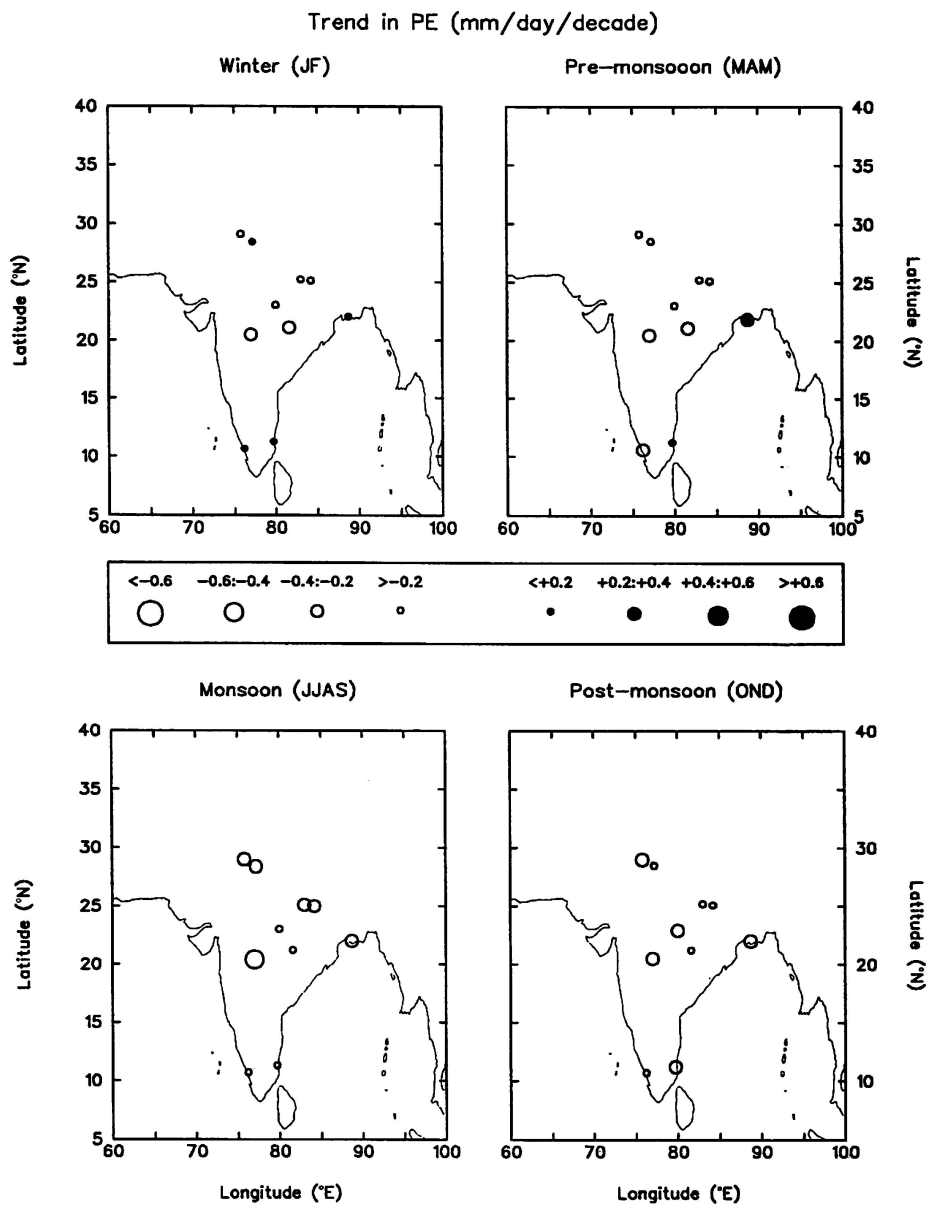


Figure 1. Mean linear trend ($\text{mm day}^{-1} \text{decade}^{-1}$) in PE for the period from 1976 to 1990 for different seasons over India based on ten stations data. Dot size is related to trend.

while few droughts occurred during 1930–1960 and 1980–2000. This suggests some kind of low frequency oscillation of the monsoon system on the decadal scale (Das, 2000). Gregory (1994) observed that over arid and semi-arid regions of India, there have been periods in the last decades of the nineteenth century and first two

decades of twentieth century when drought frequencies have been markedly higher than in recent years, though individual recent droughts may have been intense ones in some regions. There are also reports of an increase in thunderstorms over the land regions of tropical Asia (Karl et al., 1995). The frequency and severity of wild fires in grassland and rangelands in arid and semi-arid Asia have increased in recent decades (Pilifosova et al., 1996).

Low rainfall in arid and semi-arid regions dictates the formation of shallow soils, which are poor in organic matter and nutrients. Coupled with the conversion of grazing lands to farming, the arid region of India is undergoing an aggravation of desertification through erosion of lands and aeolian shifting of soil particles. In some locations, there has been a rise of water table with simultaneous increase of salinity and deterioration of soil regime. The variation of the aridity index line, computed by Penman method, over arid regions of India reveals a possible spread of arid conditions in the southeast direction (Jain, 1986).

Populations in arid or semi-arid areas of south Asia are most vulnerable because of their heavy dependence on agriculture and high population density. Monsoon depressions and tropical storms are important features of the climate in this region from the agricultural production point of view. These storms can be destructive, but also are the main source of moisture. An estimated 31% of cropland is already irrigated, which may reduce vulnerability somewhat, provided water resources remain adequate. Chronic hunger remains a problem, however, for the poorer segments of the population particularly in semi-arid and arid parts of the region (IPCC, 1995).

2.2. AFRICA

Africa is the largest tropical landmass with an east-west extent of about 6,000 km. It is the only continent, which has roughly equal landmasses within both hemispheres on either side of the equator. The vast continent is characterized by a wide range of climatic regimes. The poleward extremes of the continent experience winter rainfall associated with the passage of mid-latitude air masses. Over the rest of the continent, annual cycle is strongly determined by the position of the inter-tropical convergence zone (ITCZ), which is a primary feature of the meridional Hadley circulation (WCRP, 1999). The mean climate of Africa is further modified by the presence of large contrasts in topography and the existence of lakes across the continent (Semazzi and Sun, 1997). This basic climatic state is further significantly modified by the asymmetry of the continent, the adjacent ocean basins circulation, and the global Walker circulation, to produce the observed continental climatology (Hastenrath, 1985).

Rainfall is one of the most important natural resources for many of mainland Africa's 48 nations (Hulme, 1992). Inter- and intra-annual variability in rainfall is perhaps the key climatic element that determines the success of agriculture in these

regions, where the climatic control of soil water availability through rainfall and evaporation is most prominent. In low-rainfall years, there may be droughts; in high-rainfall years or even for short periods in low-rainfall years there may be floods. Extensive droughts have afflicted Africa, with serious episodes since independence in 1965–1966, 1972–1974, 1981–1984, 1986–1987, 1991–1992, and 1994–1995 (WMO, 1995; Usher, 1997). The aggregate impact of drought on the economies of Africa can be large: 8–9% of GDP in Zimbabwe and Zambia in 1992, 4–6% of GDP in Nigeria and Niger in 1984 (Benson and Clay, 1998).

African rainfall has changed substantially over the last 60 yr. Over tropical North Africa, this change has been notable as rainfall during 1961–1990 declined by up to 30% compared with 1931–1960. From an analysis of recent rainfall conditions in West Africa, Nicholson et al. (2000) concluded that a long-term change in rainfall has occurred in the semiarid and sub-humid zones of West Africa. Rainfall during the last 30 yr (1968–1997) has been on average some 15–40% lower than during the period 1931–1960. A similar, but smaller change has occurred in semi-arid and sub-humid regions of southern Africa.

Dennett et al. (1985) pointed out that, though the rainy season includes June through to September in most of the Sahel, the annual rainfall anomalies are related primarily to rainfall in August and, to a lesser extent, September. Sivakumar (1992) showed that at several locations in Niger, a significant decline in the annual and August rainfall has occurred since 1966. From examination of the change between 1931–1960 and 1961–1990 in mean seasonal rainfall over Africa, Hulme (1992) showed that rainfall change has been dominated by the reduction in June–July–August rainfall in the Sahel with widespread decreases of well over 0.4 mm day^{-1} . Such a large relative rainfall change between these two 30 yr climatologies is unparalleled elsewhere in the world (Hulme et al., 1992). Hulme (1992) also showed that in the Southern Hemisphere tropical margins, December–January–February rainfall rates have declined, with decreases of more than 0.4 mm day^{-1} over parts of Botswana and Zimbabwe. Nicholson et al. (2000) showed that mean August rainfall during the 1968–1997 period was 55, 37 and 26% below the 1931–1960 average in the Sahelo-Sahara, Sahel and Soudan zones, respectively.

In certain semi-arid regions, persistence in the rainfall deviations is significant. Using time series of regional rainfall anomalies, Hulme (1992) showed a striking persistence of Sahelian rainfall anomalies in marked contrast to East Africa and south-western Africa. In West Africa, there has been a pattern of continued aridity since the late 1960s that is most persistent in the more western regions (Nicholson et al., 2000). Rainfall fluctuations are also associated with a geographic pattern. Sivakumar (1989) showed that the reduction in mean annual rainfall in both Niger and Burkina Faso after 1969 was characteristic of the entire region. After 1969, the rainfall isohyets were displaced further south showing that rainfall changes affect large areas. Using latitudinal profiles of mean rainfall rates over Africa, Hulme (1992) showed that southward shifts of JJA rainfall zones of just over 1° latitude

(*ca.* 120 km) between 1931–1960 and 1961–1990 and just under 3° latitude (*ca.* 330 km) between 1950–1954 and 1983–1987. Using normalised vegetation difference index (NDVI) data, Tucker et al. (1991) estimated a shift of up to 2.2° latitude (*ca.* 240 km) in the position of the 200 mm annual isohyet in the Sahel during the decade 1980–1990.

A number of theoretical, modelling and empirical analyses have suggested that noticeable changes in the frequency and intensity of extreme events, including floods may occur when there are only small changes in climate (Wigley, 1985; Katz and Acero, 1994; Wagner, 1996). Mason et al. (1999) identified significant increases in the intensity of extreme rainfall events over about 70% of the country in South Africa between 1931–1960 and 1961–1990. Le Barbé and Lebel (1997) showed that the average number of rainy events in August was reduced by about 30%.

Hulme (1992) categorized the possible causes for rainfall changes into three broad areas: those related to land cover changes within the continent; those related to changes in the global ocean circulation and associated with patterns of sea-surface temperatures (SSTs); and those related to the changing composition of the global atmosphere.

Air temperatures in the Sahelian and Sudanian zones of West Africa (SSZ) are usually high because of the high radiation load. From south to north, temperatures increase and rainfall decreases. Environmental conditions during the stage of crop establishment in the SSZ, especially in the low rainfall areas, are usually harsh since the sowing rains follow a long and hot dry season. Mean maximum temperatures could exceed 40 °C at the time of sowing and absolute temperatures could be much higher (Sivakumar, 1989). Diurnal variations in the air temperature and soil temperatures at the surface and 5 cm depth before the onset of rains (Figure 2) show that the surface soil temperatures can increase rapidly from 27 °C at 0700 h to 56 °C at 1400 h. Although the surface soil temperatures decrease after a rain, with a short dry period and clear skies, atmospheric conditions can quickly return to those described in 2. The highland areas of eastern and southern Africa are substantially cooler than lowland regions, and there is evidence that recent warming trends may have been exaggerated in these mountain areas (Hulme, 1996a).

The widespread deterioration of large areas of savannah in the semi-arid regions of Africa is believed to be associated with the overexploitation of marginal land via the removal of wood and overgrazing (Barrow, 1987). The net change of forest area in Africa is the highest among the world's regions, with an annual net loss based on country reports, estimated at 5.3 million ha, which contributes to 56% of the total destruction of forests worldwide. Because the open forests are mainly an unmanaged ecosystem, their regeneration may pose problems.

Increasing land degradation leaves the bare surface soil susceptible to wind erosion. Data collected in Niger show (Figure 3) that the increasing wind erosion is leading to decreased visibility. As compared to the 60s, during the 80s there was a significant increase in the number of days with poor visibility (<5 km). The problem

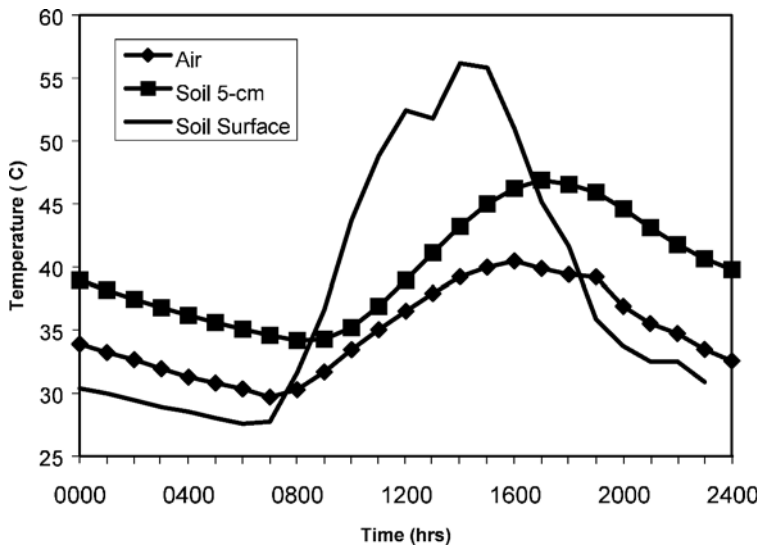


Figure 2. Diurnal variation in the air temperature and soil temperatures at the surface and 5 cm depth before the onset of rains on 10 May 1992 at Sadore, Niger.

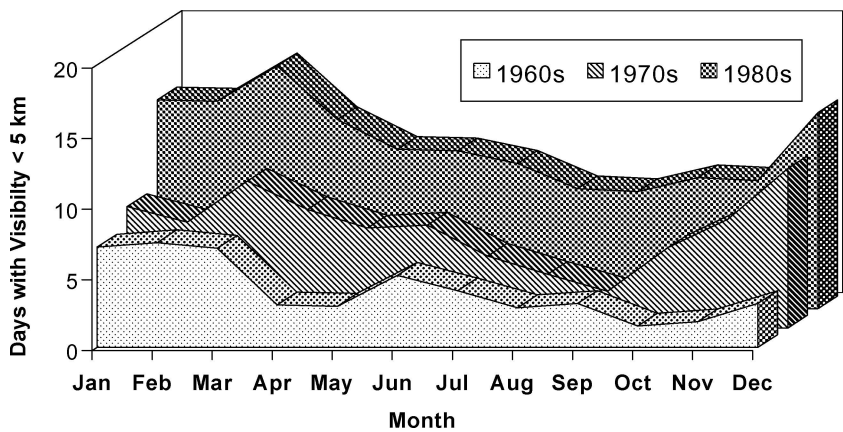


Figure 3. Changes in the visibility from the 1960s to the 1980s at Niamey, Niger (Data source: National Meteorological Services of Niger).

is becoming particularly serious at the beginning of the rainy season, when rains are usually preceded by dust storms with violent winds. Moving sand particularly affects crop establishment by damaging the seedlings by “sand blasting” and the high soil temperatures during this period cause further damage. Lack of adoption of appropriate strategies at the farm level, especially in the Sahelian zone, to reduce wind erosion and sand blasting is leading to suboptimal plant stands and replanting over large areas. This has a feedback effect on land degradation.

2.3. LATIN AMERICA

The existing climatic differences in South America are very great, climatic extremes such as the semi-arid, arid and desert are present in several countries. Due to topographic characteristics and geographical location, these climatic variations and their impact on economic activities and human beings are different from region to region.

Even though air temperature in some regions is not a limiting factor, except in the southern portion of the continent, the lack of precipitation or its irregularity is a serious problem, specially considering agricultural aspects.

Datsenko et al. (1996) analyzed the rainfall variations in the Brazilian northeast taking the city of Fortaleza as a reference. The study was carried out using the total annual precipitation data from 1849 to 1994. They observed that while the average air temperature tends to increase $0.57^{\circ}\text{C}/100\text{ yr}$, a defined tendency of increased or decreased precipitation was not observed.

Vergara et al. (2001) evaluated the precipitation trend in the 1921 to 2000 period in the northeast of the Pampa Province (Argentina), a region that is a transition area between moist and semi-arid climate which extends to the western portion of Argentina, with high vulnerability to fluctuations in rainfall pattern. For the period analyzed, a drought cycle with a peak in 1940 and lasting until 1960 was observed. Subsequently, a tendency for an increase in precipitation reaching a peak in the 1990s and with a subsequent stabilization was observed.

Scian and Donnari (1996) analyzed the history of the droughts in the semi-arid regions of Argentina using historic data from 12 locations during 1930 to 1990. Use of various indices such as the Palmer drought severity index (PDSI), rainfall abnormalities, etc. permitted the consideration of the intensity and duration of droughts and it was concluded that the most severe drought affected the region from 1936 to 1942.

Another severe drought period in Argentina was studied by Navarro et al. (1996). It was observed that 1995 was exceptionally dry, quantified both by the rainfall index abnormality and by the Hansen drought index. These indices indicated that for the region under study (Azul), since 1984 the precipitation levels were below the historic average, with a peak low decreasing until 1995.

There are close to 20 regions in the world whose climate is affected by the ENSO phases, and Latin America is also affected with different characteristics throughout the continent. In Brazil the most affected regions are the northern portion of the Northeastern Region, the Eastern part of the Amazon (tropical zone) and the Southern Region (extra-tropical zone). The most well-known climatic abnormalities and whose impacts are largest are those related to the rainfall pattern, even though the temperature pattern may also be modified.

During the positive phase, normally the northeastern region of Brazil shows an increase in the intensity of the drought with the decrease of rainfall, while in the south of Brazil the region is favoured by an increase in precipitation (Cunha, 1999).

Martelo (2000) evaluated the impact of the El-Niño phenomenon in Venezuela observing that the precipitation pattern follows this parameter as well as the temperature in the North Atlantic. Olmedo (2000) evaluated the effects of the El-Niño in the Pacific coast of the Republic of Panama, observing that the effect of this disturbance is not homogeneous in the weather behavior. When El-Niño events are sequential, they observed that in general in the first year a reduction in the number of days and in the total amount of rainfall would occur, and an increase in these two parameters would occur in the second year. They observed that the most severe phase of the El-Niño would take place in the dry period of the second year (January to March), and in 1997 the average temperature registered was 2 °C higher than the average value for some months.

Alves and Repelli (1992) analyzed the influence of El-Niño on several sub-regions in the northeast of Brazil, comparing the climatic contrast in El-Niño years in the abnormality indices of sea surface temperature (SST). They observed that there is a relationship between precipitation and the SST indices in the different phases of El-Niño, and that in both cases, there is a reduction in rainfall in the Brazilian northeast.

Moschini et al. (1996), studying the effects of the El-Niño in the region of the Pampas (Argentina), observed a close relationship between the increase or decrease of rainfall depending on the warm or cold phase of the phenomenon respectively, which was also observed by Cunha (1999). In both the studies, the authors proposed agricultural techniques to mitigate the adverse effects of these abnormalities.

Dias and Rebella (1996) evaluated the probability of changes in monthly rainfall patterns in the Pampas region (Argentina), due to El-Niño. They detected that in 78% of the cases the probability of rain in the 1961–1990 series increased when compared with the 1921–1955 series.

Marengo (2001) and Marengo et al. (2001) analyzed the various conditions and forecast models of climatic changes in Brazil and Latin America and concluded that the study of climatic changes as well as the different scenarios to be determined need better qualification and quantification for Latin America. The authors emphasized that detailed studies of these aspects, which conclusively point out the changes or tendencies of average or extreme climate, that identify a regional warming, are scarce. Although in some regions systematic changes in rainfall or in temperature are shown, they attribute this to changes over 10 yr periods such as those which occurred in the Amazon in the period.

Cunha et al. (2001) observed that in those years of the El-Niño phenomenon, the southern region of Brazil and part of Argentina and Uruguay are favored by above average rainfall. On the other hand, evaluating the El-Niño and La-Niña events from 1938 to 1998 regarding the barley crops, they concluded that in most cases La-Niña had a positive impact and El-Niño a negative one.

More recently, the standardized precipitation index (SPI) (Mckee et al., 1993) was employed to monitor and quantify the dry periods in various regions of Latin America (Seiler and Bressan, 2000; Brunini et al., 2000). Murphy et al. (2001)

correlated the SPI values with the productivity of the corn crop in Argentina. The correlation coefficient between SPI and yield was significant ($r^2 = 0.78$). Dos Anjos and Santos (2001) evaluated the correlation between the SPI values and the El-Niño and La-Niña phenomenon for the semi-arid region in the Brazilian Northeast. They observed that in the phase in which these abnormalities had greatest impact were correlated with the values of SPI-6 and SPI-9.

Through a system of dynamic monitoring, Solano Ojeda et al. (2000) determined the advance of droughts, the most affected regions and the crops that suffered the impact of this abnormality during the 1998 and 1999 period in Cuba. They observed that the frequent climatic abnormalities registered in Cuba in the last decades culminating with the 1998/1999 period, had a noticeable negative impact on all socio-economic activities. Among the adverse phenomena, drought was most outstanding, since it duplicated its chance of occurrence as well as increased considerably the extremes and intensity.

Andressen et al. (2000) evaluated the changes in precipitation of the Bolivian high plains and the effects of these variations in the desertification and drought processes. Desertification in this area is highly relevant, since 41% of the area in Bolivia was subject to this phenomena (MDSMA, 1996, cited by Andressen et al., 2000). The authors also showed that the loss of productive land amounts to 1.8 million tons per year. The variations in precipitation observed in this period were large with amplitudes up to 5000% and with highly elevated inter-annual and special oscillation. Comparing the aridity index with the P/ETP, the authors concluded that for all locations of the Bolivian high plains, 75% of the months were classified as very dry or extremely dry.

Silvia et al. (1991) observed that the rainfall distribution and the stability of the rainfall pattern in the northeast of Brazil are intrinsically related. By analyzing the annual values for temperature and rainfall in 34 locations of the Brazilian northeast and the humidity index terms according to Thornthwaite (1948), the authors concluded that there is not a strong correlation between the intensity of the drought and possible climatic changes in the arid region.

A typical case of arid region can be defined through the evaluation of the conditions of the State of Rio Grande do Norte in the Brazilian northeast, located in the area of the Drought Polygon (Medina and Maia Neto, 1991). The study showed that the region above presented serious limitations for operational and profitable agriculture due to the long periods of drought. Even irrigation may be affected, if techniques for the preservation of the reservoirs are not adopted.

The inter-annual and intra-annual variations for two locations representing the semi-arid and the sub-tropical regions are presented in Figure 4. During the El Niño years, rainfall is considerably reduced in the semi-arid regions, while in the sub-tropical area such a reduction was not so noticeable.

The use of irrigation to complement the lack of precipitation has substantially increased in the arid and semi-arid regions of Latin America. However, the most important element to keep the reservoirs at an adequate level for these practices is

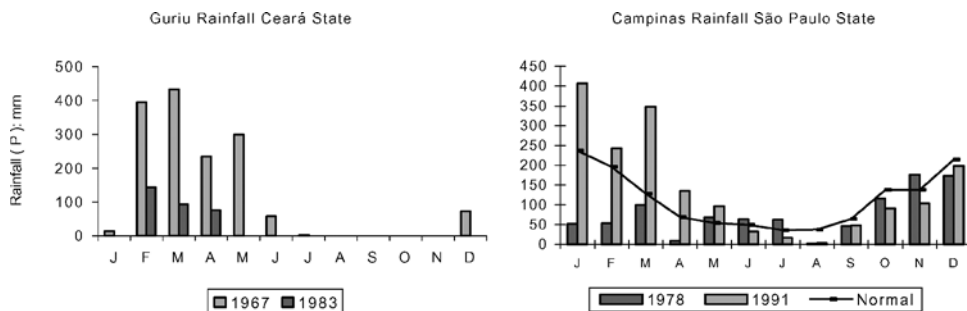


Figure 4. Seasonal rainfall variability in a semi-arid region (Gurui) and a sub-tropical region (Campinas) in Brazil.

rainfall, responsible for maintaining the volume of the reservoirs and underground water.

3. Future Climate Change Scenarios in the Arid and Semi-Arid Tropics

3.1. ASIA

The multi-century control integration of atmosphere-ocean global climate models (AOGCMs) unforced by anthropogenic changes in atmosphere composition offer an excellent opportunity to examine the skill of individual models in simulating the present-day climate and its variability on regional scales. Climate change scenarios based on an ensemble of results as inferred from skilled AOGCMs for Asia on annual and seasonal mean basis are discussed in IPCC (2001a). As a result of increases in the atmospheric concentration of GHGs the projected area-averaged annual mean warming is likely to be $1.6 \pm 0.2^\circ\text{C}$ in the 2020s, $3.1 \pm 0.3^\circ\text{C}$ in the 2050s, and $4.6 \pm 0.4^\circ\text{C}$ in the 2080s over land regions of Asia. Under the combined influence of GHGs and sulfate aerosols, surface warming will be restricted to $1.4 \pm 0.3^\circ\text{C}$ in the 2020s, $2.5 \pm 0.4^\circ\text{C}$ in the 2050s and $3.8 \pm 0.5^\circ\text{C}$ in the 2080s.

Lal et al. (1995) suggested that the surface air temperature over the Indian subcontinent (area-averaged for land regions only) is likely to rise from 1.0°C (during the monsoon) to 2.0°C (during the winter) by the middle of the next century. The rise in surface temperature could be quite significant across the semi-arid regions of NW India. The increase in surface air temperature simulated by regional climate model (RCM) over central and northern India is not as intense as in the general circulation model (GCM) and does not extend as far south (Hassel and Jones, 1999). These anomalies are linked with changes in surface hydrological variables. Over the south Asia region, a decrease in DTR on an annual mean basis during the winter and a more pronounced decreased in DTR during the summer are projected. The significantly higher decrease in DTR over south Asia during the summer is a result of the presence of monsoon clouds over the region

(Lal et al., 1996). For tropical Asia, Whetton (1994) suggested that warming would be least in the islands and coastal areas throughout Indonesia, the Philippines and coastal south Asia and Indo-China and greatest in inland continental areas of south Asia and Indo-China, except from June to August in south Asia, where reduced warming could occur.

AOGCMs projected an area-averaged annual mean increase in precipitation of $3 \pm 1\%$ in the 2020s, $7 \pm 2\%$ in the 2050s, and $11 \pm 3\%$ in the 2080s, over the land regions of Asia as a result of future increases in the atmospheric concentration of GHGs. Under the combined influence of GHGs and sulphate aerosols, the projected increase in precipitation is limited to $2 \pm 1\%$ in the decade 2020s, $3 \pm 1\%$ in 2050s, and $7 \pm 3\%$ in the 2080s. The models show high uncertainty in projections of future winter and summer precipitation over south Asia (with or without direct aerosol forcings). The effect of sulfate aerosols on Indian summer-monsoon precipitation is to dampen the strength of monsoon compared with that seen with GHGs only (Roeckner et al., 1999). Projected changes in temperature, diurnal temperature range and precipitation over tropical south Asia are presented in Table I.

On an annual mean basis, the area-averaged rainfall over the land regions of the Indian subcontinent is expected to marginally decline by the middle of the next century. No significant change in rainfall is projected during the winter months (January–February). During the monsoon season, a decline of about 0.5 mm day^{-1} in rainfall over the central plains of India is likely. The simulated decline in monsoon rainfall is due to a decrease in high intensity rainfall events throughout the season and is found to be statistically significant at 90% confidence level. Moreover, a decline in the frequency of heavy rainfall spells ($>10 \text{ mm day}^{-1}$) is likely. No significant changes are discernible in the inter-annual variability of monsoon rainfall in enhanced CO_2 simulations with respect to those in the control simulation.

Whereas an increase in rainfall is simulated by RCM (Hassel and Jones, 1999) over the eastern region of India, northwestern deserts see a small decrease in the absolute amount of rainfall. Changes in soil moisture broadly follow those in precipitation except in eastern India, where they decrease as a result of enhanced drainage from the soil. The largest reductions (precipitations reduced to $<1 \text{ mm day}^{-1}$; 60% decline in soil moisture) are simulated in the arid regions of northwest India and Pakistan. Relatively small climate changes cause large water resource problems in many areas, especially in the semi-arid regions such as NW India. If water availability decreases in this region, it could have significant implications for agriculture for water storage and distribution and for generation of hydroelectric power. For example, under the assumed scenario of a 1°C to 2°C temperature increase, coupled with a 10% reduction in precipitation, a 40 to 70% reduction in annual runoff could occur.

Recent observations suggest that there is no appreciable long term variation in the total number of tropical cyclones observed in the north Indian, southwest

TABLE I
Projected changes in surface air temperature (top), diurnal temperature range (middle) and precipitation (bottom) over tropical South Asia as a result of future increases in greenhouse gases

Temperature change (°C)			
	2020	2050	2080
Annual	1.36 (1.06)	2.69 (1.92)	3.89 (2.98)
Winter	1.62 (1.19)	3.25 (2.08)	4.25 (3.25)
Summer	1.13 (0.97)	2.19 (1.81)	3.20 (2.67)
Change in Diurnal Temperature Range (°C)			
Annual		-0.27 (-0.22)	-0.45 (-0.31)
Winter		-0.27 (0.14)	-0.46 (-0.31)
Summer		-3.06 (-4.97)	-2.89 (-4.95)
Precipitation change (%)			
Annual	2.9 (1.0)	6.8 (-2.4)	11.0 (-0.1)
Winter	2.7 (-10.1)	-2.1 (-14.8)	5.3 (-11.2)
Summer	2.5 (2.8)	6.6 (0.1)	7.9 (2.5)

Note. Numbers in parenthesis are changes when direct effects of sulphate aerosols are included (adapted from IPCC, 2001).

Indian, and southwest Pacific Oceans east of 160 °E (Neumann, 1993; Lander and Guard, 1998). Some of these studies (Krishnamurthi et al., 1998; Royer et al., 1998) suggest an increase in tropical storm intensities with carbon dioxide (CO₂) induced warming. Some of the most pronounced year-to-year variability in climate features in many parts of Asia including arid and semi-arid tropics has been linked to ENSO. Meehl and Washington (1996) indicate that future seasonal precipitation extremes associated with a given ENSO event are likely to be more intense in the tropical Indian Ocean region; anomalously wet areas could become wetter, and anomalously dry areas could become drier during future ENSO events. Several recent studies (Kitoh et al., 1997; Lal et al., 2000) have confirmed

earlier results indicating an increase in interannual variability of daily precipitation in the Asian summer monsoon with increased GHGs. The intensity of extreme rainfall events is projected to be higher in a warmer atmosphere, suggesting a decrease in return period for extreme precipitation events and the possibility of more frequent flash floods in parts of India, Nepal and Bangladesh. However, Lal et al. (1995) found no significant change in the number and intensity of monsoon depressions (which are largely responsible for the observed interannual variability of rainfall in central plains of India) in the Bay of Bengal in a warmer climate.

3.2. AFRICA

In view of the uncertainties in GCMs, it is important to interpret model outputs in the context of their uncertainties and to consider them as potential scenarios of change for use in sensitivity and vulnerability studies. While there is a good degree of certainty regarding future increases in atmospheric CO₂ concentrations and there is confidence in the range of projections of global-mean temperature and sea level, there are many uncertainties about regional patterns of precipitation and soil moisture. Much less is known about the frequencies and intensities of extreme events.

With respect to temperature, future annual warming across Africa is projected to range from 0.2 °C per decade to more than 0.5 °C per decade (Hulme et al., 2001). This warming is the greatest over the interior of the semi-arid margins of the Sahara and central southern Africa. Land areas may warm by 2050 by as much as 1.6 °C over the Sahara and semi-arid parts of southern Africa (Hernes et al., 1995; Ringius et al., 1996). Equatorial countries (Cameroon, Uganda, and Kenya) might be about 1.4 °C warmer. Sea-surface temperatures in the open tropical oceans surrounding Africa will rise by less than the global average (i.e., only about 0.6–0.8 °C); the coastal regions of the continent, therefore, will warm more slowly than the continental interior.

Future changes in mean seasonal rainfall in Africa are less well defined. Rainfall changes projected by most GCMs are relatively modest, at least in relation to present-day rainfall variability. Under the two intermediate warming scenarios, significant decreases (10 to 20%) in rainfall during March to November are apparent in North Africa in almost all models by 2050. In southern Africa, decreases of 5–15% in rainfall during the growing season during November to May are projected. Seasonal changes in rainfall are not expected to be large; Joubert and Tyson (1996) found no evidence for a change in rainfall seasonality among a selection of mixed-layer and fully coupled GCMs. Hewitson and Crane (1998) found evidence for slightly extended later summer season rainfall over eastern South Africa (though nowhere else), based on a single mixed-layer model prediction. Great uncertainty exists, however, in relation to regional-scale rainfall changes simulated by GCMs

(Joubert and Hewitson, 1997). Under the most rapid global warming scenario, increasing areas of Africa experience changes in rainfall that exceed one sigma level of natural variability. Parts of the Sahel could experience rainfall increases of as much as 15% over the 1961–1990 average. Equatorial Africa could experience a small (5%) increase in rainfall. These rainfall results are not consistent: different climate models, or different simulations with the same model, yield different patterns. The problem involves determining the character of the climate change signal on African rainfall against a background of large natural variability compounded by the use of imperfect climate models.

Little can be said yet about changes in climate variability or extreme events in Africa. Rainfall may well become more intense, but whether there will be more tropical cyclones or a changed frequency of El Niño events remains largely in the realm of speculation. The combination of higher evapotranspiration and even a small decrease in precipitation could lead to significantly greater drought risks. An increase in precipitation variability would compound temperature effects.

Changes in sea level and climate in Africa might be expected by the year 2050. Hernes et al. (1995) project a sea-level rise of about 25 cm. There will be subregional and local differences around the coast of Africa in this average sea-level rise – depending on ocean currents, atmospheric pressure, and natural land movements – but 25 cm by 2050 is a generally accepted figure (Joubert and Tyson, 1996). For Africa south of the Equator, simulated changes in mean sea-level pressure produced by mixed-layer and fully coupled GCMs are small (~ 1 hPa) – smaller than present-day simulation errors calculated for both types of models (Joubert and Tyson, 1996). Observed sea-level pressure anomalies of the same magnitude as simulated changes are known to accompany major large-scale circulation adjustments associated with extended wet and dry spells over the subcontinent.

The temperature-precipitation- CO_2 forcing of seasonal drought probably is less significant than the prospect of large-scale circulation changes that drive continental droughts that occur over several years. A change in the frequency and duration of atmosphere-ocean anomalies, such as the ENSO phenomenon, could force such large-scale changes in Africa's rainfall climatology. However, such scenarios of climate change are not well developed at the global level, much less for Africa.

3.3. LATIN AMERICA

The arid and semi-arid tropics are the ones suffering greatest impacts from climatic fluctuations from adverse phenomena such as the El Niño and La Niña. Government actions should focus on the scenery of these fluctuations, and how to mitigate its possible effects.

The IPCC report (2001a) calls for a troubling situation regarding possible global warming. There are estimates of an increase between 1.4 and 5.8 °C, taking 1990

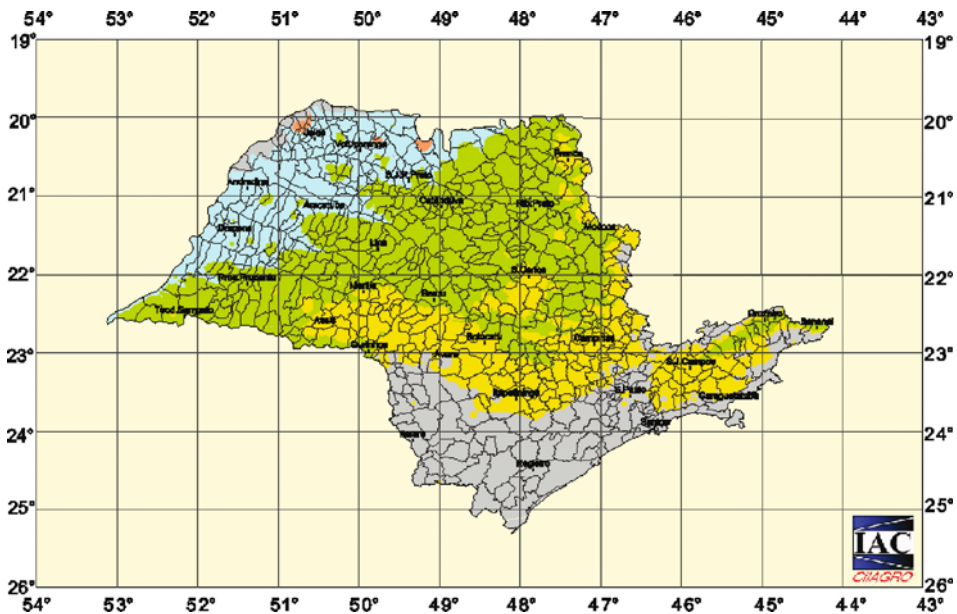


Figure 5. Climatic risk zoning for coffee crop in São Paulo State, Brazil (Pinto et al., 2000).
■ Favourable; ■ Temperature restriction; ■ Water restriction-irrigation necessary; ■ Seasonal frost; ■ Unfavourable.

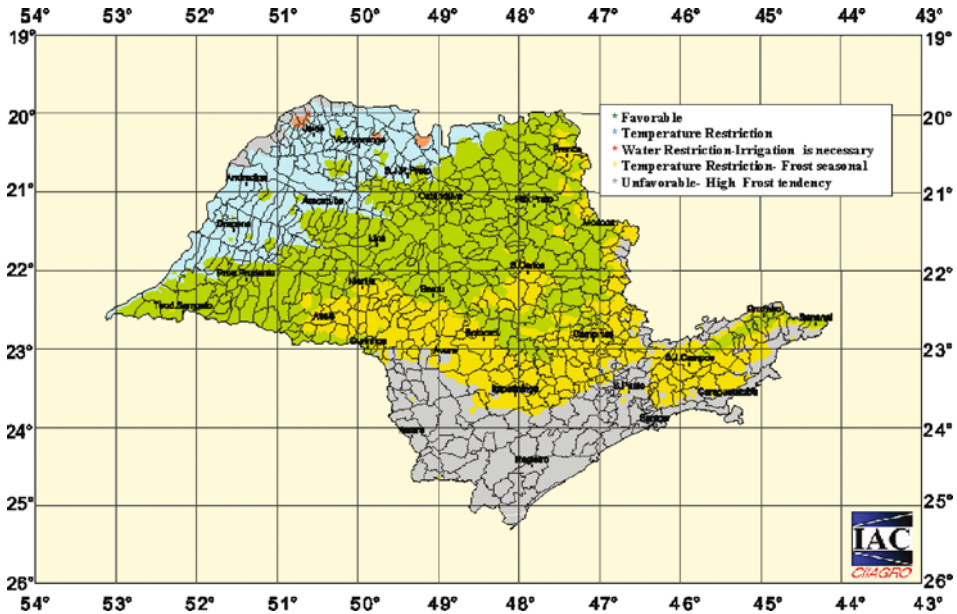


Figure 6. New scenarios for coffee producing areas in São Paulo State, Brazil, considering a climate change scenario as described by IPCC (Pinto et al., 2001).

as reference. Even though there are discrepancies about the absolute values for the increase in temperature, everyone agrees that there will be a slight increase in global temperature, and an increase in precipitation as well (Pinto et al., 2001a). Agricultural exploitation in the semi-arid and arid tropic regions will undoubtedly be greatly affected by these temperature increments.

For example, for the coffee crop, largely cultivated in the tropics, it is possible to predict the impact of possible climatic changes and on its cultivation. Pinto et al. (2000) outlined the ecologically viable areas for agricultural exploitation of this crop in the State of São Paulo (BR). On the basis of mean historical temperature values and precipitation and water balance, areas suitable for agriculture were determined (Figure 5). Assuming an average increase in temperature of 1.0 °C and an increase in precipitation of approximately 15% and by recalculating the water balance, it was shown that the areas suitable for cultivation were drastically reduced as indicated in Figure 6 (Pinto et al., 2001b). It is important to evaluate these scenarios with care, since some assumptions were made concerning water availability in the soil. Besides, this simulation indicates a trend for the next 100 yr while assuming that the current trends in global warming would continue. It is important to note that no allowance was made for changes in crop and irrigation management and genetic improvements.

4. Impacts of Climate Variability and Change in the Arid and Semi-Arid Tropics

4.1. ASIA

As reported in IPCC (1998), stress on water availability in Asia is likely to be exacerbated by climate change. Several studies aimed at understanding the nature and magnitude of gains/losses in the yield of particular crops at selected sites in Asia under elevated CO₂ conditions have been reported in the literature (e.g., Luo and Lin, 1999). These studies suggest that, in general, areas in mid- and high-latitudes will experience increases in crop yield, whereas yields in areas in the lower latitudes will decrease. Generally, climatic variability and change will seriously endanger sustained agricultural production in tropical Asia in coming decades. The scheduling of the cropping season as well as the duration of the growing period of the crop would also be affected.

Agricultural productivity in tropical Asia is sensitive not only to temperature increases, but also to changes in the nature and characteristics of monsoon. An increase in leaf-surface temperature would have significant effects on crop metabolism and yields, and it may make crops more sensitive to moisture stress (Riha et al., 1996). Experiments in India reported by Sinha (1994) found that higher temperatures and reduced radiation associated with increased cloudiness caused spikelet sterility and reduced yields to such an extent that any increase in dry-matter production as a

result of CO₂ fertilization proved to be no advantage in grain productivity. Similar studies conducted recently in Indonesia and the Philippines confirmed these results. Amien et al. (1996) found that rice yields in east Java could decline by 1% annually as a result of increases in temperature. In tropical Asia, though wheat crops are likely to be sensitive to an increase in maximum temperature, rice crop would be vulnerable to an increase in minimum temperature. The adverse impacts of likely water shortage on wheat productivity in India could be minimized to a certain extent under elevated CO₂ levels; these impacts, however, would be largely maintained for rice crops, resulting in a net decline in rice yields (Lal et al., 1998). Acute water shortage conditions combined with thermal stress should adversely affect wheat and, more severely, rice productivity in India even under the positive effects of elevated CO₂ in the future.

Simulations of the impact of climate change on wheat yields for several locations in India using a dynamic crop growth model, WTGROWS, indicated that productivity depended on the magnitude of temperature change. In North India, a 1 °C rise in the mean temperature had no significant effect on potential yields, though an increase of 2 °C reduced potential grain yields at most places (Aggarwal and Sinha, 1993). In a subsequent study, Rao and Sinha (1994) used the CERES-Wheat simulation models and scenarios from three equilibrium GCMs and the transient GISS model to assess the physiological effects of increased CO₂ levels. In all simulations, wheat yields were smaller than those in the current climate, even with the beneficial effects of CO₂ on crop yield; and yield reductions were due to a shortening of the wheat-growing season, resulting from temperature increase scenario. Wheat yield decreases could have serious impacts on food security in India, in view of the increasing population and its demand for grains. Most of the wheat production in India comes from the northern plains mostly belonging to semi-arid zone. In this tract, it is almost impossible to increase the present area of wheat under irrigation. Karim et al. (1996) also have shown that wheat yields are vulnerable to climate change in Bangladesh. Studies on the productivity of sorghum showed adverse effects in rainfed areas of India (Rao et al., 1995). Results were similar for corn yields in the Philippines (Buan et al., 1996). The likely impact of climate change on the tea industry of Sri Lanka was studied by Wijeratne (1996). He found that tea yield is sensitive to temperature, drought, and heavy rainfall. An increase in the frequency of the droughts and extreme rainfall events could result in a decline in tea yield, which would be greatest in the low-country regions (<600 m).

In Asia, where rice is one of the main staple foods, production and distribution of rice-growing areas may be affected substantially by climate change. Disparity between rice-producing countries is already visible and it is increasingly evident between developed and developing countries. The projected decline in potential yield and total production of rice in some Asian countries, because of changes in climate and climate variability would have a significant effect on trade in agricultural commodities, hence on economic growth and stability (Matthews et al., 1995).

Studies of the potential regional impacts of climate change on the forests and forestry of tropical Asia are limited. Results of research from Thailand suggest that climate change would have a profound effect on the future distribution, productivity, and health of Thailand's forests. Using climate change scenarios generated by the UKMO and GISS GCMs, Boonpragob and Santisirisomboon (1996) estimated that the area of sub-tropical forest could decline from the current 50% to either 20 or 12% of Thailand's total forest cover (depending on the model used), whereas the area of tropical forests could increase from 45 to 80% of total forest cover. Somaratne and Dhanapala (1996) used the same model for Sri Lanka and estimated a decrease in tropical rainforest of 2–11% and an increase in tropical dry forest of 7–8%. A northward shift of tropical wet forests into areas currently occupied by tropical dry forests also is projected. In semi-arid regions of tropical Asia, tropical forests generally are sensitive to changes in temperature and rainfall, as well as changes in their seasonality. Arid and semi-arid lands often carry a sizeable representation of trees and shrubs in the vegetative cover. Changes in climatic condition would affect all productivity indicators of forest (NPP, NEP and NBP) and their ability to supply goods and services. Fires, which are also influenced by these changes, significantly affect the structure, composition, and age diversity of forests in the region. Enhanced level of global warming is likely to make forest fire more frequent in arid and semi-arid regions of Asia. Deforestation along with the potential impacts of climate change, may have a negative impact on sustainable-nutrition security in south Asia (Sinha and Swaminathan, 1991).

The effect of climate change on soil erosion and sedimentation in mountain regions of tropical Asia may be indirect but could be significant. An erosion rate in the range of 1–43 tons ha⁻¹ with an average of 18 tons ha⁻¹ was calculated in three small experimental plots in central Nepal. Part of generated sediment may be deposited on agricultural lands or in irrigation canals and streams, which will contribute to deterioration in crop production and in the quality of agricultural lands. The impact of climate change on coastal areas in tropical Asia could be severe and in some areas catastrophic. The combined effects of subsidence and sea level rise could cause serious drainage and sedimentation problems in addition to coastal erosion and land loss in deltaic areas of tropical Asia.

Climate change is likely to cause environmental and social stress in many of Asia's rangelands and drylands. Precipitation is scarce and has a high annual variance in dryland areas of tropics. Very high daily temperature variance is recorded with frequent sand storm, dust ghost and intense sunshine. Nutrient contents of the soils are low. Being exposed to degradation as a result of poor land management, soils could become infertile as a result of climate change. Temperature increases would have negative impacts on natural vegetation in desert zones. Plants with surface root systems, which utilize mostly precipitation moisture will be vulnerable. Climate change also would have negative impacts on sheep breeding and lamb wool productivity. Because soil moisture is likely to decline in this region, the

least dryland type (dry sub-humid drylands) is expected to become semi-arid and semi-arid land is expected to become arid.

The survival rate of pathogens in winter or summer could vary with an increase in surface temperature (Patterson et al., 1999). Higher temperatures in winter will not only result in higher pathogen survival rates but also lead to extension of cropping area, which could provide more host plants for pathogens. Thus, the overall impact of climate change is likely to be an enlargement of the source, population, and size of pathogenic bacteria. Damage from diseases may be more serious because heat-stress conditions will weaken the disease-resistance of host plants and provide pathogenic bacteria with more favorable growth conditions. The growth, reproduction, and spread of disease bacteria also depend on air humidity; some diseases-such as wheat scab, rice blast, and sheath and culm blight of rice will be more widespread in tropical regions of Asia if the climate becomes warmer and wetter.

Surface water and ground water resources in the arid and semi-arid Asian countries play vital roles in forestry, agriculture, fisheries, livestock production and industrial activity. The water and agriculture sectors are likely to be most sensitive and hence vulnerable to climate change-induced impacts in the arid and semi-arid tropical Asia. Croplands in many of the countries in the region are irrigated because rainfall is low and highly variable (IPCC 2001b). The agriculture sector here is potentially highly vulnerable to climate change because of degradation of the limited arable land. Almost two-thirds of domestic livestock are supported on rangelands, though in some countries a significant share of animal fodder also comes from crop residue. The combination of elevated temperature and decreased precipitation in arid and semi-arid rangelands could cause a manifold increase in potential evapotranspiration, leading to severe water-stress conditions. Many desert organisms are near their limits of temperature tolerance. Because of the current marginality of soil-water and nutrient reserves, some ecosystems in semi-arid regions may be among the first to show the effects of climate change. Climate change has the potential to exacerbate the loss of biodiversity in this region.

4.2. AFRICA

Agriculture constitutes a large share of African economies, with a mixture of subsistence and commercial production. Forestry is an important complement to agriculture in many rural areas, but managed forests are less significant. Several reports (IPCC 2001b; Parry et al., 1988) refer to countries in the arid and semi-arid regions, especially in West Africa, as being vulnerable to projected climate change. Recently, IPCC (2001b) reinforced the concern that climate change resulting in increased frequencies of drought poses the greatest risk to agriculture. Consequently, the arid and semi-arid tropics, which are already having difficulty coping with environmental stress, are likely to be most vulnerable to climate change.

Agriculture in the semi-arid tropics of Africa, which is predominantly rainfed, is finely tuned to climate as it relies on the timely onset of rainfall and its regular distribution through the rainy season. Hence even a slow, small change towards a worsening climate can increase climatic risks. Waggoner (1992) concluded that if the present climate is a productive one, warmer and drier will hurt. In the semi-arid tropics of Africa, however, the present climate itself is marginally productive and this introduces a greater risk if climate worsens further.

Impacts of climate variability and change in the arid and semi-arid tropics of Africa can be described as those related to projected temperature increases, the possible consequences to water balance of the combination of enhanced temperatures and changes in precipitation and sensitivity of different crops/cropping systems to projected changes.

4.2.1. *Impacts Due to Projected Temperature Increases*

The general conclusion is that climate change will affect some parts of Africa negatively, though it will enhance prospects for crop production in other areas (see Downing, 1992, for case studies of agriculture in Kenya, Zimbabwe, and Senegal). Warmer climates will alter the distribution of agroecological zones. Highlands may become more suitable for annual cropping as a result of increased temperatures (and radiation) and reduced frost hazards. Although C3 crops exhibit a positive response to increased CO₂ (as much as 30% with 2xCO₂), the optimal productive temperature range is quite narrow. Some regions could experience temperature stress at certain growing periods – necessitating shifting of planting dates to minimize this risk.

Expansion of agriculture is important in the east African highlands. For example, agroecological suitability in the highlands of Kenya would increase by perhaps 20% with warming of 2.5 °C based on an index of potential food production (Downing, 1992). In contrast, semi-arid areas are likely to be worse off. In eastern Kenya, 2.5 °C of warming results in a 20% decrease in calorie production. In some lowlands, high-temperature events may affect some crops. Growth is hindered by high temperatures, and plant metabolism for many cereal crops begins to break down above 40 °C. Burke et al. (1988) found that many crops manage heat stress (with ample water supply) through increased transpiration to maintain foliage temperatures at their optimal range. Because a large portion of African agriculture is rain-fed, however, heat-related plant stress may reduce yields in several key crops – such as wheat, rice, maize, and potatoes. At the other extreme of the C3 temperature spectrum, several crops (such as wheat and several fruit trees) require chilling periods (vernalization). Warmer night temperatures could impede vernalization in plants that require chilling such as apples, peaches, and nectarines. Locations suitable for grapes and citrus fruit would shift to higher elevations. C4 crops are more tolerant, in general, to climate variations involving temperature ranges between 25 and 35 °C. These crops most often are located in warmer, drier climates; they are quite susceptible to water stress.

According to IPCC (2001a), the globally averaged surface temperature is projected to increase by 1.4 to 5.8 °C over the period 1990 to 2100. The number of days with temperature above a given value at the higher end of distribution will increase substantially and there will be a decrease in the days with temperature at the lower end of the distribution (IPCC, 2001a). In certain agroecological zones such as Southern Sahelian zone of West Africa, where the predominant soils are sandy in nature, increased *mean* temperature could affect the *maximum* temperatures at the soil surface substantially. It is conceivable that surface soil temperatures could exceed even 60 °C. Under higher temperatures, enzyme degradation will limit photosynthesis and growth. Increased temperatures will result in increased rates of potential evapotranspiration. In the long term, the very establishment and survival of species in both the managed and unmanaged ecosystems in this region may be threatened resulting in a change in the community structure.

Most livestock in Africa are herded in nomadic areas, though significant numbers are kept in paddocks on farms. Domestic animals, especially cattle, also will be affected by climate change. In the cold highlands of Lesotho, for example, animals would benefit from warmer winters, but could be negatively affected by a lowering of the already low nutritional quality of grazing.

4.2.2. *Consequences to Water Balance of the Combination of Enhanced Temperatures and Changes in Precipitation*

There is wide consensus that climate change, through increased extremes, will worsen food security in Africa. Evidence shows that certain arid, semi-arid and dry sub-humid areas have experienced declines in rainfall, resulting in decreases in soil fertility and agricultural, livestock, forest and rangeland production.

Projected temperature increases are likely to lead to increased open water and soil/plant evaporation. As a rough estimate, potential evapotranspiration over Africa is projected to increase by 5–10% by 2050. Since Africa is the continent with the lowest conversion factor of precipitation to runoff (averaging 15%), the dominant impact of global warming is predicted to be a reduction in soil moisture in sub-humid zones and a reduction in runoff. The prospect of global climate change has serious implications for water resources and regional development (Riebsame et al., 1995).

4.2.3. *Sensitivity of Different Crops/Cropping Systems*

Numerous cases of the devastating affects of interannual variability of rainfall on crop yields and national economies have been seen in the past five decades, but none more dramatic than the Sahelian droughts in the early 70s. Average yields of groundnut in Niger decreased from 850 kg/ha in 1966–1967 to 440 kg/ha by 1981 due mainly to drought and diseases (Toukouda, 1986).

Ojima et al. (1996) used the CENTURY (Parton et al., 1992) ecosystem process model of plant-soil interactions to analyze the impact of climate and atmospheric CO₂ changes on grasslands of the world, including seven of 31 sites in Africa. Ojima et al. (1996) looked at the effects of increasing CO₂ and climate, using climate

change scenarios based on the Canadian Climate Centre (CCC) and GFDL GCMs. They found that changes in total plant productivity were positively correlated to changes in precipitation and nitrogen mineralization (with nitrogen mineralization the most important factor). The response to nitrogen mineralization was consistent with the general observation that grasslands respond positively to addition of nitrogen fertilizer (Rains et al., 1975; Lauenroth and Dodd, 1978). Plant responses to CO₂ were modified in complex ways by moisture and nutrient availabilities; their results generally indicated that CO₂ enrichment had a greater effect with higher moisture stress. However, nutrient limitations reduced CO₂ responses. Ojima et al. (1996) concluded that increased atmospheric CO₂ will offset the negative effects of periodic droughts, making grasslands more resilient to natural (and human-induced changes in) climate variability. The strength of this beneficial effect, however, is controlled by the availability of nitrogen and other nutrients, which tend to be limited in many African landscapes.

In Africa, most mid-elevation ranges, plateaus, and high-mountain slopes are under considerable pressure from commercial and subsistence farming activities (Rogers, 1993). Mountain environments are potentially vulnerable to the impacts of global warming. This vulnerability has important ramifications for a wide variety of human uses – such as nature conservation, mountain streams, water management, agriculture, and tourism (IPCC 1996, WG II, Section 5.2).

Using the ACRU/CERES hybrid model – one of the most sophisticated crop-climate models developed in Africa – Schulze et al. (1996) have evaluated the impact of climate change on maize in South Africa. The investigators divided the diverse geography of South Africa into 712 relatively homogeneous zones, each associated with vegetation, soil, and climate data.

Daily values of temperature (minimum and maximum), rainfall, wind speed, and solar radiation are used in the crop evaluation, based on the CERES-Maize model. Recent scenario analysis of the model (see Hulme, 1996a) shows a wide range of potential maize yields in South Africa. For three scenarios of climate change (corresponding to the middle of the next century), yields decrease in the semi-arid west. For most of the country, however, potential yields would increase, generally by as much as 5 t/ha. The CO₂ enrichment effect counteracts the relatively modest changes in temperature and precipitation. In parts of the eastern highlands, particularly in Lesotho, dramatic increases in yields result from higher temperatures.

Hulme (1996b) presents an integrated view of climate impacts in southern Africa. Prospects for agriculture depend critically upon changes in precipitation. A “dry” scenario suggests less-suitable conditions in semi-arid and subhumid regions. With little decrease (or increases) in precipitation, agriculture should be able to cope with the average changes. However, shifts in drought risk need to be considered.

The extent of effects of higher temperatures on African vegetation (e.g., effects on respiration rates, membrane damage) is largely uncertain. Temperature is known to interact with CO₂ concentration, so expected increases in respiration resulting

from a temperature increase alone may be offset or even reduced by higher CO₂ concentrations (Wullschlegel and Norby, 1992).

The direct impacts of changes in the frequency, quantity, and intensity of precipitation and water availability on domestic animals are uncertain. However, increased droughts could seriously impact the availability of food and water – as in southern Africa during the droughts of the 1980s and 1990s (IPCC, 2001b).

Agricultural pests, diseases, and weeds also will be affected by climate change. Little quantitative research on these topics has been undertaken in Africa, however. Perhaps the most significant shifts could occur in tsetse fly distributions and human disease vectors (such as mosquito-borne malaria). Tsetse fly infestation often limits where livestock can be kept or the expansion of extensive agriculture (Hulme, 1996a). Declining human health would affect labor productivity in agriculture.

4.3. LATIN AMERICA

The climatic variations observed in Latin America, both in large scale and regional aspects, carry incisive socio-economic impacts on the populations involved. Agriculture and water resources are most affected through the impact of extreme temperatures (excessive heat, frost) and the changes in rainfall (drought, flooding). However, the variations that have a long-lasting effect and that bring the most damage to society are the dry periods and droughts.

As a matter of fact, there is evidence that many of the pre-Colombian civilizations had a severe decline in their culture caused by excessive drought or flooding; abnormalities associated with the El Niño phenomenon. The large variations in rainfall, which cause either drought or flooding in these areas, are associated with the El Niño and La Niña phenomena. In many cases, however, there is a joint effect between these and the variations in the temperature of the surface of the North Atlantic Ocean (Alves and Repelli, 1992).

Climatic risk zoning areas for maize in São Paulo State, Brazil, for sowing period

Peru is a typical example of a country, where El-Niño impacts and its distinct phases (cold and warm) affect the whole country, with damaging effects on agriculture. The effects observed during the 97/98 episode were droughts, frosts and flooding in different regions of the country, causing losses in over two million hectares of crop land with a reduction in crop yields of up to 50% (Cotrina, 2000).

The impact of climatic variables on economic activities, especially on agriculture, must be analyzed in a careful and pragmatic manner and remedial actions must be pro-active in order to mitigate the effects of these climatic variations. From the standpoint of food and fibre production, the remedial actions should be based on scenarios to predict the likely effects. This can be done through statistical analysis of meteorological elements, the occurrence of meteorological and adverse phenomena and how the various crops react to this negative impact. Currently, one of the tools used to reduce the impact of these climatic variations, is the climatic

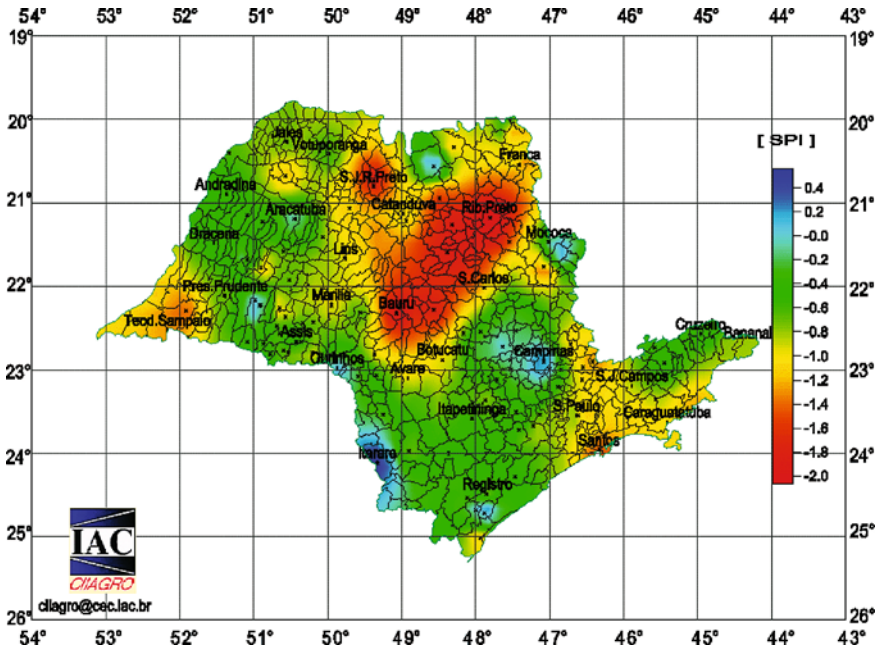


Figure 9. 24-month standardized precipitation index (SPI) by end of October 2001 in the State of São Paulo, Brazil.

support to financing programs and agricultural crop insurance allowing the farmer a minimum economic profitability.

In order to follow-up on the effects of the climatic impacts on the various activities, a continuous and systematic monitoring of the meteorological variables, plant response and the effect on economic and social activities is necessary. Several countries in Latin America (Brazil, Cuba, Argentina, Venezuela, Chile among others) have developed this type of work (Ojeda et al., 2000, Brunini et al., 2000, 2001a). In the case of Brazil, more detailed information is available from the Integrated Agrometeorological Information Center (CIAGRO) in the State of São Paulo, with the emission of two bulletins weekly to support the activities of the various economic sectors (Brunini et al., 1996). Recently, the SPI was introduced in order to quantify the drought, indicating the impact of the drought in the 1999/2001 period throughout the State (Figure 9). This methodology was useful to support government decision on irrigation policies and water resources management (Brunini et al., 2001b)

The different existing ecosystems in Latin America are subject to a wide variety of impacts, making it impossible to establish a general rule. Nevertheless, in many cases the actions of human beings contribute substantially to the fragility of these ecosystems eg., deforestation in the Amazon region, fires in the central western regions in Brazil, inadequate irrigation management and pollution in southeast Brazil, such as the São Paulo city metropolitan area, etc. Other examples could be

cited in other countries, however, naming every single one would be too excessive in detail.

5. Adaptation Potential in the Arid and Semi-Arid Tropics

5.1. ASIA

Adaptation to climate change in arid and semi-arid tropics of Asian countries depends on the cost of adaptive measures, existence of appropriate institutions, access to technology, and biophysical constraints such as land and water resource availability, soil characteristics, genetic diversity for crop breeding (e.g., development of heat-resistant rice cultivars), and topography. Adaptation measures designed to anticipate the potential effects of climate change could help to offset many of the negative effects. Adaptation measures that ameliorate the impacts of present-day climate variability include sea defences, institutional adaptations, plant breeding and adoption of new technologies in agriculture.

Sustainable development within tropical Asia's agroecosystems is crucial to provide adequate food security for traditional farming communities in developing countries and to ensure *in situ* conservation of crop biodiversity for sustaining high-input modern agriculture itself. Traditional societies have always manipulated biodiversity to ensure ecosystem resilience and to cope with uncertainties in the environment, rather than to increase production on a short-term basis. There is increasing evidence now to suggest that one could learn from their traditional ecological knowledge base (Gadgil et al., 1993) for coping with uncertainties associated with global change.

The resilience of agricultural practices in the face of climate change depends on the nature and magnitude of region-specific climate change, and the threshold and adaptive capacity of agricultural communities. Adjustment of planting dates to minimize the effect of temperature increase-induced spikelet sterility can be used to reduce yield instability, by avoiding having the flowering period to coincide with the hottest period. Adaptation measures to reduce the negative effects of increased climatic variability as normally experienced in arid and semi-arid tropics may include changing the cropping calendar to take advantage of the wet period and to avoid extreme weather events (e.g., typhoons and storms) during the growing season. Crop varieties that are resistant to lodging (e.g., short rice cultivars) may withstand strong winds during the sensitive stage of crop growth. A combination of farm-level adaptations and economic adjustments such as increased investment in agriculture infrastructure and reallocation of land and water would be desired in the agricultural sector (IPCC, 2001b). Other adaptive options included developing cultivars resistant to climate change; adopting new farm techniques that will respond to the management of crops under stressful conditions, plant pests and disease;

design and development of efficient farm implements; and improvement of post-harvest technologies, which include among other things, the use and processing of farm products, by-products and agricultural waste.

A commonly prescribed adaptation to climate change in the water sector is to enhance characteristics that offer flexibility hence enhancing resilience. Flexibility issues are particularly important with regard to the development of water resources for industry or agriculture. If hydrological patterns change markedly and irrigated agriculture is required to relocate in response, prior investment may be lost as existing infrastructures become obsolete, and additional investments will be needed. This necessitates critical scrutiny of a range of available choices that incorporate economic and environmental concerns. The potential for adaptation should not lead to complacency (Rosenzweig and Hillel, 1995).

Studies have shown that ecologically important keystone species often are socially selected by many rural societies. The possibility for species selection for rehabilitating a degraded ecosystem should be based on a value system that the local people understand and appreciate; therefore, their participation in the process of developmental activity is important. Community perceptions of soil and water management can be a powerful agent for sustainable management of natural resources. In other words, natural resource management in tropical Asia must be sensitive to social and even cultural perceptions (Ramakrishnan, 1998), as well as traditional resource management practices.

The major impact of climate change in arid and semi-arid Asia is likely to be an acute shortage of water resources associated with significant increases in surface air temperature. Conservation of water used for irrigated agriculture, therefore, should be given priority attention. With increased evapotranspiration, any adaptation strategy in agriculture should be oriented toward a shift from conventional crops to types of agriculture that are less vulnerable to evapotranspiration loss (Safriel, 1995). Expansion of commercial and artesian fisheries also could help reduce dependence on food productivity. Protection of soils from degradation should be given serious consideration. Trying out salt water resistant varieties of crops in the areas where drainage is poor; diversifying agriculture and food habits of the people primarily limited to some specific cereals, improving to management of irrigation systems; implementing crop livestock integration; changing crop varieties in cropping patterns to suit changing climatic conditions; implementing agro-forestry systems etc. are the other adaptive options to be considered (Luo and Lin, 1999). Optimum use of fertilizers and ecologically clean agrotechnologies would be beneficial for agriculture.

Cropping systems may have to change to include growing suitable cultivars (to counteract compression of crop development), increasing crop intensities (i.e., the number of successive crop produced per unit area per year) or planting different types of crops (Sinha et al., 1998). Farmers will have to adapt to changing hydrological regimes by changing crops. For example, farmers in Pakistan may grow more sugarcane if additional water becomes available and they may grow less rice if

water supplies dwindle. The yield ceiling must be raised and the yield gap narrowed while maintaining sustainable production and a friendly environment. Development of new varieties with higher yield potential and stability is complementary to bridging the yield gap.

Improvements in run-off management and irrigation technology (i.e., river run-off control by reservoirs, water transfers and land conservation practices) will be crucial. Increasing efforts should be directed toward rainwater harvesting and other water-conserving practices to slow the decline in water levels in aquifers. Recycling of wastewater should be encouraged in drought-prone countries in tropical Asia.

Although the core population of the species may become extinct because of global warming, resistant types in peripheral populations will survive and can be used to rehabilitate and restore affected ecosystems (Kark et al., 1999). The geographic locations of such species usually coincide with climatic transition zones, such as at the edges of drylands or along the transition between different types of drylands. Identifying regions with concentrations of peripheral populations of species of interest and protecting their habitats from being lost to development therefore can play a role in enhancing planned adaptation for semi-arid and arid regions of Asia.

5.2. AFRICA

While there is universal agreement that the direction of climate change, especially at the regional scale, is somewhat uncertain, it should not lead us to a degree of complacency that adaptation to climate change will be easy. The importance of the rate of climate change must be assessed by comparing the rate at which the systems that might be affected change and adapt (Ausubel, 1991). Adaptations are expensive and the level of technological and economic development of a country determines the extent to which countries can cope with climatic changes.

The sensitivity of a crop to climate change depends not only on its physiological response to temperature or moisture stress, but also on other components of the system. The poor soils in the arid and semi-arid regions of Africa with low native soil fertility are a major component affecting this sensitivity. With the reduced ratio of the length of fallows to cropping years, soil fertility has been declining. According to Mudahar (1986), average use of fertilizers in the sorghum (*Sorghum bicolor* (L.) Moench) and pearl millet (*Pennisetum glaucum* (L.) R.Br.) growing countries of West Africa was only 5 kg/ha. In the absence of added manure or fertilizers on these poor soils, the nutrient reservoir of the soil under continuous cropping is dropping to levels that can no longer sustain the desired yield levels.

Whether or not there will be a significant climatic change, the inherent climatic variability in the arid and semi-arid regions of Africa makes adaptation unavoidable. Environmental problems facing this zone are serious and certain. The need for

development and implementation of sustainable agricultural strategies on a regional scale is crucial in this marginal region that is already threatened by environmental degradation. Pre-meditated adaptation that begins with anticipation and information (NAS, 1991b) is a good strategy for this region. The approaches we need should be prescriptive and dynamic rather than descriptive and static.

5.2.1. *Improve Monitoring*

In order to assess carefully the impact of future climate change on the managed and unmanaged ecosystems in the SSZ, it is crucial to monitor local climate, and natural changes in species adaptation, if any. It will be necessary to install improved methods of climate monitoring by taking advantage of recent developments in automatic weather stations, which enable easy recording of the occurrence of extreme events on a routine basis. For species adaptation, it will be useful to set up phenological gardens at benchmark sites to carefully assess the changes in their adaptation and in the duration of the developmental stages.

5.2.2. *Use Strategies for Efficient Natural Resource Use*

Increasing the promotion and strengthening of resource conservation is the first step in coping with the climate change. These strategies will include, for example: soil and moisture conservation, better moisture use efficiency, collection and recycling of run-off, reducing deforestation, increasing reforestation, and reduction of biomass burning. Strategies that can increase the water use efficiency, such as relay cropping during years with early onset of rains, are now available and should be transferred to the farm level.

5.2.3. *Implement Sustainable Agricultural Practices*

It is important to increase the emphasis on the development and adoption of technologies that may increase the productivity or efficiency of crops consistent with the principles of sustainable development. Sivakumar et al. (1991) discussed possible strategies for management of sustainable systems in the SSZ. These include techniques such as minimum/no till systems, traditional agro-silvi-pastoral systems, choice of appropriate crop varieties, intercropping/relay cropping of cereals with legumes, *Faidherbia albida* systems, mixed tree/grass/crop systems, rotations, use of manures with a limited quantity of fertilizer, and use of crop residues.

5.2.4. *Enforce Effective Intervention Policies*

One of the adaptation strategies recommended by NAS (1991) is the intervention by governments to manipulate the circumstances of choices. The criteria laid down for government action (NAS, 1991) apply to the Sudano-Sahelian zone even now:

- a) Amount of time needed to carry out the adaption is so long that we must act now.
- b) Action is profitable even when climate does not change.
- c) Penalty for waiting a decade or two is great.

The need for good, timely climate information in the drought-prone regions is too well known to be stressed. Recent developments in the information technology now make it possible to quickly acquire and sort the enormous amount of information into items relevant to the end user. Implementation of policies to provide timely information, improved weather and climate forecasts and good markets should help the farmer adapt quickly.

5.3. LATIN AMERICA

The process of potential adaptation of crops and human beings to environmental impacts in the arid and semi-arid tropics is challenging and is highly dependent on existing technologies.

In the humid tropics, where drought is not a constant phenomenon but rather a periodic abnormality, from year to year, or even in the rainy season, several agricultural practices can be used such as: direct planting, irrigation, choice of drought tolerant varieties. This has been a technological adaptation widely used in countries, such as Brazil, Argentina, Uruguay, and Paraguay among others. On the other hand, in the arid and semi-arid regions where the low rainfall is a limiting factor, the most feasible solution or technological adaptation is to use supplemental irrigation.

For this purpose, large reservoirs have been built in conjunction with power generation. In many cases perennial rivers are exploited for irrigation. These techniques are quite challenging in many cases, especially when improper irrigation methods bring about more damage to the environment by salinization of agricultural soils or depletion of scarce natural resources.

It is possible that intercropping and techniques for sustainable agriculture are more appropriate for these regions. Many options must involve a combination of efforts to reduce land degradation and foster sustainable management of natural resources.

A number of adaptive processes designed to prevent further deterioration of forest cover are already being implemented to some degree. Some of these measures involve natural responses when particular tree species develop the ability to make more efficient use of reduced water and nutrients under elevated CO₂ levels. Other adaptive measures involve human-assisted action programs (such as tree planting) designed to minimize undesirable impacts. These strategies will include careful monitoring and microassessment of discrete impacts of climate change on particular species.

6. Conclusions

The agricultural climate of the arid and semi-arid tropical regions in Asia, Africa and Latin America is characterized by low and variable rainfall and consistently

high temperatures during the growing season. Climate variability – both inter- and intra-annual – is a fact of life in these regions with a traditionally low agricultural productivity. The projected climate change and the attendant impacts on water resources and agriculture in the arid and semi-arid tropical regions add additional layers of risk and uncertainty to an agricultural system that is already impacted by land degradation due to growing population pressures. Farmers in these regions have over centuries adopted cropping strategies, such as inter cropping and mixed cropping, that minimize the risk and ensure some degree of productivity even in poor years. Such strategies are based on their understanding of natural climatic variability, but the projected climate change is not factored into this understanding. Hence it is important to examine crop responses to a range of possible changes, especially in the nature, frequencies and sequences of extreme climatic changes. Issues such as sustainability or land productivity, changes in erosion, degradation and environmental quality also need careful consideration. Improved management strategies are necessary for coping with the projected global climatic change in the arid and semi-arid tropical regions of the world.

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IMPACTS OF PRESENT AND FUTURE CLIMATE VARIABILITY ON AGRICULTURE AND FORESTRY IN THE HUMID AND SUB-HUMID TROPICS

YANXIA ZHAO^{1,2}, CHUNYI WANG¹, SHILI WANG¹ and LOURDES V. TIBIG³

¹*Chinese Academy of Meteorological Sciences, China Meteorological Administration, Beijing, China*

²*School of Physics, Peking University, Beijing, China*

³*Philippine Atmospheric, Geophysical and Astronomical Services Administration, Quezon City, Philippines*

Abstract. Although there are different results from different studies, most assessments indicate that climate variability would have negative effects on agriculture and forestry in the humid and sub-humid tropics. Cereal crop yields would decrease generally with even minimal increases in temperature. For commercial crops, extreme events such as cyclones, droughts and floods lead to larger damages than only changes of mean climate. Impacts of climate variability on livestock mainly include two aspects; impacts on animals such as increase of heat and disease stress-related death, and impacts on pasture. As to forestry, climate variability would have negative as well as some positive impacts on forests of humid and sub-humid tropics. However, in most tropical regions, the impacts of human activities such as deforestation will be more important than climate variability and climate change in determining natural forest cover.

1. Introduction

Based on the third assessment reports (TAR) of IPCC (2001), the globally averaged surface temperatures have increased 0.6 ± 0.2 °C over the 20th century with sharper increases in the mid- and high latitudes of the northern hemisphere continents. It is very likely that precipitation has increased by 0.5–1% per decade over most of the mid- and high latitudes of the northern hemisphere continents and that rainfall has increased by 0.2–0.3% per decade over the tropical land areas. Although the changes of mean climate for the tropics have not been obvious, climate variability and extreme events, (dominated by inter-decadal to multi-decadal variability) have likely increased in intensity and frequency in some places. The projected climates in the future include not only changes of mean climate such as global warming that varies with region, and increases and decreases in precipitation, but also changes in the variability of climate and changes in the frequency and intensity of some extreme climate phenomena.

Climate variability will affect agriculture and forestry through effects on crops and forests; soils; weeds, pests and diseases; and also livestock. Variation of climatic conditions across the world leads to different local and regional impacts although the humid and sub-humid tropics have much more special climates and ecosystem

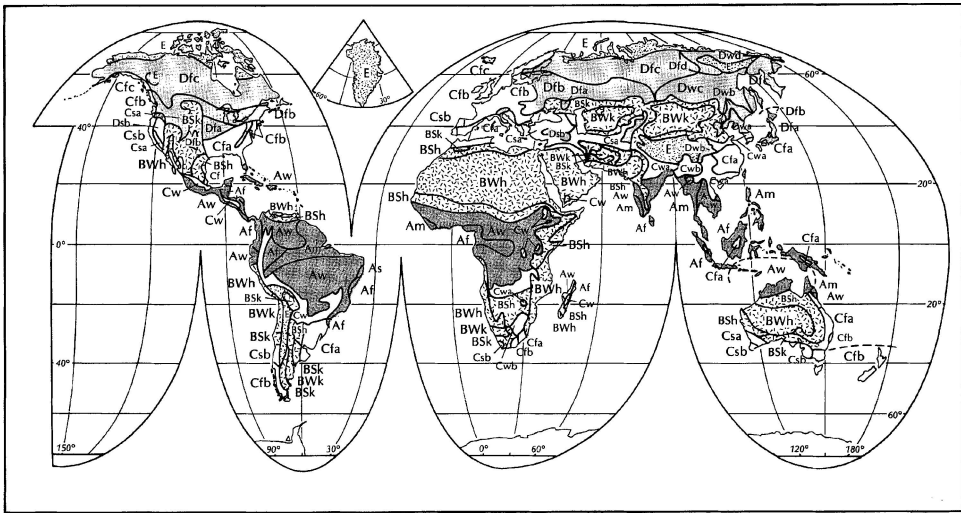


Figure 1. World map showing Koppen's climate classification (Af: tropical rainy; Aw: tropical wet-and-dry; Am: tropical monsoon).

environments. Climate variability and extreme events will definitely bring impacts on agriculture and forestry in these latitudes.

2. Characteristics of Climate of Humid and Sub-humid Tropics

Humid and sub-humid tropics usually refer to the tropical rainy climate zones and most parts of the tropical monsoon or tropical wet–dry climate zones. The tropical rainy climate prevails mainly in lowlands within 5° N and 5° S of the equator (also known as the equatorial climate). The climate is characterized by a combination of constantly high temperatures and abundant rainfall well distributed throughout the year. Humid tropics are commonly associated with the luxurious evergreen forests. The tropical monsoon climate differs from the tropical rainy climate in that it has a distinct dry season; its annual rainfall totals and temperature conditions are similar to those in the tropical rainy climate but rainfall regime is similar to that of tropical wet–dry climate. The tropical wet–dry climate has alternating wet and dry seasons. Annual rainfall totals are less than those in the tropical rainy and monsoon climates. The dry season here is severe and has a profound effect on vegetation and crops unlike in the monsoon tropical climate.

Humid and sub-humid tropical conditions are found over nearly 50% of the tropical land mass and 20% of the earth's total land surface (Figure 1). This total is distributed among three principal regions (Oliver and Hidore, 1984). Tropical Central and South America contain about 45% of the world's humid and sub-humid tropics; Africa, about 30%; and Asia, about 25%. As many as 62 countries are located partly or entirely within the region.

Tropical monsoon Asia is dominated by the two monsoons; the summer southwest monsoon influences the climate of the region from May to September, and the winter northeast monsoon controls the climate from November to February. The monsoons bring most of the region's precipitation. The equatorial monsoon climate comprises of the Indonesian archipelago, Malaysia, New Guinea and some other islands. The wet-dry monsoon climate prevails in the Indian subcontinent, including the northern parts of Sri Lanka and coastal parts of Bangladesh, Burma, Thailand and Indo-China; Philippine archipelago; and northern Australia, and southeastern Indonesia. Tropical cyclone is another important feature of the weather and climate in this region. Two core areas of cyclogenesis exist; one in the northwestern Pacific Ocean, which particularly affects Philippines and Vietnam, and the other in the northern Indian Ocean, which particularly affects Bangladesh. In addition, geographically much more extensive is the El Niño–Southern Oscillation (ENSO) phenomenon, which has an especially important influence on the climate and interannual variability of climate in a number of countries in these latitudes and also over the globe.

The region of humid and sub-humid central and western Africa consists of three main areas; the Congo Basin, between about 5° N and 5° S, the southern coast of western Africa, at latitudes between 5° N and 9° N; and the remaining parts of the region at latitudes between 15° N and 15° S. Climatic conditions differ from those in the tropical monsoon Asia in many ways. The climate of the first two areas is characterized by heavy rainfall throughout the year. Convection is the main process causing precipitation; seasonal variations are mainly the result of large-scale air-mass movements and the movements of the intertropical convergence zone (ITCZ). The common feature of this climate is the gradual decrease in the length of the rainy season and in the total amount of rainfall with latitude, basically characterized by wet-dry climate.

The most important topographic feature of Central America and the northern part of South America is the high and continuous mountain backbone of the Andes range, which has important climatological consequences. The Caribbean islands and Atlantic coastal areas of Central America all have a similar climate. The trade winds are the dominating element of its general circulation, which bring much rainfall. The Pacific side of Central America is generally drier than the Atlantic side because of the influence of the subtropical high-pressure cell over the North Pacific. The largest humid part of tropical South America lies to the east of the Andes Mountains. It is a predominantly flat area, with a low center, occupied by the Amazon Basin. The general circulation over this region, the seasonal movements of which are much smaller than over Southeast Asia or tropical Africa, is controlled by the position of the ITCZ. Although Central America and the northern part of South America are characterized largely by humid and sub-humid conditions, important areas (e.g., northeastern Brazil) are subject to droughts and floods due to the ENSO phenomenon.

Atmospheric extremes which are seen as hazards in the humid and sub-humid tropics mainly include droughts, floods, and tropical cyclones. Droughts and floods

often occur in the tropical monsoon and wet-dry climate zones. For a number of countries in tropical Asia, the major hazards are tropical cyclones and floods. Droughts, on the other hand, are severe in the northern part of South America and some regions of sub-humid Africa.

3. Features of Agriculture and Forestry in the Humid and Sub-Humid Tropics

Agriculture is very important for most countries in the humid and the sub-humid tropics. Take tropical Asia as an example. In tropical Asia, agriculture is a key economic sector. In 1993, it had employed more than half of the labor force, accounting for 10–63% of the GDP in most countries of the region (IPCC, 1998). Substantial foreign exchange earnings also are derived from exports of agricultural products. Climate-sensitive crops – such as rice, other grains and cereals, vegetables, and spices – are particularly important in this region. Rice is the most important cereal crop. About 88.5% of the world's rain-fed lowland rice is cultivated in South and Southeast Asia. In almost all the countries, rice constitutes over 80% (even 98% individually) of total cereal production. Maize and wheat are the second important cereals (IPCC, 1998).

However, there already exists some degree of vulnerability of the agriculture in the humid and sub-humid tropics due to a number of factors. Tropical Asia supports a large population so that there is a relatively high population density per hectare of intensely cultivated land. Tropical cyclones are one of the most important climatic features and often cause great damages to agriculture. Except for Africa, where food security has been a pressing problem for a number of years now, agriculture of the other countries in the humid and sub-humid tropics is also vulnerable, but with less severity than those in tropical Asia due to their moderate population density and relatively large croplands.

3.1. CROPS AND LIVESTOCK

In the wet equatorial climate zone, commercial agriculture is largely based on perennials, such as rubber, oil palm, bananas, liberica coffee and, to a lesser extent, coconut and cocoa. Some other perennials, such as arabica and robusta coffee, mango and citrus, which need a short drier and cooler spell, are not well suited to the climate. Native farming often includes a plot of fruit trees and other perennials of economic value, but roots are commonly the most important food crops, especially yams, cassava, cocoyams, dasheen or eddo and tannia. Rice is grown extensively. It thrives best in climates with a brief dry season, but the main rice-producing zones here have climates with a more pronounced dry season. Maize is the only other cereal grown appreciably, and its successful cultivation demands adapted varieties. Efficient cultivation and weed control, especially in annual crops, are difficult

because of the continuous wet weather during which, weed growth is extremely rapid and luxuriant. Soil fertility is commonly limited by nutrient deficiencies. Apart from pigs and poultry, livestock are unimportant mainly because there are no extensive natural grasslands and there are endemic diseases (Webster and Wilson, 1980).

In areas with good rainfall, usually two rainy seasons with only short dry seasons, perennial crops such as coffee, tea and bananas can be satisfactorily grown. There are two cropping seasons a year for annuals, the first commonly devoted to food crops and the second generally to cotton or vegetable. In the southern coast of west Africa, the chief perennial crops are oil palms and cocoa, while annuals are mainly maize, pulses, yams and cassava. Rice is the chief annual crop under similar climatic conditions in Southeast Asia. Owing to the absence of good natural grasslands and the presence of endemic diseases, livestock have hitherto been relatively unimportant.

In the areas with two short rainy seasons and pronounced intervening dry seasons, climatic conditions are far less suitable than the preceding type for perennial crops, except for some markedly drought-resistant types. The commonest crops are maize, sorghum, finger millet, sweet potatoes, cassava, groundnuts, beans and other pulse crops. The importance of cattle varies considerably, depending upon the presence or absence of tsetse fly and, in part, on traditional agricultural systems.

In the wet climates of the tropical windward coasts, mainly along the east of the Malagasy Republic, Central America and the northern part of South America, the high rainfall and absence of a severe dry season permit the cultivation of a wide range of perennial and annual crops, such as rice, maize, yams, tannia, dasheen, sweet potato, arrowroot, sugarcane, cocoa, coconut and nutmeg. Perennials such as coffee and citrus, which do best under more moderate rainfall and with a short dry season accompanied by lower temperatures, are commercially profitable. Crops requiring a lower rainfall and a more pronounced dry season for harvesting, such as cotton, tobacco or groundnut, are difficult in the wetter areas, but grown quite extensively in the dry parts of the zones (Webster and Wilson, 1980).

3.2. FORESTRY

Tropical forests represent about 40% of the world's forested area and contain about 60% of global forest biomass. Rainforests and monsoon forests are two major types in the humid and sub-humid tropics. Rainforests grow in ever-wet conditions where rainfall is heavy and spread throughout the year, such as in the Amazon Basin and the Congo delta. These forests are evergreen or semi-evergreen and include lowland, montane, and swamp forests. Monsoon forests grow in the Southeast Asian region where rainfall is high but unevenly spread throughout the year. Most monsoon forest trees are deciduous; they shed their leaves in the dry season. Owing to no management, under the pressure of increasing population, many of these two types of forest are degraded by logging, farming, and fire. In the Asia-Pacific region,

where most of the world's managed tropical forests are found, less than 20% of production forests receive systemic silvicultural treatment (FAO and UNEP, 1981). Only 0.2% of the world's humid and sub-humid tropical forests is being managed for sustained timber production (Poore et al., 1990).

Except large areas of tropical natural forest biome, plantation forestry also plays an important role in the humid and sub-humid tropics. Most tropical tree plantations were established after the 1960s, particularly in sub-humid and premontane tropics (Lugo, 1988). Plantations are usually established on damaged or deforested lands for sawn wood, veneer, and pulpwood production, environmental protection, or for supplying firewood. Mixed tree systems, a kind of tree plantation known as home gardens and mixed tree orchards, is also a common form for the harvest of various forest products including firewood, food for the household and marketplace, medicines, and construction materials, and the environmental benefits such as resulting in more local reforestation.

Humid and sub-humid tropical forest is one of the richest regions in biodiversity. Frontier forests in Asia are home of more than 50% of the world's terrestrial plant and animal species (Rice, 1998). Central America has about 8% of the world's biodiversity concentrated in only 0.4% of the emerged surface of the planet. But biodiversity in this region is at risk due to climate change, land-use, and population pressure.

3.3. SYSTEMS OF AGRICULTURE AND FORESTRY

The efficiency of tropical agriculture and forestry is determined by a combination of environmental factors that include climate, soil, and biological conditions, social, cultural, and economic factors. Agriculture and forestry systems and techniques that have evolved over time to meet the special environmental conditions and economic demands of the region include the paddy rice systems of Southeast Asia; terrace, mound, and drained field systems; raised bed system; and a variety of agroforestry, and shifting cultivation. Monocultural systems have been successfully introduced over large areas of the humid and sub-humid tropics, and include production of coffee, tea, bananas, citrus fruits, palm oil, rubber, sugarcane, and other commodities produced primarily for export (National Research Council, 1993).

3.3.1. *Intensive Cropping Systems*

Intensive cropping systems are concentrated in lands with adequate water, naturally fertile soils, low to modest slope, and other environmental characteristics conducive to high agricultural productivity. But the systems face critical challenges in order to respond to the food and other subsistence needs of expanding populations. Fallow period that allowed for the accumulation of nutrients and the suppression of pests have essentially been removed from the crop rotation sequence. Furthermore, pressures from pests and diseases are increasing as the area devoted to the cultivation of new varieties (Fearnside, 1987). In some countries in some regions, lowland areas that are relied on for producing staple and cash crop are in danger of becoming

unfit for crop production as a result of improper management, such as nutrient loading from fertilizers, water contamination from pesticides and herbicides, and waterlogging and salinization.

3.3.2. *Shifting Cultivation*

Shifting cultivation is one of the most widespread farming systems throughout the humid and sub-humid tropics. Temporary forest clearings are planted for a few years with annual or short-term perennial crops, and then allowed to remain fallow for a longer period than they were cropped. However, it is often labeled as the most serious land use problem in the tropical world (Grandstaff, 1981). In many of the areas, where it had formerly been practiced successfully for centuries, population and poverty pressures have forced the shortening of the fallow period and field rotation cycle and consequently, a loss of productivity.

3.3.3. *Agropastoral System*

Agropastoral systems combine crop and animal production. In Asia, the animal components of small farming operations vary with cropping systems. In lowland rice-farming areas, buffalo, cattle, fowl, and swine are commonly raised. In highland areas, swine, poultry, buffalo, and cattle are raised in combination with rice, maize, cassava, bean, and small grains. In humid Africa, these systems are dominated by crops such as rice, yams, and plantains, and animals such as goats and poultry. The small farms of Latin America typically include crop mixtures of beans, maize, and rice. Cattle, swine and poultry are dominant animals. Agropastoral systems can enhance agroecosystem productivity and stability through efficient nutrient management, integrated management of soil and water resources, and a wider variety of both crop and livestock products. At the same time, it may provide relatively high levels of income and employment in resource-poor areas.

3.3.4. *Cattle Ranching*

Livestock production in the humid part of Africa is not important as an economic activity; only few lands are cleared for cattle pasture (Brown and Thomas, 1990), and cattle are vulnerable to the effect of trypanosomiasis and tsetse fly (Linear, 1985). Cattle raising on pasturelands takes place in some countries of Southeast Asia, but it is not a significant factor in increasing deforestation since crop production systems are dominant. However, cattle ranching on a large scale has been identified as a leading contributor to deforestation and environmental degradation in the humid and sub-humid parts of Latin America where cattle raising is common due to its socio-economic and ecological importance. Overall pasture degradation is the primary problem that cattle ranching faces in the humid and sub-humid tropics (particularly evident in Latin America) due to its low soil fertility.

3.3.5. *Agroforestry System*

Agroforestry systems include a range of options in which woody and herbaceous perennials are grown on land that also supports agricultural crops or animals. Under

ideal conditions, such as a compatible association of trees, annual crops and animals, these systems offer multiple agronomic, economic, environmental, and socio-economic benefits for resource-poor small-scale farmers, including enhanced nutrient cycling, fixing of atmospheric nitrogen through the use of perennial legumes, efficient allocation of water and light, conservation of soil, natural suppression of weeds, and diversification of farm products (Lal, 1991). It is important to note, however, that trees have both positive and negative effects on soils. Negative effects include growth suppression caused by competition for limited resources (nutrients, water, and light). Mismanagement of trees (for example, through improper fertilizer application or inadequate water control) can also cause soil erosion, nutrient depletion, water logging, drought stress, and soil compaction.

4. Climate Variability

Climate variability means the alternation between the “normal climate” and a different, but recurrent, set of climatic conditions over a given region of the world (IPCC, 1998). Natural climate variability can produce floods, droughts, cyclones, heat waves, frosts, and other extremes in the humid and sub-humid tropics. GHG-induced climate change could further alter the frequency and magnitude of the climate extremes and associated disasters.

Over the past 100 years, the amount of changes of mean surface temperatures and precipitations has been less in the tropics than the global average, but either in the past climate or in the projected scenarios, climate variability, particularly multidecadal ones, are obvious (IPCC, 1998). Across the tropical Asia, there have not been observed identifiable changes in the number, frequency, or intensity of tropical cyclones in the two core regions of cyclogenesis over the past 100 years; but there is some evidence of substantial multidecadal variability of increases in the intensity or frequency of some extreme events on regional scales throughout the 20th century. Increased precipitation intensity, particularly during the summer monsoon, could increase flood-prone areas in temperate and tropical Asia. There is potential for drier conditions in sub-humid Asia during summer, which could lead to more severe drought. Many countries in temperate and tropical Asia have experienced severe droughts and floods frequently in the 20th century (IPCC, 2001). In the Latin American region, there is ample evidence of climate variability and high confidence that ENSO is responsible for a large part of the climate variability at interannual scales (TAR). For example, El Niño is associated with dry conditions in northeast Brazil, northern Amazonia, the Peruvian-Bolivian Altiplano, and Pacific coast of Central America. The most severe droughts in Mexico in recent decades have occurred during El Niño years, whereas southern Brazil and northwestern Peru have exhibited anomalously wet conditions (Horel and Cornejo-Garrido, 1986). La Nina is associated with heavy precipitation and flooding in Colombia and drought in southern Brazil (Rao et al., 1986).

TABLE I
Climate change scenarios of humid and sub-humid tropics

Regions	Temperature	Rainfall
Africa	Increase	–
Asia		
South Asia	Increase	Increase
Southeast Asia	Increase	Increase
Latin America		
Mexico	Increase	Decrease
Costa Rica		
Pacific sector	Increase	
Southeast Caribbean sector	Increase	Small increase
Nicaragua		
Pacific sector	Increase	Decrease
Caribbean sector	Increase	Decrease
Brazil		
Central and south central sector	Increase	Increase for autumn, decrease for summer

Source: Construction based on WGII TAR Sections 10.1.4, 11.1.3, 14.1.2.

For the projected climate changes based on TAR, temperature will increase and precipitation increase or decrease in humid and sub-humid tropics (see Table I). High-resolution modeling studies suggest that over some areas the peak wind intensity of tropical cyclones is likely to increase by 5–10% and precipitation rates may increase by 20–30%, but none of the studies suggest that the locations of the tropical cyclones will change. There is little consistent modeling evidence for changes in the frequency of tropical cyclones (WGI TAR Box10.2). Current projects show little changes or a small increase in amplitude for El Niño events over the next 100 years. But many models show a more El Niño-like mean response in the tropical Pacific (particularly in Latin America). Even with little or no change in El Niño strength, global warming is likely lead to greater extremes of drying and heavy rainfall and increase the risk of droughts and floods that occur with El Niño events in many different regions (WGI TAR Section 9.3.5-6, WGII TAR Section 14.1.2). In short, there is a potential for an increased occurrence of droughts, floods and heavy rainfall and some other extreme weather events in most of humid and sub-humid tropics (see Table II).

It should be noted that there is great uncertainty in projections of likely changes in tropical cyclones, El Niño and monsoons so that vulnerabilities related to these hazards are qualitative and scientists do not discount possibilities of “climate surprises” in the future (IPCC, 2001).

TABLE II

The examples of climate variability and extreme climate (related to tropics) and examples of their impacts (related to agriculture and forestry)

Projected changes during the 21st century in extreme climate phenomena and their likelihood	Representative examples of projected impacts (all high confidence of occurrence in some areas)
Higher maximum temperature, more hot days and heat waves over nearly all land areas (very likely)	Increased heat stress in livestock and wildlife Increased risk of damage to a number of crops
Higher minimum temperature, fewer cold days, frost days and cold waves over nearly all land areas (very likely)	Decrease risk of damage to a number of crops, and increased risk to others Extend range and activity of some pest and disease vectors
More intense precipitation events (very likely, over some areas)	Increased flood, landslide, and mudslide damage Increase soil erosion
Increased in tropical cyclone peak wind intensities, mean and peak precipitation intensities (likely, over some areas)	Increased damage to coastal ecosystems such as mangroves
Intensified drought and floods associated with El Niño events in many different regions (likely)	Decreased agricultural and rangeland productivity in drought- and flood-prone regions
Increased Asian summer monsoon precipitation variability (likely)	Increase in flood and drought magnitude and damages in tropical Asia

Source: Adapted from WGII TAR Table SPM-1.

5. Impacts of Climate Variability on Agriculture and Forestry

Agriculture and forestry, due to their direct dependence on climate and weather, are two of the widely studied sectors in the context of climate change. There are two aspects of climate change on agriculture: firstly, the potential direct effect of increased CO₂ and secondly, the potential effects of changes in temperature, precipitation. The changes in climate parameters could also have an influence on factors constraining their growth such as soil quality, pests, and diseases. Either in the past or at present, a number of the studies capture impacts due to change in average climate. It is widely believed, however, that changes in climate variability would imply much larger impacts than those due to changes in average climate alone. Agricultural production in lower-latitude and lower-income countries is more likely to be negatively affected by climate change (IPCC, 1996, 1998, 2001). It is seen that climate variability and climate change, particularly in terms of frequency/intensity of droughts, have larger impacts on the sub-humid than on the humid regions. If climate variability induced disasters become more common, widespread, and persistent, many countries in

the sub-humid and humid tropical regions may have difficulty in sustaining viable agricultural and forest practices. Increasing atmospheric CO₂ levels could elevate the photosynthetic rate and stimulate plant growth and will generally be beneficial to the crop and forest in the humid and sub-humid tropics.

5.1. IMPACTS ON CROP AGRICULTURE

In general, it is expected that areas in mid- and high-latitudes will experience increases in crop yield; yields in lower latitudes generally will decrease (IPCC, 2001). The response of crop yields to climate change varies, depending on the species, cultivar, soil conditions, CO₂ direct effects, and other locational factors. Based on TAR, there is high confidence that, in the tropics, where some crops are near their maximum temperature tolerance, yields would decrease generally with even minimal changes in temperature; higher minimum temperatures will be beneficial to some crops, especially in temperate regions, and detrimental to other crops, especially in low latitudes. Degradation of soil is one of the major future challenges for tropics agriculture. It is established with high confidence that this process is likely to be intensified by adverse changes in temperature and precipitation. But another important advance in research on the direct effects of CO₂ on crops suggest that beneficial effects may be greater under certain stressful conditions, including warmer temperatures and drought. So that would be a positive aspect for agriculture.

Globally, the economic impacts of climate change on agriculture are expected to be relatively minor, decreasing food production in some areas will be balanced by increases in productivity in others (Rosenzweig and Parry, 1993; IPCC, 2001). However, *based on TAR, the adaptive capacity of human systems in Africa, Asia and Latin America is low and vulnerability is high*. Changes in average climate conditions and climate variability could have significant effects on agriculture in many parts of the humid and sub-humid tropics. Agriculture in these regions, particularly in the sub-humid areas, is vulnerable to many environmental hazards – including frequent floods, droughts, tropical cyclones and storm surges and high temperatures. Low-income rural populations that depend on traditional agricultural systems or on marginal lands are particularly vulnerable (Amadore et al., 1996). Table III shows excerpts of a table of recent studies of yield and production in selected countries in the humid and sub-humid regions.

Food security is facing a threat because there would then be rapid changes in supply and demand structures most especially in the developing countries, especially in the tropics. Assessments of the consequences of climate for the number of people at risk of hunger as defined by the Food and Agriculture Organization (FAO) have also been done. Results of the study by Parry et al. (1999) indicate that the additional number of people at risk of hunger as a result of climate change by 2080 is estimated to be about 80 million and those at higher risk are from the arid and sub-humid tropics.

TABLE III
Recent agricultural studies

Study	Scope	Crops	Climate scenario	Yield impact without adaptation	Yield impact with adaptation	Socio-economic impact	Comments
Parry et al. (1999)	Global	Wheat, rice, maize, soybeans	Transient scenarios: 4 HadCM2 ensemble scenarios, 1 HadCM3 (both assume IS92a forcing)	(a) Studies with explicit global economics and/or global yields All cereals by 2080s: NA (–10 to +3%); LA (–10 to +10%); WE (0 to +3%); EE (–10 to +3%); AS (–10 to +5%); AF (–10 to +3%)		By the 2080s: global cereal production (–4 to –2%), cereal prices (+13 to +45), number of people at risk or hunger (+36 to +50%)	Farm-level adaptations (changes in plant date, varieties, irrigation, fertilizer); economic adjustments (increased investment, reallocation of resources, more land in production); no feedback between economic adjustments and yields; CO ₂ direct effects included
Winters et al. (1999)	Africa, Asia, Latin America	Maize, rice, wheat, coarse grains, soybean, “cash crops”	GISS, GFDL, UKMO	Africa [maize (–29 to –23%), rice (0%), wheat (–20 to –15%), coarse grains (–30 to –25%), soybean (–2 to +10%), cash crops (–10 to –4%); Asia [maize (–34 to –20%), rice (–12 to –3%), wheat (–54 to 8%), coarse grains (–34 to –22%), soybean (–9 to +10%), cash crops (–13 to +2%); Latin America [maize (–26 to –18%), rice (–26 to –9%), wheat (–34 to –24%), coarse grains (–27 to –19%), soybean (–8 to +12%), cash crops (–20 to –5%)]		Africa [total agricultural production (–13 to –9%), GDP per capita (–10 to –7%), agricultural prices (–9 to +56%); Asia [total agricultural production (–6 to 0%), GDP per capita (–3 to 0%), agricultural prices (–17 to +48%); Latin America [total agricultural production (–15 to –6%), GDP per capita (–6 to –2%), agricultural prices (–8 to +46%)]	Yield impacts based on Rosenzweig and Parry (1994) values for “level 1” (farm level) adaptations and CO ₂ direct effects; yield impacts are weighted (by production) average of country-level yield changes; values for total agricultural production and per capita GDP include both yield and price impacts; range for agricultural prices is across food and cash crops, and GCMS

(b) Studies with of yield and production in economies-in-transition and developing regions, nations, and sub-national regions						
Matthews et al. (1997)	Asia	Rice	Sensitivity analysis (+1 °C, +2 °C, +4 °C); GFDL, GISS, UKMO	+1 °C (-7 to 26%), +4 °C (-31 to -7%), -8 to +5% change in variety	+14 to +27% (with change in cropping system (+37 to +44%), region with change in variety (+13 to +25%))	Includes CO ₂ direct effects; adaptation (single to double cropping system, planting date shift, change in variety) CO ₂ direct effects considered in all cases but Mongolia: adaptation in Mongolia consists of earlier seeding
Smith and co-workers (1996)	The Gambia	Maize, millet-early, millet-late, groundnuts	CCC, GFDL, GISS	-26 to -15%, -44 to -29%, -21 to -14%, +40 to +52%		
	Zimbabwe	Maize	CCC, GFDL	-14 to -12%		
	Kazakhstan	Spring wheat, winter wheat	CCC, GFDL CCC, GFDL, incremental scenarios	-70 to -25%		
	Mongolia	Spring wheat	GFDL, GISS	-35 to +17%		
	Czech Republic	Winter wheat	Incremental scenarios	-3 to +16%		
Amien et al. (1996)	Indonesia	Rice	GISS transient	2050 (-14 to -9%)		Includes direct effects of CO ₂
Buan et al. (1996)	Philippines (six sites)	Rice, corn	CCC, GFDL, GISS, UKMO	Rice (-13 to +9%), corn (-14 to -8%)		Includes direct effects of CO ₂
Karim et al. (1996)	Bangladesh	Rice, wheat	CCC, GFDL	Rice (-17 to -10%), wheat (-61 to -20%)		CO ₂ direct effects not considered
Jinghua and Erda (1996)	China	Maize	GFDL, UKMO, MPI	-19 to +5%	Change in production: -6 to -3%	CO ₂ direct effects not considered

5.1.1. *Africa*

Per capita food production in Africa, as a whole has already decreased over the recent years. Food security in Africa is affected severely by extreme events, particularly flood and droughts. For example, the 1998 ENSO floods had wrought extensive damage to crops in Kenya which was estimated at US\$ 1 billion (Ngecu and Mathu, 1999). Irrespective of whether climate change will cause more frequent or more intense extreme events, it is seen that agricultural productivity is sensitive to climate hazards such as droughts and floods. The already deficient food production in many areas of Africa could result in worsening the problems of food security.

The TAR further cites some specific examples of impacts on crops here. Among these are the studies done by Pimentel (1993) that indicates that global warming is likely to alter production of rice, wheat, corn, beans and potatoes which are major food crops in Africa and by Odingo (1990) that notes that rice may disappear because of higher temperatures in the tropics.

Projections indicate the dominant impacts of increase in temperature which show decreases in growing season and reduction in runoff. And although increased CO₂ could increase photosynthesis rates and water use efficiency in crops like wheat, rice and soybeans, increased temperatures could have deleterious effects on crops during sensitive development stages which could lead to a decline in grain yield and quality. In addition, the risks of adverse effects on agriculture in the sub-humid areas of the region with more frequent and prolonged droughts could also be considerable (IPCC, 2001). There is a consensus in all IPCC assessment reports (1996, 1998) that climate variability and climate change (primarily droughts) would generally have significant impacts on almost all farming systems in Africa.

The most significant constraint for African agriculture is water supply. Due to the relatively rich water sources, climate change and variability would lead to less impacts on the agriculture in humid and sub-humid Africa, compared with other areas in Africa.

5.1.2. *Asia*

According to TAR, the developing countries of temperate and tropical Asia already are quite vulnerable to extreme climate events such as floods, typhoons/cyclones, and droughts. Climate change and variability would exacerbate these vulnerabilities with high confidence. Increased precipitation intensity, particularly during the summer monsoon, could increase flood-prone areas. There is potential for drier conditions in sub-humid Asia during summer, which could lead to more severe drought (medium confidence). The expected increase in the frequency and intensity of climatic extremes will have significant potential effects on crop growth and agricultural production, as well as major economic and environmental implications.

The IPCC (2001) has defined a number of vulnerabilities of the agricultural productivity in Asia. Asia is a region in which climate-change-induced vulnerabilities are highly dependent on the population density and rate of economic growth in each of the countries. The growth rate of rice production in a number of countries

such as Philippines, Indonesia and Sri Lanka has been unable to match, much less cope with fast population growth rate due to a number of factors which includes the impacts of a highly variable climate. Food insecurity also appears to be the primary concern for Asia.

The variability of rainfall in the developing countries of tropical Asia is rather high so that these countries have also been rendered quite vulnerable to extreme climate events such as droughts and floods. Moisture stress due to prolonged dry spells/droughts and in some sub-humid areas, coupled with heat stress, have already been seen to affect crops, especially when these environmental conditions occur during the critical stages of the crops (Rounsevell et al., 1999). On the other hand, excessive moisture also causes substantial crop losses due to floodings and loss of nutrients and soil erosion. The predicted increase in frequency and/or severity of extreme events could further exacerbate adverse impacts. Furthermore, all climate scenarios point to an increase in area-averaged annual mean precipitation over its entire region which could lead to increased frequency and severity of floods. So, it is seen that agricultural productivity in this region could suffer severe losses.

Results also show that increasing minimum temperatures could have an impact on rice yields while wheat crops are likely to be sensitive to increases in maximum temperatures. The adverse impacts due to temperature increases could also be further exacerbated by the occurrence, development and spread of crop diseases because some common diseases such as wheat scab, rice blast, and sheath and culm blight of rice could be more widespread as a result of warmer and wetter climates. Ninety percent of the more than 10,000 different species of insect pest found in the tropics are active in the humid areas. Higher temperature during winter is highly favorable to pathogen survival rates.

Results of a large number of simulations/experiments confirm beneficial effect of elevated CO₂ on crops (IPCC, 1996), but variations in crop response among species exist, depending on availability of plant nutrients, temperature, and water stress. When impact assessments combine the effects of increasing temperatures, changing rainfall patterns/amounts and rising CO₂ concentrations, varied results are seen. Three impact assessment studies done on rice crops in South and Southeast Asia are summarized in Table IV. The results of the Matthews et al. (1995) show substantial variation across the entire Asian region among the climate scenarios used. Decreased rice yields are seen for the low-latitude areas, but increased rice yields for higher latitudes. Such results indicate a possible shift in the rice-growing regions away from the equatorial regions to higher latitudes. In the rice-producing countries of China, India, Bangladesh, Japan, South Korea, Malaysia, Myanmar, Philippines and Vietnam, doubled-CO₂ scenarios give results showing positive effects of enhanced photosynthesis, although these are more than offset by the negative effects of increases in temperatures greater than 2 °C (Kropff et al., 1995; Matthews et al., 1995). Additionally, the tea industry (considered as the main source of income) in Sri Lanka is also expected to suffer adverse impacts since the island will experience extreme rainfall intensities and warmer temperatures as a result

TABLE IV
Summary of some recent impact studies in South and Southeast Asia

Study	Scenario	Geographic scope	Crops	Yield impact (%)	Comments
Rosenzweig and Iglesias	GCMs	Pakistan	Wheat	-61 to +67	UKMO, GFDL, GISS, and +2, +4 °C and $\pm 20\%$ precipitation. Range is over sites and GCM scenarios with direct CO ₂ effects; scenarios w/o CO ₂ and w/adaptation also were considered. CO ₂ effects important in offsetting losses of climate-only effects; adaptation unable to mitigate losses
Parry et al. (1992)	GISS	India	Wheat	-50 to +30	Indonesia: low estimates consider adaptation; also estimated overall loss of farmer income ranging from US\$ 10 to 130 annually
		Bangladesh	Rice	-6 to +8	
		Thailand	Rice	-17 to +6	
		Philippines	Rice	-21 to +12	
		Indonesia	Rice, soybean, maize	Approximately -4, +10 to -10, -25 to -654	
		Malaysia	Rice, maize, oil palm, rubber	-12 to -22, -10 to -20, increase, -15	
Matthews et al. (1995)	Three GCMs	Thailand	Rice	5-8	GISS, GFDL, UKMO scenarios; included the direct CO ₂ effects; range is across GCMs; varietal adaptation was shown to be capable of ameliorating detrimental effects of a temperature increase in currently high-temperature environments
		India	Rice	-12 to +23	

(Continued on next page)

TABLE IV
(Continued)

Study	Scenario	Geographic scope	Crops	Yield impact (%)	Comments
		Bangladesh		-12 to -2	GISS, GFDL, UKMO scenarios; included the direct CO ₂ effects; range is across GCMs; varietal adaptation was shown to be capable of ameliorating detrimental effects of a temperature increase in currently high-temperature environments
		Indonesia		-6 to +22	
		Malaysia		+21 to +26	
		Myanmar		-9 to +30	
		Philippines		-2 to +12	
		Thailand		-20 to -34	

Source: *Water, Air and Soil Pollution*, vol. 92.

of climate change (Wijeratne, 1996). The Howden et al. (1999) study, however, as reported in the TAR indicate that deleterious effects of higher temperatures could be offset for cropping systems with growth in the cooler months. And, it also appears that there is greater relative enhancement of growth due to increased CO₂ under drier soils.

5.1.3. Latin America

Extremes in climate variability already severely affect agriculture in Latin America. There is high confidence that a decreased yield for numerous crops (e.g., maize, wheat, barley) is projected, even when the direct effects of CO₂ fertilization and implementation of moderate adaptation measures at the farm level are considered (IPCC, 2001).

The largest area with marked vulnerability to climate variability in Latin America is northeast Brazil. Periodic occurrences of severe El Niño-associated droughts in northeastern Brazil have resulted in occasional famines (Hastenrath, 1993; Kovats et al., 1999; IPCC, 2001). The Rosenzweig et al. model simulations indicate that any change in climate could mean major consequences in northeastern Brazil. Under doubled-CO₂ scenarios, yields are projected to fall by 17–53%, depending on whether direct effects of CO₂ are considered.

It is also seen that temperature increases in the future could exacerbate losses caused by extreme events and also could offset the positive physiological effects

TABLE V
Assessment of climate change impacts on annual crops in Latin America

Study	Climate scenario	Scope	Crop	Yield impact (%)
Downing (1992)	+3 °C, -25% precipitation	Norte Chico, Chile	Wheat, maize, potato, grapes	Decrease, increase, increase, decrease
Baethgen (1994)	GISS, GFDL, UKMO	Uruguay	Wheat, barley	-30, -40 to -30
de Siqueira et al. (1994)	GISS, GFDL, UKMO	Brazil	Wheat, maize, soybeans	-50 to -15, -25 to -2, -10 to +40
Liverman et al. (1994)	GISS, GFDL, UKMO	Mexico	Maize	-61 to -6
Sala and Paruelo (1994)	GISS, GFDL, UKMO	Argentina	Maize	-36 to -17
Baethgen and Magrin (1995)	UKMO	Argentina, Uruguay (nine sites)	Wheat	-5 to -10
Conde et al. (1997a)	CCCM, GFDL	Mexico (seven sites)	Maize	Increase-decrease
Magrin et al. (1997a)	GISS, UKMO, GFDL, MPI	Argentina (43 sites)	Maize, wheat, sunflower, soybean	-16 to +2, -8 to +7, -8 to +13, -22 to +21

Source: IPCC (2001).

under enriched CO₂ scenarios in some areas. The assessment done on wheat, maize and soybean production under doubled-CO₂ scenario in Brazil by de Siqueira et al. in 1994 predicted declines in yield for the first two crops and -10 to +40% yield for the last one as shown in Table V which summarizes assessments of climate change impacts on annual crops in Latin America.

Information about some cash crops in countries of the Central American isthmus indicate that under current climate conditions, the productivity of banana crops is severely affected particularly in flood-prone areas. These crops could be additionally stressed if climate change-induced variability includes increasing frequency of storms and precipitation (IPCC, 1998).

In addition, for some tropical inlands such as Cook Islands, the possible changes in climate parameters could affect some species/cultivars of crops such as papaya, citrus, and vegetables, which are more sensitive to climate. Increase in sea level can dramatically affect the Islands. They may see greater flooding of by seawater and can cause major damage of agricultural production.

5.1.4. *Uncertainty*

It should be considered, however, the impacts of climate change and variability on agriculture remains uncertain on some extent, not only because of uncertainties in climate projections, but also because the agronomic and economic models used to predict these changes are not perfect. Some models do not include changes in insects, weeds and disease; changes in soil management practices; changes in water supply. Moreover, the magnitude and persistence of effects of increased CO₂ concentration on crop yield under realistic farming conditions, and other uncertainties.

5.2. IMPACTS ON LIVESTOCK

Climate affects livestock in four ways; through the impact of changes on availability and price of feedgrain, impacts on livestock pastures and forage crops, the direct effects of weather and extreme events on animal health, growth, and reproduction, and changes in the distribution of livestock diseases.

For developing countries, the impact of climate variability on livestock is generally negative in the humid and sub-humid tropics, particularly in the latter. For animals, heat stress has a variety of detrimental effects, with significant effects on milk production and reproduction in dairy cows, and swine fertility (Berman, 1991; Hahn and Mader, 1997; Hahn, 1999). Moreover, warming in the tropics during warm months would likely impact livestock reproduction and production negatively (e.g., reduced animal weight gain, dairy production, and feed conversion efficiency) (Klinedinst et al., 1993). Impacts, however, may be minor for relatively intense livestock production systems.

5.2.1. *Africa*

Range-fed livestock in any African region is dependent on annual precipitation. Any change in mean annual precipitation is expected to have a negative impact on pastoral livelihood.

Livestock distribution and productivity could be indirectly influenced by the changes in the distribution of vector-borne livestock diseases (Hulme, 1996). Livestock in humid areas in Africa are prone to diseases such as those carried by the tsetse fly. With warming, its distribution could extend westward in Angola and northeast in Tanzania but with reductions in the prevalence of tsetse in some current areas of distribution. In areas with high moisture content, animal productivity is limited by the protein content of the fodder (Ellery et al., 1996; IPCC, 2001). Protein availability will not increase with the increase in rainfall or the CO₂ concentration, hence livestock would not respond to the direct effects of climate change. Additionally, since even the domestic livestock should be under a certain climate environment for optimal performance, any change that could alter the limits of this climate environment could have an impact on the meat and milk production.

5.2.2. *Asia*

There is very little literature on impact of climate variability and climate change on livestock production in tropical Asia. However, because of the increasing trend for meat consumption, there is a higher demand for livestock feed. Production of feed grain in Asia, especially maize, is adversely affected by climate variability and climate change. Livestock productivity is also highly dependent on the climate environment. Any change that is beyond the limits of the optimal climate environment would impact livestock production.

5.2.3. *Latin America*

Livestock in much of Latin America is raised in rangelands. It is predicted that its production would be negatively affected by increased variability of precipitation since those areas which are drought/flood-prone would be severely affected.

Compared with animals, pastures in the sub-humid tropics are more vulnerable to the climate variability. Rangelands are noted for high climatic variability and high frequency of drought events. They have a long history of human use. The combination of climatic variability and human land use make rangeland ecosystems more susceptible to rapid degeneration of ecosystem properties (Parton et al., 1996). Seasonal water availability and chronically low soil-nutrient availability appear to be the most limiting factors in the pasture of the region (Solbrig et al., 1992). In addition, the already low nutritional value of most tropical grassland and savannas may decrease as a consequence of increased C:N ration (Oechel and Strain, 1985; Gregory et al., 1999). Thus, the carrying capacity for herbivores may be reduced. For example, because of an alteration in the amount and pattern of rainfall, the occurrence of extreme events (e.g., hurricanes, drought), and the ENSO which could become more frequent and bring more severe weather under the $2 \times \text{CO}_2$ -climate, the northern South America savannas could fail to function as they do now (Aceituno, 1988).

5.3. IMPACTS ON FORESTRY

Tropical forests cover about 1.9 billion ha of the world's surface, representing about 40% of the world's forested area. They contain more than half of all plant and animal species. The impacts of climate change on forests includes to effect forest physiological processes, geographical distribution and biodiversity.

There are different impacts of climate change on forests; some are likely to be detrimental while others can be beneficial. When considered separately, temperature increases could have direct effects on plant growth by changing photosynthesis and respiration rates, and plants can tolerate even extremely high temperatures, provided sufficient water is available (Kirschbaum, 1998). Increasing CO_2 concentration can increase photosynthetic rates and this effect is more pronounced in C_3 plants at higher temperatures and under water-limited conditions. For different

combinations of increases in temperature and CO₂ concentration and for systems primarily affected by water and nutrient limitations, different overall effects on plant productivity could be expected.

Most tropical forests are likely to be more affected by changes in soil water availability (e.g., seasonal droughts). Some evergreen species of the humid forest clearly will be at a disadvantage in areas that experience more severe and prolonged droughts. Significantly, drought affects the survival of individual species; those without morphological or physiological adaptations to drought often die. Species in moist tropical forests, including economically important hardwoods, are the least drought-adapted in the tropics, and their survival in some areas must be considered at risk from climate change. Droughts would favor forest fire; therefore, with a likely increase of droughts, the incidence of forest fires may also increase.

Humid and sub-humid tropical forests contain large numbers of insects and pathogens that can cause serious damage to some plant species and may play a role in regulating species diversity. Based on FAO (1997), insect and disease outbreaks are reported mostly for plantation forests; although relatively less is known about these in native forests. Many factors have been associated with the susceptibility of tropical plants to pest and diseases and with the virility of pests and pathogens. Drought stress can sometimes increase host plant suitability, whereas high temperatures and humidities can decrease the growth rate, survival, and fecundity of some insects (IPCC, 1996). Consequently, there is still great uncertainty as to whether the impacts of climate change on the relationship between host plants and pests and pathogens will lead to forest loss or gain.

However, studies show that climate variability also has positive effects on forests. Strong winds associated with tropical cyclones frequently damage tree canopies, but also create gaps in the forest, and modify the forest structure and micrometeorological environment. This may allow more radiation to reach the forest floor, increase soil temperature, and make more soil water and nutrients available, which could promote the growth of new vegetation (IPCC, 1996). The effects in fertilization of elevated CO₂ concentrations are also beneficial to sub-humid and humid forest.

In addition, it should be noted that although climate variability would generally have some negative effects on forests of the humid and sub-humid tropics, the impacts of human activities such as deforestation will be more important than climate change and climate variability in determining natural forest cover. It has been seen that the main causes of deforestation in tropical region are population resettlement schemes, forest clearance for large-scale agriculture, demands of forestry production, and, in particular, shifting cultivation. The rate of deforestation had been highest in Africa (1.7%), followed by Asia (1.4%) and Latin America (0.9%). The areal extent of deforestation, however, was highest in Latin America (7.3 million ha), followed by Africa (4.8 million ha) and Asia (4.7 million ha) (National Research Council, 1993).

5.3.1. *Africa*

The moist tropical forests of the Congo constitute the second most extensive rain-forest in the world. A large fraction of the population lives in rural areas, totally dependent on trees and shrubs for their subsistence. Climate change could render vulnerable this large part of the African population.

The following are some of the indicated vulnerabilities in the TAR:

- Dry sub-humid areas have experienced declines in rainfall which result in decreases in soil fertility and range, and forest production.
- Untested assumptions are the transformation of parts of Africa, largely in the sub-humid tropics, into pastures. Increased cattle production means more tree-cutting, which could lead to a number of cascading effects.
- The desertification during the last half of the 20th century have caused a 25–30 km southwest shift in Sahel, Sudan and Guinea vegetation zones at an average rate of 500–600 m per year. This rate could increase further in a CO₂-induced climate change (Davis and Zabinski, 1992; IPCC, 2001).
- Dry woodlands and savannas in sub-humid areas could be subjected to more drying as climate change leads to increasing temperatures. Risks from vegetation fires could also be exacerbated.
- Geographical shifts in the ranges of individual species and changes in productivity are the most likely impacts of CO₂-induced climate change. Research in countries like Senegal has confirmed the retraction of mesic species to the areas of higher rainfall and lower temperature. Meanwhile, simulations of forest species distribution in Tanzania and the Gambia indicate changes from mesic to xeric vegetation in these two countries (Jallow and Danso, 1997).

Floristic biodiversity hotspots could be threatened by shift in rainfall patterns and these include the mountains of Cameroon, the island-like Afromontane habitats that stretch from Ethiopia to the higher latitudes of Africa at altitudes above 2000 m (Mace et al., 1998). Montane centers of biodiversity could be rendered at risk by increases in temperatures because there could be no possibility of migration.

5.3.2. *Asia*

In the developing countries of Asia, sensitivity of natural systems like forests is linked to the projected climate change-induced impacts, the degree to which natural systems have been degraded and the unsustainable utilization of resources. Examples are the increased risks of uncontrolled forest fires due to the conversion of natural forests to palm oil plantations in a number of Southeast Asian countries (e.g., Indonesia). Increase in population often result in the conversion of forest lands to cultivation and more intensive farming. There are also expected impacts on soil erosion, fertility in the soils, depletion of water resources and genetic variability of crops (Sinha et al., 1998; IPCC, 2001).

As many as 16 countries of tropical Asia are situated within the humid tropical forest region. Climate change is expected to affect the boundaries of forest

types and areas, primary productivity, species population and migration, the outbreak/incidence of pests and diseases and forest degeneration in these countries.

More than 50% of the world's terrestrial plant and animal species are in the frontier forests in Asia. There already are trends of increasing risks to this rich array of living species being seen in China, India, Malaysia, Myanmar and Thailand partly due to the degeneration of their habitat (IPCC, 2001). Since distribution of species is limited to a narrow range of environmental conditions, there are possibilities that climate change could change these conditions which could result in it being unsuitable. This could cause the loss of a large number of unique species that currently inhabit the world's tropical forests (Kirschbaum, 1998).

With climate change, the distribution of suitable habitat will change. Species will respond individually and differently to environmental changes. For some species, a temperature increase of even 2 °C can change the environment from being suitable to totally unsuitable (Bazzaz, 1998). Species with narrow tolerances are likely to be lost at the expense of species with broader tolerances. For tropical forests, this could lead to the loss of many of these unique species at the expense of those that can tolerate the new conditions or species that have the potential to invade newly suitable habitats (Phillips, 1997; Bawa and Dayanandan, 1998; Bazzaz, 1998) and ultimately, species composition of forests could change.

The fact however remains that tropical forests are currently endangered more by land use practices than by climatic change. Much of the tropical forest is affected by deforestation due to land conversion and increasing resource use (Fearnside, 1995). Large areas of undisturbed forests are being impacted by removal of wood for timber and fuel (Brown et al., 1997). In addition, there are pressures on them through increasing incidence of wildfires (Goldammer and Price, 1998) and ecological threats through habitat fragmentation (Skole and Tucker, 1993) and selective removal of indigenous or introduction of exotic species (Phillips, 1997).

Specific examples of projected impacts on forests in tropical Asia are those seen in studies in Thailand and Sri Lanka. In Thailand, despite the many uncertainties in the models used in the studies, it is seen that climate change could lead to a shift in the boundaries of major forest types in the country (Boonpragob and Santisirisomboon, 1996). Areas of tropical dry forests would appear and there could be an increase in tropical moist and tropical wet forests. A northward shift of tropical wet forests into areas currently occupied by tropical dry forest is also being predicted due to climate change-driven increases in temperature and rainfall in the northern part of the islands. Table VI shows the areas of major forest types in Thailand under current and changed climate conditions.

Similarly in Sri Lanka, climate change would cause a northward shift of tropical wet forests into areas currently occupied by tropical dry forests due to the predicted increase in temperature and in rainfall also in the northern parts of the country (Somaratne and Dhanapala, 1996). The approximate areas of current and potential life zones in Sri Lanka under climate change conditions as a result of the

TABLE VI

Areas of major forest types in Thailand under current and changed climate conditions according to three GCM scenarios

Forest type	Current area ($\times 10^3$ km ²)	Climate change area ($\times 10^3$ km ²)		
		UK89	GISS	UKMO
Subtropical dry forest	5.9 (1.2)	—	—	—
Subtropical moist forest	234.5 (47.7)	87.7 (17.8)	9.5 (1.9)	59.4 (12.1)
Subtropical west forest	22.2 (4.5)	6.6 (1.3)	5.3 (1.1)	1.8 (0.4)
Tropical very dry forest	—	—	11.9 (2.4)	3.0 (0.6)
Tropical dry forest	156.5 (31.8)	218.6 (44.4)	341.3 (69.3)	290.1 (58.9)
Tropical moist forest	71.5 (14.5)	166.8 (33.9)	120.5 (24.5)	128.0 (26.0)
Tropical wet forest	1.6 (0.3)	12.6 (2.6)	3.7 (0.8)	9.9 (2.0)

Source: *Water, Air and Soil Pollution*, vol. 92. Values given in parentheses are percentage.

simulations using the Holdridge Life Zone Classification with current climate and climate scenarios are shown in Figures 2a–2c.

5.3.3. Latin America

There have also been a number of natural and human activities that have borne adverse impacts on the forests of Latin America. These could be exacerbated by climate change-driven impacts. A continued conversion of large areas of humid tropical forests to pasture/agricultural activity could reduce water cycles and precipitation in the region. There is high confidence that if extent of deforestation in the Amazonia expands to substantially larger areas, reduced evapotranspiration would lead to less rainfall during its dry periods. If this dry period becomes larger and more severe, it could have deleterious impacts on the forest. Many trees could die due to increased water stress. Greater severity of droughts coupled with deforestation could lead to erosion in what remains of the forests in this region. Moreover, occasional severe droughts likely to occur during the El Niños would kill many trees of susceptible species and would result in a replacement of tropical moist forests with drought-tolerant species (Shukla et al., 1990).

Additionally, it is being projected that human action could now turn even less intensive El Niño events into catastrophes in terms of forest fires because there already have been considerable incursions of these fires into standing forest in the eastern Amazonia during dry years. Previously, burning in the Amazonia forests had been limited to where trees had been felled and the fire had previously stopped upon reaching the edge of the clearing.

There is also medium confidence that increases in the amount of biomass burning could affect nutrient cycling in the Amazonia forest ecosystems, although the extent to which nutrient sources such as smoke and dust could increase the growth of

Amazonia forests is still not known. But as a consequence, forest composition could be altered.

Globally, climate-driven scenarios at doubled- CO_2 concentration point to 10–15% expansion of the area that is suitable for tropical forests with tropical rainforests expanding from 7 to 40% (Solomon et al.), but these simulations have not, however, taken into consideration the influence of human populations. By and large, the combination of forces responsible for continued deforestation may not at all allow tropical forests to expand; although one particular model, which includes climate and human changes, has indicated decreases in forest areas in Latin America by about 5% by 2050 (Zuidema et al., 1994). And for plantation forestry, a major land use in Brazil, climate change could reduce silvicultural yields due to changes in water availability, spawning adverse impacts on pests and fire hazards.

Latin America accounts for one of the Earth's largest concentrations of biodiversity, and the impacts of climate change can be expected to increase the risk of biodiversity loss with high confidence (IPCC, 2001). The remaining Amazonian

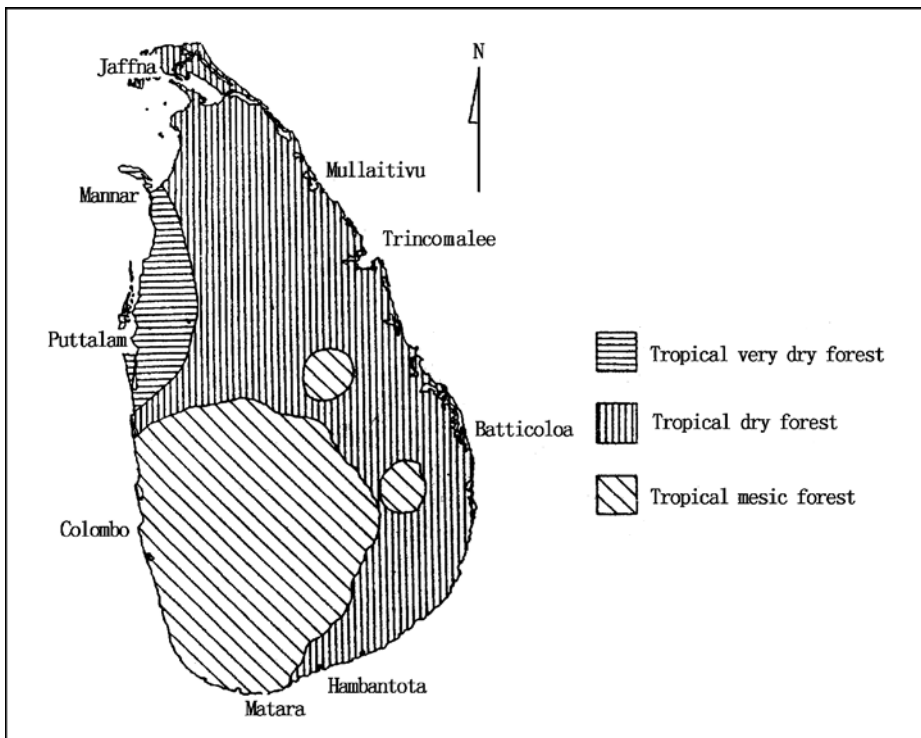


Figure 2. (a) Holdridge life zones of Sri Lankan forests under current climate conditions. (b) Holdridge life zones of Sri Lankan forests under CCCM derived climate change scenarios. (c) Holdridge life zones of Sri Lankan forests under GFDL derived climate change scenarios.

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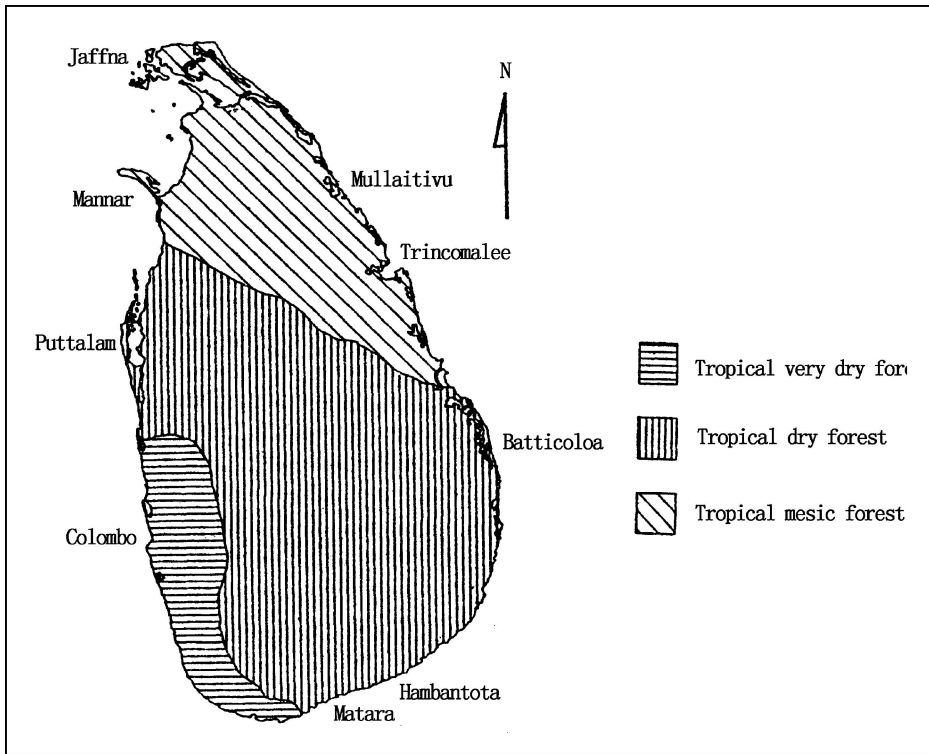


Figure 2. (Continued)

forest is threatened by the combination of human disturbance, increase in fire frequency and scale, and decreased precipitation from evapotranspiration loss, global warming, and El Niño.

5.4. CASE STUDIES

5.4.1. *Philippines*

Philippines lies at the western rim of the Pacific Ocean and just off the southeastern portion of the Asiatic continent. It consists of approximately 7100 islands and islets distributed over an area from 4.7 to 22.5°N and about 117 to 127°E. It has relatively warm temperatures and mean annual rainfall ranging from 2000 to 4000 mm. Extreme climate events consist an inherent component of Philippine climate system and natural hazards due to these extreme events are strong winds, storm surges, floods, and droughts. And like its neighboring countries, it is much affected by ENSO events.

5.4.1.1. Impacts of Climate Variability on Philippine Agriculture. Agriculture is the economic lifeline of Philippines. Total agricultural land amounts to about 10

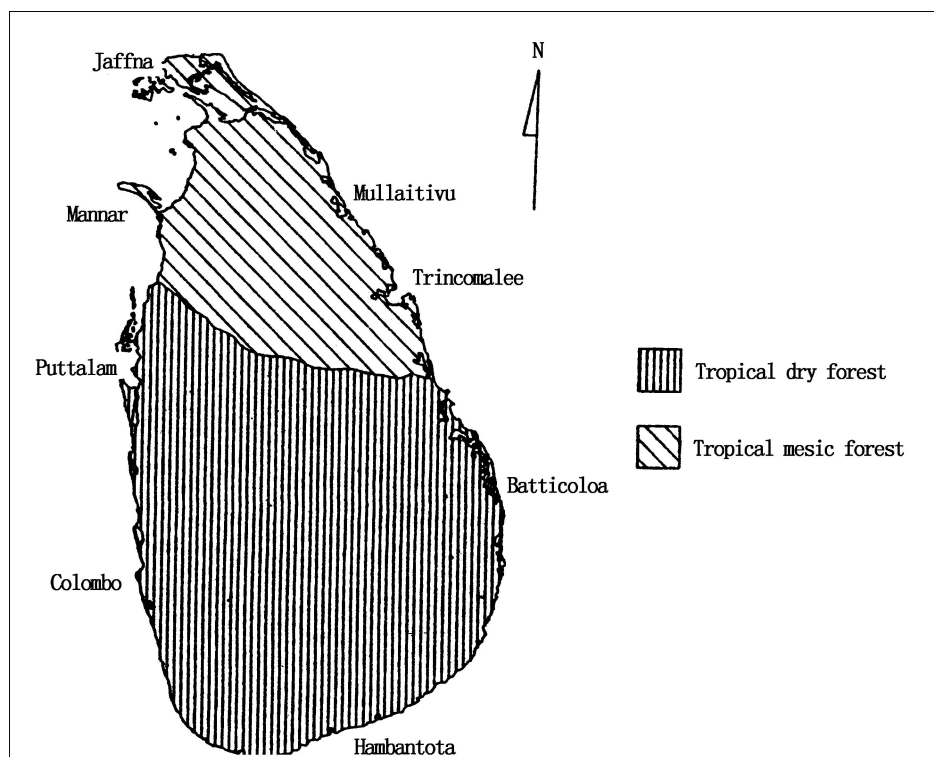


Figure 2. (Continued)

million ha, 45% of which is located in lowlands and 33% in the uplands. Rice and corn, being the country's staple food, remain its most important crops. Coconut, sugarcane and some cash crops like bananas constitute important export commodities. Rice production plays a dominant role in Philippine agriculture and its economy as a whole. Rice production growth rate has been pegged at 2.33% annually. However, population growth rate has been estimated to be 2.4% per annum, so that Philippines will most likely continue to depend on rice imports for about 5% of its national requirements.

There are also a number of non-climate factors which could affect the degree of vulnerability of the sector. These include population growth, land use conversion that leads to depletion of agricultural/riceland areas, inadequate development of irrigation facilities, deterioration of agricultural resources and the country's entry into international economic agreements.

In the documentation and analysis study (PAGASA, 2001) conducted to determine the impacts of and responses to extreme climate events during the 1961–2000 period, the following results are indicated:

- Declines in GVAs (defined as differences between *gross outputs* or gross value of the good and services produced during the accounting period and the

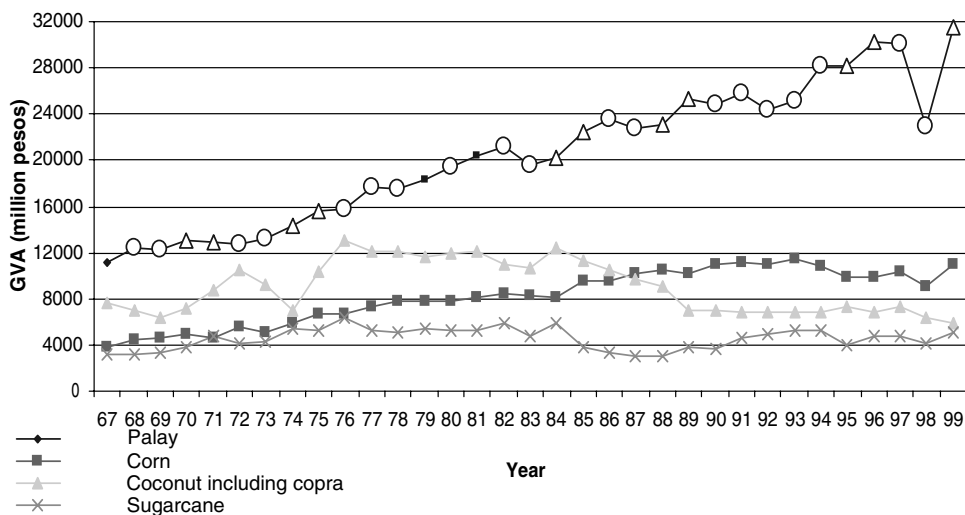


Figure 3. Gross value added in four principal crops at constant 1985 prices.

intermediate outputs or value of goods and services such as raw materials and supplies, fuel, etc. used in the production process during the accounting period estimated at constant 1985 prices) and in volume of production in four principal crops namely rice, corn, sugarcane and coconut, generally coincide with El Niño years; while the increases concur with La Niña years (see Figure 3). Sharpest falls in GVAs and volume of production in the agricultural sector had been in 1982–1983 and 1997–1998, the periods, which saw the birth, peaks and decay of the two strongest El Niños of the 20th century. On the other hand, increases in GVAs in rice and corn had been attributed mainly to favorable rainfall conditions during the La Niña years.

- Livestock and poultry as a sub-sector had not been sensitive to extreme climate events as shown in Figure 4; although, at the farm level, there could have been impacts of climate variability/extreme events.
- Some third-order impacts had also been indicated such as shortfalls in the projected annual economic growth due to dips in the agricultural growth rates, increased burden on urban resources as a result of the migration of displaced agricultural workers to the cities for jobs and/or increased dependence of these workers on government aid, worsening poverty situation, etc.

5.4.1.2. Impacts of Climate Change on Philippine Agriculture. Projected impacts as a result of enriched CO₂ concentration will range from a likely intensification of the degradation of soil and water resources due to increases in temperature and changes in precipitation. There could be decreases in agricultural productivity due to thermal (temperature/heat increases) and water stresses. Increased intensity of rainfall would increase flood risks and would therefore cause an increase in

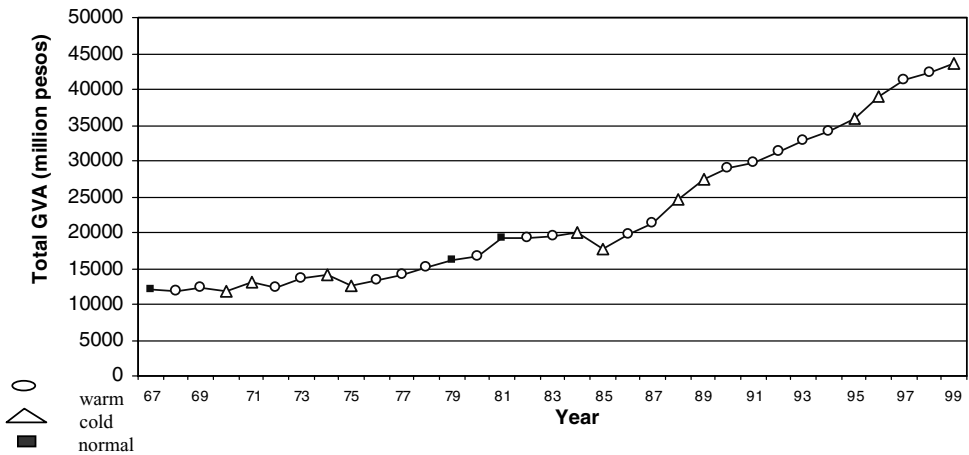


Figure 4. Gross value added in poultry and livestock at constant 1985 prices.

production losses; and there would be more declines in crop yields if frequency and intensity of El Niño events increase. Incidence of pests and diseases is also likely to increase and could cause more negative impacts. Tropical cyclones would diminish food security if their intensities and peak winds increase.

There would be more consistent yield losses from climate change if no adaptation measures are put in place. However, there could be increases in rice yields, provided correct management and farm practices are put in place.

Vulnerability assessments done on rice and corn production using global circulation models (GCMs) to give simulations of climate change scenarios and process-based crop models gave varied results.

Simulations showed, generally, increases in rice yield except for those scenarios generated by the GISS model, but decreases in corn yield (Centeno et al., 1995; Buan et al., 1996). Assessments done by Escaño and Buendia at the International Rice Research Institute, as part of the Rosenzweig and Iglesias study in 1994 gave varied results. Changes in rice yields varied from a decrease of 21% to an increase of 12%, depending on the GCM and the site used. Results of the simulations employing adaptation options showed adaptation was unable to mitigate losses. The Centeno et al. study simulated potential rice yields in 16 sites using the ORYZA1 rice crop model under various scenarios of changed climate. Results were a yield increase of about 30% at doubled- CO_2 with no temperature increment, decreased yields with increasing temperatures but at current levels of CO_2 and more pronounced decreases during the dry season due to the already high temperatures, usually prevailing during this period, and decreases in yield in all increments of CO_2 concentration in both seasons and with a $+4^\circ\text{C}$ increase in temperature.

The projected rice yields over all sites and all seasons under climate change were computed. Overall, it was predicted that the national rice production of the country would change by $+6.6$, -14.0 and $+1.1\%$ for the GFDL, GISS and UKMO doubled- CO_2 scenarios respectively as could be seen in Table VII.

TABLE VII
Estimated changes in rice production in each administrative region and in the whole Philippines

Region	Current (t)	GFDL		GISS		UKMO	
		% Change	t	% Change	t	% Change	t
NCR	152,559	2.6	156,476	-11.1	135,669	16.9	178,319
I	898,584	-3.8	864,238	-17.0	745,538	2.2	918,241
II	1,033,615	-3.8	994,108	-17.0	857,571	2.2	1,056,226
III	1,748,491	2.6	1,793,379	-11.1	1,554,911	16.9	2,043,730
IV	1,118,085	10.2	1,232,604	-6.2	1,048,730	-0.4	1,113,437
V	744,223	5.4	784,357	-32.0	506,260	-20.5	591,716
VI	1,183,887	11.9	1,324,583	-11.1	1,053,064	-7.4	1,096,816
VII	207,700	11.9	232,384	-11.1	184,749	-7.4	192,424
VIII	382,954	11.9	428,465	-11.1	340,637	-7.4	354,789
IX	399,038	18.5	473,040	5.7	421,617	11.1	443,166
X	531,777	10.5	587,861	-22.1	414,386	-39.5	321,605
XI	688,302	13.3	779,593	-16.9	571,880	-1.4	678,580
XII	584,047	13.3	661,510	-16.9	485,259	-1.4	575,798
Total	9,673,262		10,312,598		8,320,271		9,564,847
% Change from current			6.6		-14.0		-1.1

Source: IRRI (1995).

Further analysis was done using a number of adaptation strategies which include changing planting dates, applying irrigation, employing more site-specific fertilizer management, etc. For rice, yields would definitely increase when planted in some suitable times of the year, especially with the application of irrigation and the more site-specific crop and soil management. Corn yield, however, would be more negatively affected.

These simulation results, however, could only serve as a range of what could be expected inasmuch as there are inherent limitations in the climate scenarios and in the process-based crop models used. For instance, the Buan et al. (1996) model did not consider the effect of extreme climatic events, including that of strong winds due to tropical cyclones. Moreover, one of the assumptions made was that the soil conditions during the simulations are the same even when CO₂ is doubled.

What is certain though is that when the agricultural sector in any local area has already been rendered vulnerable by increasing climate variability, including occurrences of extreme events, and other non-climatic factors like increasing population, diminished/degraded agricultural areas and ineffective/insufficient agricultural support services such as lack of irrigation facilities, the projected adverse impacts will certainly contribute to decreases in crop yield.

5.4.1.3. *Impact of Climate Variability on Philippine Forest Resources.* Philippine forests can equal any of those in many areas of the tropics in terms of diversity. Indigenous flowering plants are estimated to be around 8000 species, belonging to almost 6500 genera and 20 families. They contain quite a diverse collection of plants and animals; thus, there is a gene pool of living organisms with a value that could exceed much beyond its current market price.

Forest-based industries used to constitute a major contributor to the country's GNP for three decades from the 1950s until the 1970s. With the massive deforestation that had taken place over a number of years, its contribution had come down to only 0.18% in 1995. Yet, it remains a major source of income for many upland dwellers, including a good number of indigenous tribes. More than 9 million people are estimated to inhabit the forestlands, where they marginally subsist through cultivation and utilization of the already degraded forest resources. Forest-based industries continue to generate more than 300,000 employment opportunities, not including those who are employed in downstream industries. Any further deterioration of the forest resources is certain to diminish these opportunities and will not augur well for those who inhabit these lands and depend on them for subsistence.

Results of the study done by Cruz, in 1997, indicated that forest resources which are already highly vulnerable are timber, water and biodiversity. Timber resource is already highly depleted due to a number of pressures. Among these is climate variability, both directly and indirectly. For example, excessive floods have caused soil erosion which ultimately has degraded the land. Also, when man gets little harvests from upland cultivation, he is driven to scavenge wood products/wood which could augment his income. Similarly, water resource has been highly degraded due to the denudation of watershed forest cover. Many watersheds are already suffering from non-climate factors like destructive cultivation, encroachment and improper management, and from climate-related pressures such as excessive soil erosion and surface runoff due to floods.

Biodiversity in many of the country's forested areas may have been affected by natural variability of climate because prolonged dry periods may have threatened some species. When climatic factors combine with untenable practices like excessive logging and lack of protection and unsustainable management, then local biodiversity becomes at risk. Forest boundaries in the country may also have been changed due to prolonged dry periods during El Niño events. Droughts have been known to cause significant damages to the productivity and biological integrity of forest ecosystems.

Furthermore, the documentation and analysis of impacts of extreme climate events on the environment sector (PAGASA, 2001) indicate that forest fires due to El Niño events pose a threat to the remaining forest reserves. Figure 5 shows the forest fire destruction in the country. Areas damaged by forest fires were extensive during the 1982–1983, 1991–1992 and 1997–1998 El Niño events because of the prolonged dry spell.

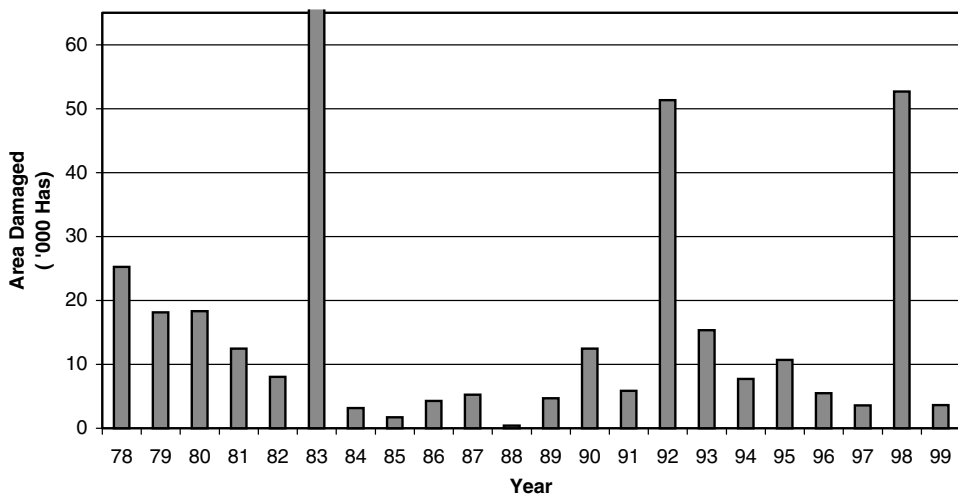


Figure 5. Extent of forest fire destruction in Philippines (1978–1999).

5.4.1.4. Impacts of Climate Change on Philippine Forest Resources. In the case of Philippine forestry sector, no simulation studies have been made yet, although there is now an on-going 3-year integrated assessment of watersheds. The initial vulnerability assessment done was based on the current projections and IPCC assessment reports for Asia and two national studies (that of Thailand and of Sri Lanka) because of resource constraints. Results of the related regional and national studies were used as analogues of the potential impacts of future climate change on Philippine forests. Changes expected to happen in Philippine forests include the likelihood of the expansion of its rainforests as temperature is expected to increase substantially, along with modest increase in precipitation in many areas which already get excessive moisture. On the other hand, the generally increasing trend in precipitation especially during the wettest months will possibly cause serious soil erosion and flood problems in currently denuded forests and watersheds which are dominated by grasses. This could exacerbate the declining productivity of these denuded watersheds and the downstream areas that act as repository of silt transported by surface runoff and streamflow. However, in areas where temperature is expected to increase significantly but rainfall is projected to remain unchanged or even decrease, the expected loss in forested areas may be small. This, however, may lead to the loss of a few species of plants and animals that can significantly erode the biodiversity in these areas and also in the forest in the adjacent areas. And because climate change could exacerbate the loss of local biodiversity already brought about by other pressures through extinction and inhibition of re-immigration from adjacent areas, the greatest impacts are on those whose subsistence depends on the goods and services these forest resources provide.

Additionally, the increase in the frequency of drought/floods due to changes in El Niño will likely render many areas currently under cultivation unfit for agricultural

production. Population growth and shrinking arable lands could increase the pressure of forested areas to be converted, thereby challenging the protection of the remaining natural forests. Grasslands and other areas dominated by shrub and shrub species could become more vulnerable to fire with the increase in temperature and the inadequate increase or even marked decrease and rainfall. This could be further aggravated by any prolonged dry periods which are bound to happen during El Niños. Frequent fires could make these areas more difficult to rehabilitate.

Any changes in temperature and precipitation may result in the outbreak of pests and diseases. This can significantly change the species composition, structure and functions of forest ecosystems in ways similar to the disturbances that come about through forest destruction by man.

5.4.2. *Malaysia*

Malaysia sits on the South China Sea at the center of Southeast Asia. The country is crescent-shaped, starting with Peninsular Malaysia (West Malaysia) and extends to another region, Sabah and Sarawak (East Malaysia), located on the island of Borneo. The total area of Malaysia is approximately 330,000 km², with most of it island of Borneo. Peninsular Malaysia comprises approximately only 40% of the total area.

Peninsular Malaysia is located entirely within the equatorial zone. It had 82% of the nation's population in 1990. Economic activity accounted for 84% of Malaysia's gross domestic product in 1987, and 74% of Malaysian land in agricultural use was in Peninsular Malaysia in 1990. Tree crops represent the principal agricultural land use in Peninsular Malaysia. Rubber, oil palm, coconut, and cacao accounted for 83% of the area devoted to agriculture in 1988. Agriculture (including forestry and wood products) is a major sector of Peninsular Malaysia's economy and is important on a global scale as well. Malaysia is the world's largest producer and exporter of natural rubber, palm oil, and tropical logs and sawn wood.

Malaysia's climate is hot and humid with relative humidity ranging from 80 to 90%, except in the highlands. The temperature averages from 20 to 30 °C throughout the year. The tropical climate is experienced year-round with the rainy season varying on the coasts of Peninsular Malaysia. The west coast has its rainy season from September through December with the east coast (and Sarawak and Sabah) experiencing it from October through February. East Malaysia (the northern slopes) gets up to 5080 mm of rain a year *versus* West Malaysia's 2500 mm. There exists the possibility of drought in West Malaysia (i.e., Peninsular Malaysia which is the major agricultural area) although the weather disaster of Malaysia is floods.

There are forests covering over half of Malaysia, with notable tropical forests in Sabah and Sarawak. Deforestation is a problem the country is dealing with due to logging and hydroelectric projects.

5.4.2.1. *Climate Change and Variability in Malaysia.* Like many countries in the world, temperature records in Malaysia in the last 50 years have shown warming trends (see Figure 6). Climate change may bring about an increase in the frequency

TABLE VIII
Climate change scenarios for Malaysia

	2020	2040	2060
Northern hemisphere summer			
Changes in temperature	+0.3to + 1.4 °C	+0.4to + 2.4 °C	+0.6to + 3.4 °C
Changes in rainfall	-0.4 to +14%	-0.7 to +23%	-1.0 to +32%
Northern hemisphere winter			
Changes in temperature	+0.4 to +1.9 °C	+0.7 to +3.2 °C	+1.0 to +4.5 °C
Changes in rainfall	-4.0 to +7.0%	-7.0 to +12%	-10 to +17%



Figure 6. Temperature records in Malaysia in the last 50 years.

and intensity of extreme weather events, such as, drought, storms and floods. There is still, however, insufficient data to determine whether the frequency of extreme events has indeed increased. It has been observed that, since 1977, there have been more frequent ENSO warm phase episodes. This behavior, especially the persistent warm phase from 1990 to mid-1995, was unusual in the last 120 years and significantly influenced rainfall in Malaysia.

Table VIII is the climate change scenarios for Malaysia. Generally, the temperature will increase; rainfall may increase probably, but there exists possibility of some decreases. The impacts of climate change on Malaysia agriculture are estimated based on the combinations of higher temperature and increasing rainfall, and higher temperature and decreasing rainfall.

5.4.2.2. *Impacts of Climate Change and Variability on Malaysia Agriculture.* Most of the materials for this case study are drawn from the Malaysia initial National Communication as an output of the UNDP/GEF Project: Enhancement of Technical

Capacity to Develop National Response Strategies to Climate Change.

(1) *Impacts on rubber.* Rubber flourishes in a tropical climate with a high mean daily air temperature of between 25 and 28 °C and high rainfall exceeding 2000 mm per year. Even distribution of rainfall with no dry seasons exceeding 1 month and at least 2100 h of sunshine per year are ideal conditions for growing rubber. The following impacts of climate change on rubber are expected:

- If the mean daily air temperature increases by 4.5 °C above the mean annual temperature, more dry months and hence more moisture stress can occur. A crop decrease of 3–15% due to drought conditions is projected if mean annual temperature increases to 31 °C. The degree of yield decrease will be dependent on clonal susceptibility, as well as the length and severity of the drought.
- Based on the above climate change scenario, some states may experience a reduction in production. It is projected that 273,000 ha of land, or 15% of current rubber land, may be affected. With the availability of higher yielding clones and improved cultural practices, this impact, however, may be minimized.
- If rainfall increases, loss of tapping days and crop washout occur. As a result, yielding losses can range from 13 to 30%. Thus, if the number of rain days were to increase, then most parts of the country will suffer from rainfall interface with tapping.
- If sea level rises by 1 m, low-lying areas may be flooded. Rubber cultivation in these areas would not be possible.

Table IX shows the projected rubber yield in relation to climate change over time.

(2) *Oil palm.* Oil palm is best suited to a humid tropical climate in which rain occurs mostly at night and days are bright and sunny. For optimum yield, minimum monthly rainfall required is around 1500 mm with absence of dry seasons, and an evenly distributed sunshine exceeding 2000 h per year. A mean maximum temperature of about 29–33 °C and a mean minimum temperature of 22–24 °C favor the highest bunch production.

- A high mean annual temperature of 28–31 °C is favorable for high production. If these higher temperatures lead to drought conditions, however, an estimated 208,000 ha of land or 12% of the present oil palm areas would be considered marginal-to-unsuitable for oil palm cultivation, particularly in drought-prone areas.
- Increased rainfall favors oil palm productivity unless it leads to flooding. With an anticipated sea level rise of 1 m, an estimated 100,000 ha of area, currently planted with oil palm, may be deemed unsuitable and would have to be abandoned.

TABLE IX
Projected rubber yield with climate change

Year 2020			
CO ₂ (ppm)	400	400	400
Temperature Increase °C	0.3	0.85	1.4
Rainfall change (%)			
+14%	1.26	1.26	1.23
+7%	1.44	1.44	1.42
+0.4%	1.60	1.60	1.60
0%	1.60	1.60	1.60
−0.4%	1.60	1.60	1.60
−7%	1.55	1.55	1.54
−14%	1.46	1.46	1.44
Year 2040			
CO ₂ (ppm)	600	600	600
Temperature Increase °C	0.4	1.4	2.4
Rainfall change (%)			
+23%	1.42	1.42	1.42
+11%	1.53	1.53	1.53
+0.7%	1.80	1.80	1.80
0%	1.80	1.80	1.80
−0.7%	1.80	1.80	1.80
−11%	1.69	1.69	1.69
−23%	1.53	1.53	1.49
Year 2060			
CO ₂ (ppm)	800	800	800
Temperature Increase °C	0.6	2	3.4
Rainfall change (%)			
+32%	1.40	1.40	1.40
+15%	1.58	1.58	1.58
+1%	2.00	2.00	2.00
0%	2.00	2.00	2.00
−1%	2.00	2.00	1.82
−15%	1.80	1.78	1.72
−32%	1.60	1.60	1.52

Table X shows the projected oil palm yield in relation to climate change. It can be seen that a decrease in rainfall affects yield significantly.

- (3) *Cocoa*. Although cocoa is planted in areas where annual rainfall is in the range of 1250–2800 mm, it prefers areas where annual rainfall is in the range of 1500–2000 mm and the number of dry months is three or less. It should not be

TABLE X
Projected oil palm yield with climate change

Year 2020			
CO ₂ (ppm)	400	400	400
Temperature Increase °C	0.3	0.85	1.4
Rainfall change (%)			
+14%	21.5	21.5	21.5
+7%	23.0	23.0	23.25
+0.4%	22.5	22.5	22.75
0%	22.0	22.0	22.0
−0.4%	22.0	22.0	22.0
−7%	17.6	17.6	17.0
−14%	15.4	15.4	15.4
Year 2040			
CO ₂ (ppm)	600	600	600
Temperature Increase °C	0.4	1.4	2.4
Rainfall change (%)			
+23%	24.0	24.0	24.0
+11%	25.0	25.0	25.0
+0.7%	24.5	24.5	24.5
0%	24.0	24.0	24.0
−0.7%	23.5	23.5	23.0
−11%	19.2	19.2	18.7
−23%	15.6	15.6	14.9
Year 2060			
CO ₂ (ppm)	800	800	800
Temperature Increase °C	0.6	2	3.4
Rainfall change (%)			
+32%	26.0	26.0	26.0
+15%	27.0	27.0	26.0
+1%	26.0	26.0	25.0
0%	26.0	26.0	26.0
−1%	24.0	24.0	22.0
−15%	18.0	18.0	15.6
−32%	14.3	14.3	13.0

planted in areas with annual rainfall below 1250 mm, unless irrigation is provided. Areas with annual rainfall exceeding 2500 mm are also not favorable as it reduces yield by 10–20% due to water logging. Besides, the excessive rainfall causes high disease incidence, especially *Phytophthora* and pink diseases.

- Most of the cocoa-growing areas have maximum temperature ranges of 30–32 °C and minimum temperature of 18–21 °C. The temperatures in Malaysia is within this range throughout the year. The temperatures exceeding 32 °C may result in moisture stress, leading to yield of 10–20%.
- Based on these considerations, the states that experience a distinct dry season are marginal areas for cocoa cultivation. Irrigation is required in these areas if cocoa is to be cultivated.
- Some areas, which register high rainfall, are not suited for cocoa cultivation due to the high incidence of diseases. This can result in yield loss of more than 20%.
- With climate change, a high incidence of drought is expected to reduce yield. On the other hand, excessive rainfall with reduced insolation can also result in low yields. In addition, under such weather conditions, a high incidence of fungal diseases such as vascular streak disease and black pod can depress yields.

Table XI shows that cocoa yield is sensitive to both excessive and reduced rainfall. In both cases, the yield is decreased.

- (4) *Rice*. Rice constitutes 98% of total cereal production in Malaysia. Generally, long periods of sunshine are favorable for high rice yields. Growth is optimal when the daily air temperature is between 24 and 36 °C. The difference between day and night temperatures must be minimal during flowering and grain production.

Climate change can affect rice production in the following ways:

- Grain yields may decline by 9–10% for each 1 °C rise in temperature.
- If drought conditions are prolonged, the current flooded rice ecosystem can not be sustained. It may be necessary to develop non-flooded and dry land rice ecosystem to increase the level of national rice sufficiency.

National food security may thus be threatened in both cases. Table XII shows that rice yield is sensitive to climate change.

5.4.2.3. *Impacts of Climate Change on Forestry*. Table XIII shows the impacts of climate change on forests in Malaysia by examining its physiological process, geographical distribution and biodiversity.

- (1) *Physiology of the forest*. Several climate variables such as air temperature, moisture availability and the concentration of ambient CO₂ have direct effects on forest physiology, depending on the species, location, nutrient levels of the soil and the other environmental conditions. Current scientific understanding indicates that elevated CO₂ concentrations may lead to increased biomass growth by as much as 40%, resulting from stimulated photosynthesis, leading

TABLE XI
Projected cocoa yield with climate change

Year 2020			
CO ₂ (ppm)	400	400	400
Temperature Increase °C	0.3	0.85	1.4
Rainfall change (%)			
+14%	1.86	1.59	1.54
+7%	2.10	1.85	1.79
+0.4%	3.10	2.65	2.56
0%	3.10	2.65	2.56
−0.4%	3.10	2.65	2.56
−7%	2.79	2.39	2.30
−14%	2.79	2.39	2.30
Year 2040			
CO ₂ (ppm)	600	600	600
Temperature Increase °C	0.4	1.4	2.4
Rainfall change (%)			
+23%	1.55	1.33	1.02
+11%	2.17	1.86	1.44
+0.7%	3.10	2.65	2.05
0%	3.10	2.65	2.05
−0.7%	3.10	2.65	2.05
−11%	2.79	2.39	1.85
−23%	2.48	2.12	1.64
Year 2060			
CO ₂ (ppm)	800	800	800
Temperature Increase °C	0.6	2	3.4
Rainfall change (%)			
+32%	1.33	1.25	0.95
+15%	1.59	1.50	1.14
+1%	2.65	2.50	1.90
0%	2.65	2.50	1.90
−1%	2.65	2.50	1.90
−15%	2.39	2.25	1.71
−32%	1.59	1.50	1.14

to in increased concentrations of CO₂ inside the leaves. On the other hand, higher CO₂ level may reduce the nitrogen to carbon ration in plant tissue that may affect the rate of litter breakdown. Trees in the forest also respond positively to temperature increase; the temperature and primary productivity

TABLE XII
Projected rice yield with climate change

Year 2020			
CO ₂ (ppm)	400	400	400
Temperature Increase °C	0.3	0.85	1.4
Rainfall change (%)			
+14%	6.15	5.81	5.59
+7%	6.65	6.31	6.09
+0.4%	7.20	6.86	6.64
0%	7.20	6.86	6.64
−0.4%	7.20	6.86	6.64
−7%	6.67	6.38	6.18
−14%	6.19	5.90	5.71
Year 2040			
CO ₂ (ppm)	600	600	600
Temperature Increase °C	0.4	1.4	2.4
Rainfall change (%)			
+23%	7.34	6.94	6.54
+11%	8.20	7.80	7.40
+0.7%	9.04	8.64	8.24
0%	9.04	8.64	8.24
−0.7%	9.04	8.64	8.24
−11%	8.05	7.69	7.34
−23%	6.96	6.65	6.35
Year 2060			
CO ₂ (ppm)	800	800	800
Temperature Increase °C	0.6	2	3.4
Rainfall change (%)			
+32%	8.62	8.06	7.50
+15%	9.83	9.27	8.71
+1%	10.96	10.4	9.84
0%	10.96	10.4	9.84
−1%	10.96	10.4	9.84
−15%	9.32	8.84	8.37
−32%	7.45	7.07	6.69

are positively correlated by this and depend on the availability of water, which is in turn is dependent on rainfall distribution.

- (2) *Forest distribution.* Given the temperature and CO₂ concentration projections of some global climate models, the expansion of upland forest by 5–8% may be expected. This would however be nullified by a loss between 15 and 20% of mangrove forests located along the coastline as a result of sea level rise. The

TABLE XIII
Impacts of climate change on forests in Malaysia

Process/habitat	Impacts
Physiological process	Up to 40% increase in biomass growth due to increase in photosynthesis processes
Forest distribution/habitat	
Upland tropical rainforest	Expansion of suitable forest areas by 5–8%
Mangrove forest	Reduction in mangrove area by 15–20% due to sea level rise
Forest plantation	Minimal impacts due to its limited area
	Increased susceptibility to pest and infestation of diseases
	Increased fire occurrence

problem of climate-change-induced disease infestation in forest plantation species may also occur.

Forest biodiversity. Tropical forests in Malaysia are rich in diversity, and therefore, the impacts of climate change on biodiversity are of great concern. The change in the climate has likely effects on species composition of the forest, but marked variations are expected due to local effects of soil and topography. Given the intricate interrelationships between plant and animal species in tropical forests, the impact on any species will have inevitable consequences for other species as well.

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IMPACTS OF PRESENT AND FUTURE CLIMATE VARIABILITY ON AGRICULTURE AND FORESTRY IN THE TEMPERATE REGIONS: EUROPE

GIANPIERO MARACCHI,¹ OLEG SIROTENKO,² and MARCO BINDI³

¹IBIMET-CNR, Piazzale le delle Pascine 18, 51044 Florence, Italy

²ARRIAM, Lenin Street 82, 249020 Obninsk, Russia

³DISAT-UNIFI, Piazzale le delle Pascine 18, 51044 Florence, Italy

E-mail: marco.bindi@unifi.it

Abstract. Agriculture and forestry will be particularly sensitive to changes in mean climate and climate variability in the northern and southern regions of Europe. Agriculture may be positively affected by climate change in the northern areas through the introduction of new crop species and varieties, higher crop production and expansion of suitable areas for crop cultivation. The disadvantages may be determined by an increase in need for plant protection, risk of nutrient leaching and accelerated breakdown of soil organic matter. In the southern areas the benefits of the projected climate change will be limited, while the disadvantages will be predominant. The increased water use efficiency caused by increasing CO₂ will compensate for some of the negative effects of increasing water limitation and extreme weather events, but lower harvestable yields, higher yield variability and reduction in suitable areas of traditional crops are expected for these areas. Forestry in the Mediterranean region may be mainly affected by increases in drought and forest fires. In northern Europe, the increased precipitation is expected to be large enough to compensate for the increased evapotranspiration. On the other hand, however, increased precipitation, cloudiness and rain days and the reduced duration of snow cover and soil frost may negatively affect forest work and timber logging determining lower profitability of forest production and a decrease in recreational possibilities. Adaptation management strategies should be introduced, as effective tools, to reduce the negative impacts of climate change on agricultural and forestry sectors.

Introduction

The role of climate variability in affecting human activities and the natural environment is well accepted. This may range from an extreme event lasting only a few hours (i.e. hurricane, thunderstorm and showers) through to the multi-year droughts (e.g. West and Sahelian Africa and Iberian Peninsula drought spells).

Climate change due to the enhanced greenhouse effect is also expected to strongly affect these activities and environments. Primary sectors, such as agriculture and forestry, will be more sensitive than secondary and tertiary sectors, such as manufacturing and retailing (Parry, 2000). In particular, in Europe the balance of impacts of climate change will be more negative in marginal regions (south and east) than in core regions (metropolitan northwest) aggravating current economic

and social problems. Consequently, climate change will have major implications for Europe's policies of development and environmental management.

This work is focussed on reviewing the impact of climate variability and climate change on European agriculture and forestry. In particular, the paper illustrates the responses of ecosystems to changes in mean and variability of climate, as well as the main management strategies adopted to avoid or at least reduce negative climate change impacts.

Agriculture and Forestry in Europe

Europe is one of the world's largest and most productive suppliers of food and fibre; it accounts for substantial outputs of both arable crops and animal products (FAOSTAT, 2001). The agriculture in Europe accounts for a small part of the total GDP and the total employment. Thus, the vulnerability of the overall economy to changes that affect agriculture is generally low (Reilly, 1996), but local effects may be large.

Five major agricultural regions can be discerned in Europe as described by Kostrowicki (1991). These regions are determined by both environmental and socio-economic factors. *Zone I* is the northern region, where agriculture is mainly market oriented, with extensive cattle breeding. *Zone II* includes the Atlantic and Central Continental regions that are characterised mainly by intensive and market-oriented agriculture. *Zone III*, including the Mediterranean countries, shows diverse patterns of agriculture, ranging from a market-oriented type with mainly typical crop cultivation (e.g. fruit trees, olive and grapes) to considerable areas of traditional type. *Zone IV* is the eastern region, where traditional agriculture is still predominant, but the proportion of market-oriented and socialised agriculture has been rapidly changing. *Zone V* is the European part of the former USSR, which was dominated by large-scale socialised agriculture, but is now slowly adapting to a more quality oriented agriculture. The trends in European agriculture are dominated by the Common Agricultural Policy (CAP) of the European Union. This occurs because the EU member states cover a large proportion of the agricultural production in Europe, and because several countries are currently seeking membership of the EU and in this process are adjusting their policy to match the CAP.

Agriculture in Europe competes with other sectors for land and employees. This has caused in the last 30 years a strong reduction in the agricultural area and employment. Thus, the future of the European agriculture will be related to the need to feed the world's population. The population of Europe is not expected to increase substantially, whereas in the other parts of the world the population and the type of diet are expected to rapidly increase and change, respectively (Penning de Vries et al., 1995).

The forests in Europe range from semiarid condition in the Mediterranean region, through temperate in western and central Europe, to cool in northern Europe. In

agreement with these different climate conditions over Europe, the forests may be divided into: (a) Boreal, that are the forests in the European part of the boreal zone; (b) Temperate, that are located in central Europe, and are divided into Atlantic and Continental forests on the basis of the differences in the availability of soil water; and (c) Mediterranean, that are the forests in the dry temperate zone in the Mediterranean Basin (Kellomäki, 2000).

In total, the forest area in Europe is 956 Mha, of which 85% is Boreal, 2% Atlantic, 9% Continental and 4% Mediterranean (Kellomäki, 2000). The stocking and growth per hectare is larger in the Atlantic and Continental forests than in the Boreal and Mediterranean forests. In each forest region, however, growth exceeds cutting with increasing stocking and maturing of forest resources. Throughout Europe, the majority of forests are managed except in north-western Russia where there is a dominance of old-growth natural forests. In northern Europe, forestry is mainly based on native tree species, which invaded this region post-glacially. The role of introduced species is especially large in the Atlantic forests. The productivity of the introduced conifers exceeds substantially that of the native deciduous species making the introduced conifers economically attractive (Kellomäki, 2000).

Climate of Europe

The climate of Europe shows large differences from west (Maritime) to east (Continental) and from north (Arctic) to south (Mediterranean) (Figure 1). The climatic effects of the distribution of land and ocean are further complicated by numerous high mountain ranges which act as physical barriers to atmospheric circulation and often introduce large precipitation gradients within small regions (Frei and Schär, 1998).

The studies carried out using the European long data records have shown some evident trends in European climate. Most of Europe has revealed increases in surface air temperature during the 20th century which, averaged across the continent, amounts to about 0.8 °C in annual temperature (ECSN 1995; EEA 1998; Beniston et al., 1998) (Figure 2). This warming has been largest over north-western Russia and the Iberian Peninsula (Nicholls et al., 1996; Onate and Pou, 1996) and stronger in winter than in summer (Maugeri and Nanni, 1998; Brunetti et al., 2000). An exception is Fennoscandia, which has recorded cooling in both mean maximum and mean minimum temperature during (1910–1995) in winter but warming in summer (Tuomenvirta et al., 1998). The last decade in Europe (1990–1999) has been the warmest in the instrumental record, both annually and for winter. Increases in growing season length have also been observed in Europe, for example in western Russia (Jones and Briffa, 1995) and in Fennoscandia (Carter, 1998). The evidence for longer growing seasons in Europe is also supported by phenological data collected in central Europe (Menzel and Fabian, 1999). Trends in annual precipitation differ between northern Europe (wetting) and

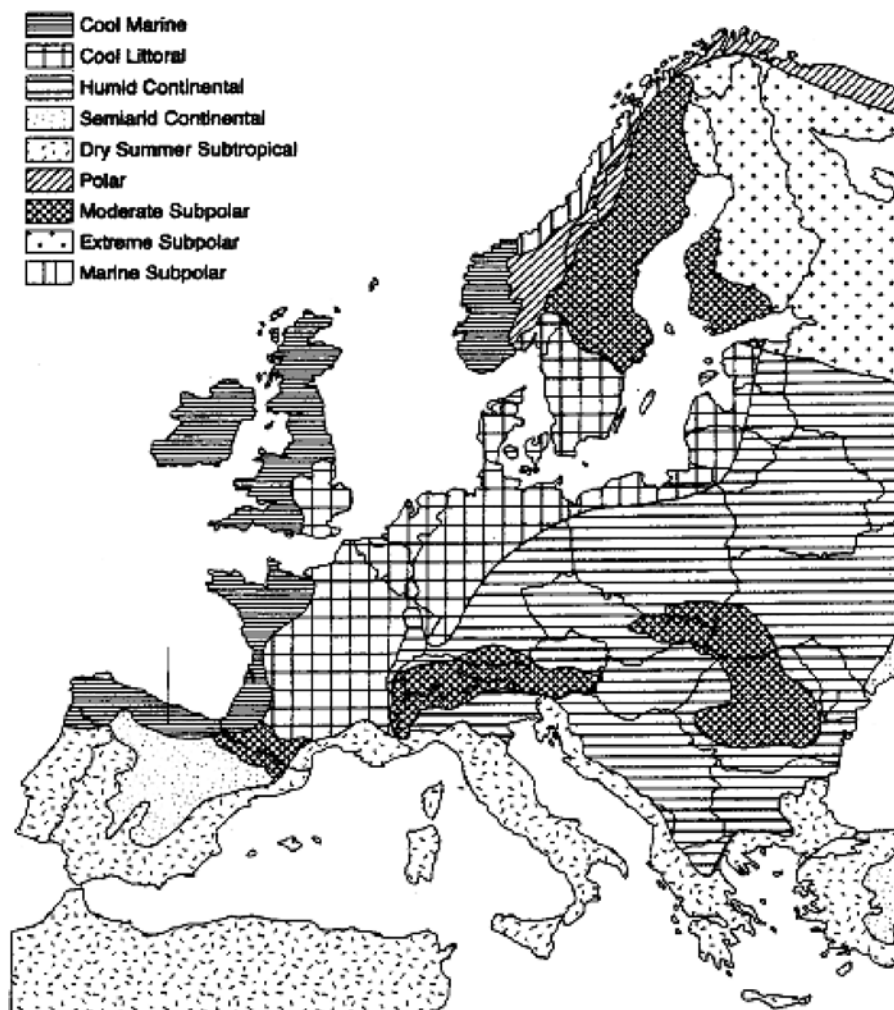


Figure 1. Climate classification for Europe (adapted from Koeppel and de Jong, 1958) (Palutikof, 2000).

southern Europe (drying), reflecting a wider hemispheric pattern of contrasting zonal-mean precipitation trends between high and low latitudes (Dai et al., 1997; Hulme et al., 1998). Precipitation over northern Europe has increased by between 10 and 40% in the 20th century, whereas some parts of southern Europe have dried by up to 20%.

Analyses of trends in extreme weather events in Europe have generally been limited to national studies, making it difficult to provide a Europe-wide overview. However, the studies made by Gruza et al. (1999) over Russia and that made by Osborn et al. (2000) over UK showed a diffuse increase in hot/cold day frequencies, precipitation intensities, etc.

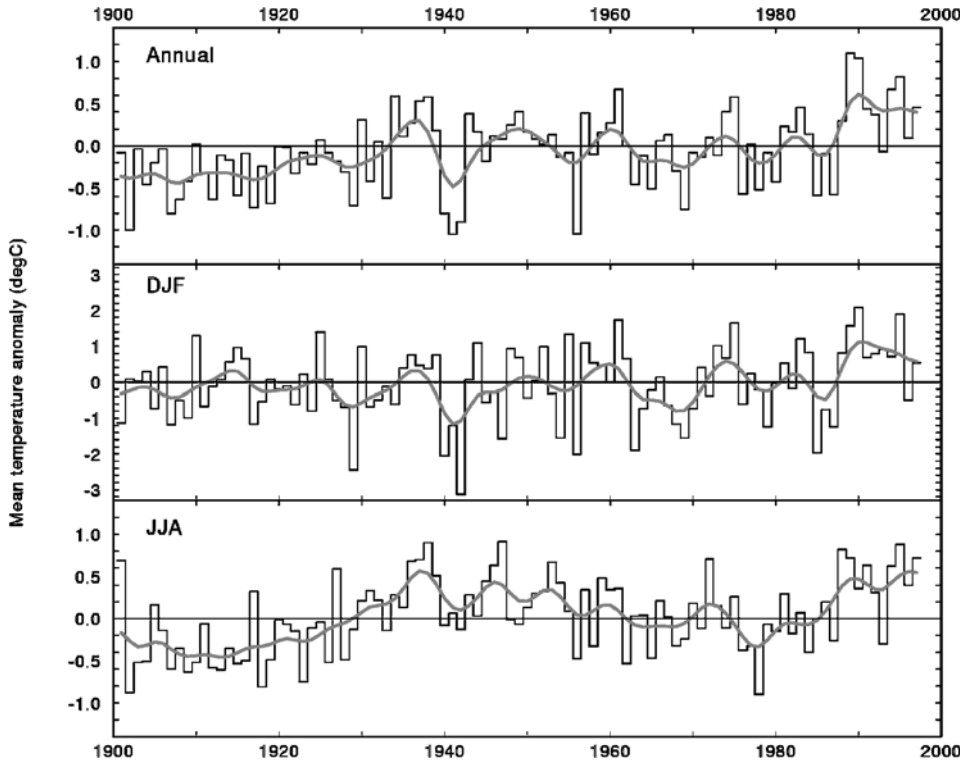


Figure 2. European mean temperatures anomalies over land, 1901–1997, with respect to 1961–1990 average. Annual (top), winter (middle) and summer (bottom) (data from IPCC DDC).

Projection of future climate in impact studies are mainly obtained using climate scenarios based on General Circulation Model simulations. A recent work carried out within the ACACIA project and subsequently developed further for the IPCC (Hulme and Carter, 2000) has provided a complete set of future climate scenarios for Europe.

Annual temperatures over Europe warm at a rate of between 0.1 and 0.4 K per decade. This warming of future annual climate is greatest over southern Europe (Spain, Italy, Greece) and northeast Europe (Finland, western Russia), and least along the Atlantic coastline of the continent. Seasonal patterns indicated that in winter, the continental interior of eastern Europe and western Russia warm more rapidly than elsewhere. Whilst in summer, the pattern of warming displays a strong south-to-north gradient, with southern Europe warming at a lower rate than northern Europe.

The general pattern of future change in annual precipitation over Europe is for widespread increases in northern Europe (between +1 and +2% per decade), rather smaller decreases across southern Europe (maximum: –1% per decade), and small or ambiguous changes in central Europe (France, Germany, Hungary, Belarus).

There is a marked contrast between winter and summer patterns of precipitation change. Most of Europe gets wetter in the winter season (between +1 and +4% per decade), the exception being the Balkans and Turkey where winters become drier. In summer, there is a strong gradient of change between northern Europe (wetting of up to +2% per decade) and southern Europe (drying of up to -5% per decade).

The scenarios do not explicitly quantify changes in daily weather extremes. However, it is very likely that frequencies and intensities of summer heat-waves will increase throughout Europe, likely that intense precipitation events will increase in frequency, especially in winter, and that summer drought risk will increase in central and southern Europe (Hulme and Carter, 2000).

Impact of Climate on Agriculture and Forestry in Europe

Temperature, incoming solar radiation, water and nutrient availability are the main factors that generally determine agriculture production. Biological systems are based primarily on photosynthesis, and thus dependent on incoming radiation. The potential for production determined by the radiation is greatly modified by temperature and rainfall. The main effect of temperature is to control the duration of the growth period (Long and Woodward, 1988). Moreover, also other processes linked with the accumulation of dry matter (leaf area expansion, photosynthesis, respiration, evapotranspiration, etc.) are affected by temperature. Rainfall and soil water availability may affect the duration of growth through leaf area duration and the photosynthetic efficiency through stomatal closure.

Also, animal behaviour and production are affected by these factors. These like man are homoeotherms, thus they have a comfort zone within which the climatic factors produce no stress on metabolism. When ambient heating exceeds or is insufficient to maintain temperature within this zone, cold and heat stresses are produced. These stresses may be mediated by low temperatures, precipitation and high wind speeds, or by high temperatures and droughts, respectively. Both stresses cause lower food and higher water intake, which results in lower general performance (Fuquay, 1989). Moreover climatic factors have indirect effects on animal production (loss in weight and condition) via decreases in quality and quantity of forage.

These general climatic constraints on agricultural production are modified by local climatic constraints. In Northern countries the length of growing season, late spring and early autumn frost and solar radiation availability are typical climatic constraints. In these environments the duration of the growing season (frost or snow-free period) limits the productivity of crops. For example, in Germany the growing season is 1-3 months longer than in Scandinavian countries (Mela, 1996). The short growing season is the main cause of the lower cereal grain yields in the

Nordic countries. Moreover, night frosts in the late spring or early autumn increase the agricultural risk in these environments.

The wet conditions along the Atlantic coast and in the mountainous regions causing cold and rainy summers, limit the availability of solar radiation and cause yield and quality losses of many arable crops. This is the main reason for the low cereal area on the British Isles and Alpine countries compared with other regions.

In the Mediterranean countries cereal yields are limited by water availability, heat stress and short duration of the grain filling period. Cereals are therefore less important in this region. Permanent crops (olive, grapevine, fruit trees, etc.) are important here. These crops are affected by extreme weather events (such as hail and storms) which can reduce or completely destroy yield. Irrigation is important for crop production in many Mediterranean countries due to high evapotranspiration and restricted rainfall.

The continental climate of eastern Europe (from central Poland and eastwards), causing drier conditions and greater amplitude of the annual temperature cycle, limits the range of crops that can be grown. The most productive regions in Europe in terms of climate and soils are located in the great European plain stretching from Southeast England through France, Benelux and Germany into Poland. There are additional lowland regions, e.g. Hungarian plains, where equally favourable conditions are available.

The range of European forests is limited primarily by climate, either through moisture availability or through temperature (both absolute amounts and seasonal distributions) (Berninger, 1997). Some forests (particularly in the North) are also nutrient-limited. The structure and composition of many forests is further influenced by the natural disturbance regime (fire, insects, wind-throw, etc.). Most European forests are managed for one or several purposes, such as timber production, water resources, or recreation. This management has reduced forest area or strongly modified forest structure in most of Europe, and presently existing forests often consist of species that are different from those that would occur naturally.

Examining in detail the influence of climate on European forests, the existing south–north climate gradient implies decreasing temperature and increasing humidity with decreasing water limitation and increasing temperature limitation for forests. Whilst, on the west–east climate gradient, the maritime climate turns to the continental one with decreasing humidity and increasing water limitation for forests. In line with these gradients over Europe, and as has been already reported previously, the forests may be divided into Boreal forests (boreal zone), Atlantic forests (humid temperate forests), Continental forests (dry temperate forests) and Mediterranean forests.

In the Boreal forest, the growth and productivity are mainly limited by winter temperatures that determine the length of the growing season through the duration of snow cover and soil frost. In Atlantic forests, strong winds play an important role in determining the forest productivity through their effects on evapotranspiration and then water availability. In the southern parts of the Atlantic forests, in the Continental

and Mediterranean forests the summer precipitations are the main constraint factor of forest growth and productivity through their role in determining the frequency of droughts.

Impact of Climate Change on Agriculture and Forestry

Many recent studies have assessed effects of climate change on agricultural productivity (e.g. Harrison et al., 1995a, 2000). These studies have been mainly made on cropping systems (annual and perennial crops, grassland, etc.), however, livestock systems have also been examined.

The climate warming is expected to expand the area of cereal cultivation (e.g. wheat and maize) northwards (Kenny et al., 1993; Harrison et al., 1995b; Carter et al., 1996) (Figure 3). For wheat, a temperature rise will lead to a small yield reduction, whereas an increase in CO₂ will cause a large yield increase and the net effect of both for a moderate climate change is a large yield increase (Harrison and Butterfield, 2000; Nonhebel, 1996). Drier conditions and increasing temperatures in the Mediterranean region and parts of eastern Europe may lead to lower yields and the need for new varieties and cultivation methods. Yield reductions have been estimated for eastern Europe, while yield variability may increase, especially in the steppe regions (Alexandrov, 1997; Sirotenko et al., 1997). In Figure 4 the response of wheat yields to change of climate and CO₂ concentration for a GCM scenario for 2050 (Harrison and Butterfield, 2000) is reported. The largest increases in yield occur in southern Europe, particularly in northern Spain, southern France, Italy and Greece. Relatively large yield increases (3–4 t ha⁻¹) are also seen in Fenno-Scandinavia. In the rest of Europe, yields are between 1 and 3 t ha⁻¹ greater than

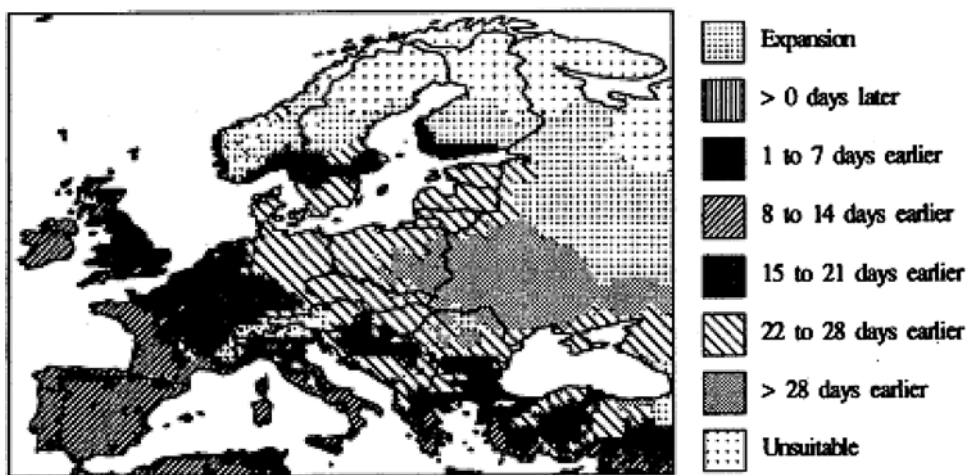


Figure 3. Change in the duration from sowing to maturity for winter wheat (cv. Avalon) under UK Transient scenario 2066-75 (from Harrison et al., 1995b).

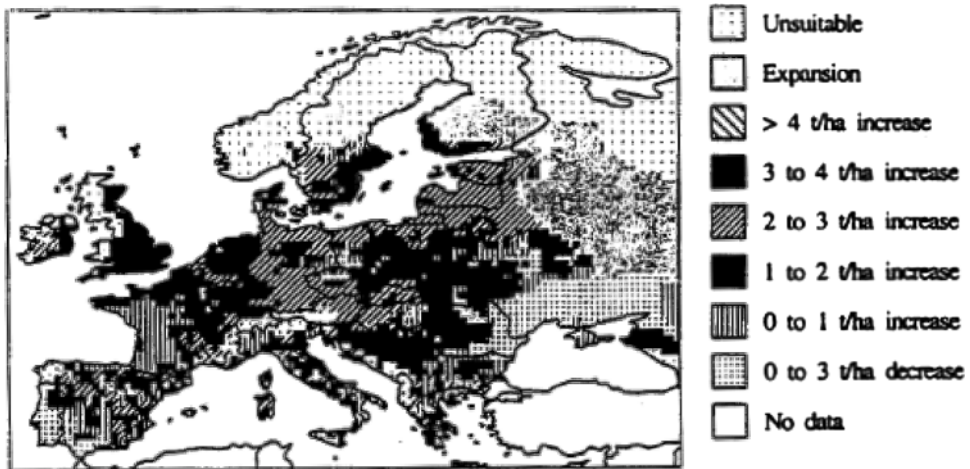


Figure 4. Change in water limited yield for wheat using HadCM2 scenarios for 2050 (from Harrison and Butterfield, 2000).

at present. There are small areas where yields are predicted to decrease by up to 3 t ha⁻¹, such as in southern Portugal, southern Spain and the Ukraine. For maize, future climate scenario analyses carried out for selected sites in Europe suggest mainly increases in yield for northern areas and decreases in southern areas (Wolf and van Diepen, 1995). This is due to a small effect of increased CO₂ concentration on growth (maize is a C₄ plant which responds less positively to CO₂ increases than C₃ plants such as wheat and barley) and a negative effect of temperature on the duration of growing season. This latter effect, however, can largely be prevented by growing other maize varieties (Wolf and van Diepen, 1995).

Seed crops are generally determinate species, and the duration to maturity depends on temperature and day length. A temperature increase will therefore shorten the length of the growing period and possibly reduce yields (Peiris et al., 1996). At the same time, the cropping area of the cooler season seed crops (e.g. pea, faba bean and oil seed rape) will probably expand northwards into Fenno-Scandinavia, leading to increased productivity of seed crops there. There will also be a northward expansion of warmer season seed crops (e.g. soybean and sunflower). Harrison et al. (1995b) estimated this northward expansion for sunflower, but also found a general decrease in water-limited yield of sunflower in many regions, particularly in western Europe (Figure 5). Analysis of effect of climatic change on soybean yield for selected sites in western Europe suggests mainly increases in yield (Wolf, 2000a). This is due to a positive effect of CO₂ concentration on growth and only a small effect of temperature on crop duration.

Vegetable responses to changes in temperature and CO₂ varies among species, mainly depending on the type of yield component and the response of phenological development to temperature change. For determinate crops such as onions, warming

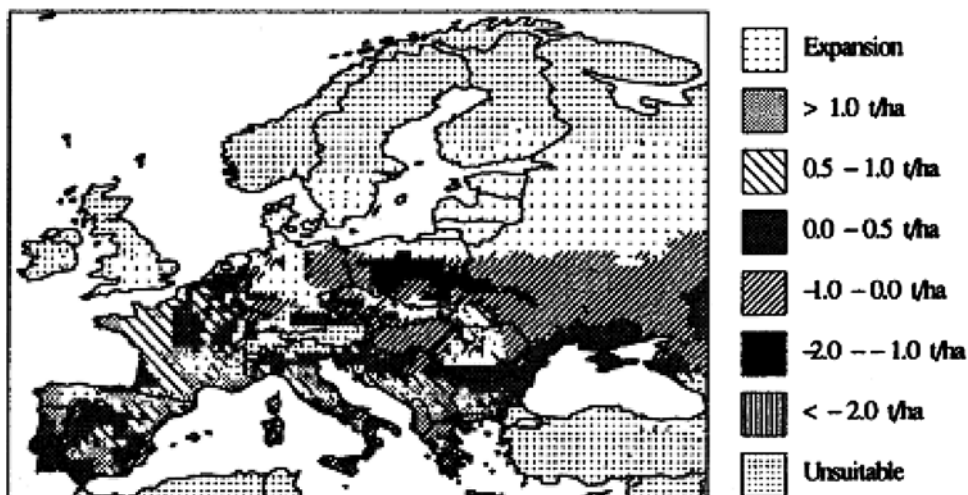


Figure 5. Change in water limited yield for sunflower (cv. Cerflor) under UK Transient scenario 2066–75 (from Harrison et al., 1995b).

will reduce the duration of crop growth and hence yield (Harrison et al., 1995b), whereas warming stimulates growth and yield in indeterminate crops such as carrots (Wheeler et al., 1996). Onion yields are sensitive to the degree of warming (Harrison et al., 1995b), with a yield decrease for warmer future climate scenarios and a yield increase for cooler future climate scenarios. There is also a spatial gradient with yield increases in northwest Europe to decreases in southeast Europe (Figure 6). For lettuce, temperature has been found to have little influence on yield, whereas yield is

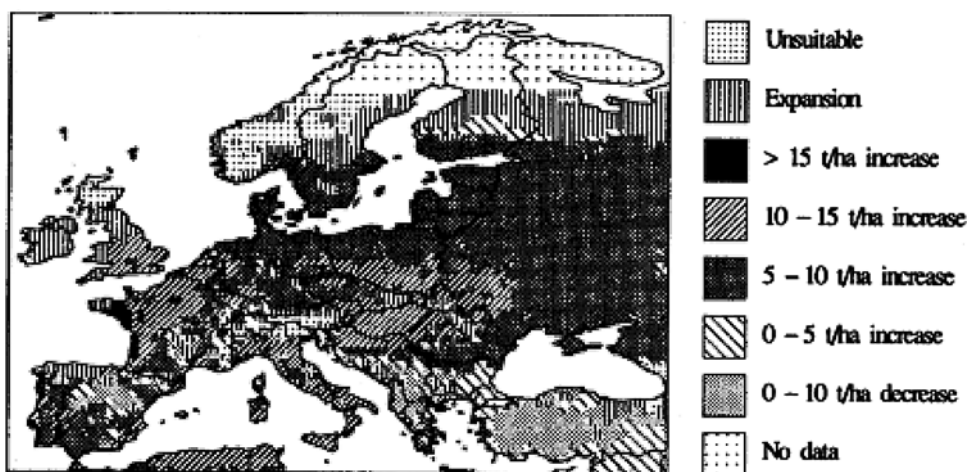


Figure 6. Change in potential yield for onion under UK Transient scenario 2066–75 (from Harrison et al., 1995b).

stimulated by increasing CO₂ (Pearson et al., 1997). For cool-season vegetable crops such as cauliflower, large temperature increases may decrease production during the summer period in southern Europe due to decreased yield quality (Olesen and Grevsen, 1993).

Root and tuber crops are expected to show a large response to rising atmospheric CO₂ due to their large underground sinks for carbon and apoplastic mechanisms of phloem loading (Farrar, 1996; Komor et al., 1996). On the other hand, warming may reduce the growing season and enhance water requirements with consequences on yield. Climate change scenario studies performed using crop models show increases in potato yields in northern Europe and decreases or no change in the rest of Europe (Wolf, 2000b). The simulation results showed an increase in yield variability for the whole Europe, which enhance the risk for this crop. Indeterminate root crops such as sugar beet may be expected to benefit from both the warming and the increase in CO₂ concentrations (Davies et al., 1997).

Perennial crops (e.g. grapevine, olive and energy crops) have been relatively less studied than annual crops. For grapevine, a study on the potential cultivation of grapevine in Europe under future climate scenarios has shown that there is a potential for an expansion of the wine growing area in Europe and also for an increase in yield (Figure 7). Moreover, detailed predictions made for the main EU viticultural areas have shown an increase in yield variability (fruit production and quality) (Bindi et al., 1996, 2000). For olive, it was shown that in 2 × CO₂ case, the suitable area for olive cultivation could be enlarged in France, Italy, Croatia, and Greece due to changes in temperature and precipitation patterns (Bindi et al., 1992). For indeterminate energy crops that are favoured by the longer growing season and by increased water use efficiency due to higher CO₂ levels, higher temperatures and CO₂ concentrations would generally be favourable. A study of willow production in

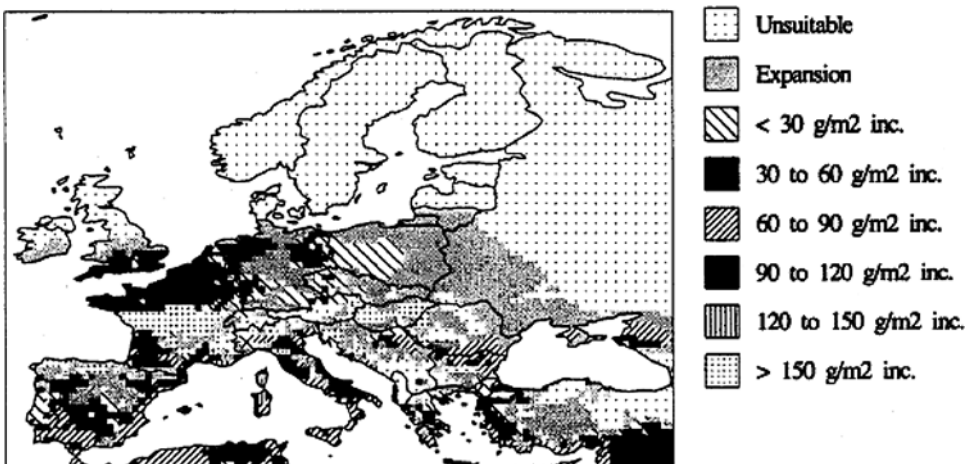


Figure 7. Change in potential yield for grapevine using HadCM2 scenarios for 2050 (from Harrison and Butterfield, 2000).

the UK thus found that a warming would generally be beneficial for production with increases in yield up to 40% for a temperature increase of 3 K (Evans et al., 1995).

Livestock systems may be influenced by climate change directly by means of effects on animal health, growth, and reproduction, and indirectly through impacts on productivity of pastures and forage crops. Heat stress has several negative effects on animal production, including reduced reproduction and milk production in dairy cows and reduced fertility in pigs (Furquay, 1989). This may negatively affect livestock production in summer in currently warm regions of Europe. Warming during the cold period for cooler regions is likely to be beneficial due to reduced feed requirements, increased survival, and lower energy costs. The impact of climate change on grasslands will affect the indirectly livestock living of these pastures. In Scotland studies of the effect on grass-based milk production indicate that these vary depending on the locality. For herds grazed on grass-clover swards milk output may increase regardless of site, due to the CO₂ effect on nitrogen fixation (Topp and Doyle, 1996).

The response of forest ecosystems to climate change can be expressed in terms of boundaries shift, changes in productivity and in risk of damages (e.g. fire damage).

In northern Europe, Boreal forests are dominated by *Picea abies* and *Pinus sylvestris*; these species under warmer conditions would invade tundra regions (Sykes and Prentice, 1996). In the southern Boreal forests, these species will be expected to decline due to a concurrent increase of deciduous tree species (Kellomäki and Kolström, 1993). Most climate change scenarios suggest a possible overall enlargement of the climatic zone suitable for Boreal forests by 150–550 km over the next century (Kirschbaum et al., 1996). In particular, in the Russian region tundra and taiga areas would be sharply reduced and replaced by leaf-bearing and steppe (Sirotenko et al., 1997).

In large areas of western and central Europe, the temperature increase would determine a replacement of natural conifers with the more competitive deciduous trees. Site-specific assessments performed for Germany suggests that conifers (e.g. *Picea abies*) may be replaced by deciduous species (e.g. *Fagus sylvatica*) (e.g. Kräuchi, 1995; Bugmann, 1997). Furthermore, the increase in winter temperature seems to allow the survival of exotic species (e.g. *Nothofagus procera* in Britain) (Cannell, 1985).

In southern Europe, most forests consist of sclerophyllous and some deciduous species that are adapted to summer soil water deficit. Climate scenarios indicate reduced water availability in the summer months and associated increases in temperature. These conditions may determine the relative importance of sclerophyllous and deciduous species changes, with, for example, expansion of some thermophilous tree species (e.g. *Quercus pyrenaica*) when water availability is sufficient (e.g. Gavlán and Fernández-González, 1997).

Global warming, increasing CO₂, increased nitrogen deposition and changes in management practices are all factors assumed to favour increase of forests productivity. In northern Europe, effects of precipitation changes are likely to be much less

important than the effects of temperature changes (Kellomäki and Väisänen, 1996; Talkkari and Hypén, 1996); thus it could be concluded that climate change and CO₂ increase would be favourable for northern forests, e.g. due to increased regeneration capacity. In central and southern Europe, limited moisture due to increasing temperature and (possibly) reduced summer rainfall may regionally generate productivity decline. However, CO₂ enrichment will likely increase water use efficiency, which makes growth less drought-sensitive (Kellomäki, 2000). Furthermore, in the Mediterranean region, the elevation of summer temperature and reduction of precipitation may further increase fire risk. In temperate eastern Europe, forest fire increase is less likely, but very dry and warm years could occur more frequently, and promote pest and pathogen development. Estimates of the possible influence of climate change on insect infestation are uncertain due to complex interactions between forests, insects and climate. However, some preliminary studies indicates that increases in climate aridity would promote occurrence of some diseases (e.g. root and stem fungi decays) (Kellomäki, 2000).

Vulnerability of Agricultural and Forestry Ecosystems

Climate change could produce positive or negative effects on agriculture depending on the region and the ways in which the climate changes. Northern and southern regions of Europe will be particularly sensitive and in some cases vulnerable to these changes. Agriculture in northern Europe is likely to benefit from both a warming and the direct effect of increasing CO₂ concentration (Mela, 1996). The increased productivity will, however, be accompanied by an increased need for fertiliser and pesticide inputs with possible negative environmental effects, e.g. Sirotenko et al. (1997) showed an increase in the length of growing periods (15–22 days) and heat availability (460–560 °C) for agricultural crops in the Russian area that, however, in some arid regions might be partially offset by an reduction in soil moisture content in the warm season.

In southern Europe, climate changes are expected to produce limited benefit for agriculture, especially for summer crops. The combined increase in temperature and reduction in precipitation during summer may enhance the problem of water shortage. Moreover, the increases in climatic inter-annual variability and extreme events may also affect crop production. Thus, lower yield (shorter growing season, increase in water shortage, heat stress) and higher yield variability (increase in extreme events) is expected (Harrison et al., 2000). No areas may become completely unsuitable for agriculture. A reduction of suitable areas for traditional crops is however expected. This may be overcome by the introduction of new crops.

Particularly vulnerable regions throughout Europe are those areas where there is a large reliance on traditional farming systems and production of quality foods. Where such farming and production systems rely on favourable climatic conditions, climate change may cause large disruptions in the rural society. Farms with

large investments in infrastructure, buildings, machinery, land, etc., may be more vulnerable to rapid changes and require long lead times in decision making, especially in converting from one farming system to another.

In the boreal region, the current forests are most vulnerable at the polar and alpine timberline, because the structure and tree species composition of forests may be modified with a loss in their value for conservation, recreation and landscaping and reindeer husbandry. At the same time, however, the timber producing capacity of these forests may increase substantially, thus providing more opportunities for forestry.

In the Atlantic region, the forests at the coastal areas on sandy soils with low water holding capacity (e.g. Denmark) may be vulnerable due to limited water supply during summer time and the risk of wind damage. The summer drought may also affect the forests in continental Europe, especially the homogenous *Picea abies* forests may suffer for enhancement of attacks of insects and fungi and increase the risk of forest fire.

The vulnerability of forests will be very high in the Mediterranean region. This is mainly due to the summer precipitation, which no longer supports the present forest cover. This negative effect will be further enhanced by increasing the fire risk.

Adaptation Strategies

For spring crops, climate warming will allow earlier planting or sowing than at present. Earlier planting in spring increases the length of the growing season; thus earlier planting using long season cultivars will increase yield potential, if soil moisture is adequate and the risk of heat stress is low. Otherwise, earlier planting combined with a short-season cultivar would give the best assurance of avoiding heat and water stresses (Tubiello et al., 2000). For winter crops (i.e. cereals), a specific growth stage has to be reached before the onset of winter to ensure winter survival, thus they are often sown when temperatures approach the time when vernalisation is most effective (Harrison et al., 1995b). This may mean later sowings in northern Europe under a climatic warming (Harrison et al., 2000; Olesen et al., 2000). A specific study reported by Wolf (2000b) of the effectiveness of changes in potato crop management (i.e. variety, planting date, irrigation) showed that in northern Europe the impact of the crop variety on the calculated change in irrigated tuber yield under the climatic change scenarios was nil, whereas in water-limited conditions, yield increases were larger for the earlier varieties. Cultivation of earlier varieties resulted in more positive or less negative tuber yield changes under the climatic change scenarios in Southern Europe, because the hot summer period was avoided, both with and without irrigation. Moreover, also an advanced planting date would determine higher yields. Finally, both an early crop variety and an earlier planting date would considerably reduce irrigation requirements.

Changes of land use may be used as adaptation strategies to the differential response of crops to climate change. Studies reported by Parry et al. (1988) for central Europe showed an “optimal land use” in which the area cultivated with winter wheat, maize and vegetables increased, while the allocation to spring-wheat, barley, and potato decreased. Changes in land allocation may also be used to stabilise production or for the conservation of soil moisture.

The introduction of optimal agricultural technology (machine, fertiliser, fungicide, etc.) may be considered as a fundamental strategy for adapting agriculture to climate change, especially in east Europe. A simulation study made by Sirotenko et al. (1997) for the entire Russia showed as the introduction of the present-day technological level could allow to overcome the negative impact of climate change on cereal production.

Changes in farming systems may be necessary in some areas for farming to remain viable and competitive. This will be true especially for those farms, specialised in either specific livestock or arable farming, that are often linked to the local soil and climatic conditions. Their responses will be probably more sensitive to climate change than mixed farms. On mixed farms with both livestock and arable production there are more options for change, and thus a larger resilience to change in the environment.

Some of the main adaptive measures for forest regions have been illustrated by Kellomäki (2000). These include shorter rotations and regular thinnings that in the Boreal and northern parts of Atlantic forests may be developed to meet the faster growth of several existing tree species, due to increasing precipitation and reducing drought. The regular thinnings will also increase the mechanical strength of trees due to enhanced growth and thus reduce the risk of abiotic damage.

In southern parts of the Atlantic forests, shorter rotation, regular thinnings with wider spacing, and more tolerant species (e.g. conifers) may be included to avoid the increasing drought risk, determined by the reduction of precipitation. Furthermore, the increasing fire risk requires special measures.

In the Continental and Mediterranean forests, soil management and planting techniques, that are presently adopted in dry sub-tropics climate, need to be developed to meet the special conditions caused by increasing drought. The impacts of drought may also be reduced through using wider spacing in plantations and later thinnings. The increase in fire risk will require special measures, especially in the Continental forests.

Conclusions

The effects of global change on Europe are likely to increase productivity of agricultural and forestry systems, because increasing CO₂ concentration will directly increase resource use efficiencies of plants, and because warming will give more favourable conditions for plant production in northern Europe. In southern areas,

however, the benefits of the projected climate change will be limited, while the disadvantages will be predominant. The increased water use efficiency caused by increasing CO₂ will compensate only partially for the negative effects of increasing water limitation. Furthermore, in the southern areas the increase in water shortage and extreme weather events (e.g. heat waves, wind speed, etc.) may cause higher yield variability and an increase in abiotic and biotic damages (i.e. wind, fire, pest-disease damages). These negative impacts could be addressed in supporting the development and introduction of specific agricultural and forestry adaptive management measures (e.g. agronomic and water conservation practices, modification of microclimate, regular forest management, shorter rotations, etc.)

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IMPACTS OF PRESENT AND FUTURE CLIMATE CHANGE AND CLIMATE VARIABILITY ON AGRICULTURE IN THE TEMPERATE REGIONS: NORTH AMERICA

RAYMOND P. MOTH¹ and WOLFGANG BAIER²

¹*U.S. Department of Agriculture, 1400 Independence Avenue, S.W., Room 5143 South Building,
Washington, DC 20250, U.S.A.
E-mail: rmotha@oce.usda.gov*

²*Eastern Cereal and Oilseed Research Centre, Neatby Building, Room 4105, Ottawa,
Ontario, K1A0C6, Canada
E-mail: WBAIER@Sympatico.ca*

Abstract. The potential impact of climate variability and climate change on agricultural production in the United States and Canada varies generally by latitude. Largest reductions are projected in southern crop areas due to increased temperatures and reduced water availability. A longer growing season and projected increases in CO₂ may enhance crop yields in northern growing areas. Major factors in these scenarios analyzed are increased drought tendencies and more extreme weather events, both of which are detrimental to agriculture. Increasing competition for water between agriculture and non-agricultural users also focuses attention on water management issues. Agriculture also has impact on the greenhouse gas balance. Forests and soils are natural sinks for CO₂. Removal of forests and changes in land use, associated with the conversion from rural to urban domains, alters these natural sinks. Agricultural livestock and rice cultivation are leading contributors to methane emission into the atmosphere. The application of fertilizers is also a significant contributor to nitrous oxide emission into the atmosphere. Thus, efficient management strategies in agriculture can play an important role in managing the sources and sinks of greenhouse gases. Forest and land management can be effective tools in mitigating the greenhouse effect.

1. Introduction

The science of climate is a complex issue. While the physical aspects of this issue are most understood, both climate variability and climate change resulting from natural causes are altered by many anthropogenic influences. Further, the impact of climate variability varies greatly across geographic regions. All ecosystems have evolved to survive changes in climate and environment throughout the ages. Some ecosystems have been able to adjust better than others. The impacts of climate variability and climate change focus on key aspects of this complex issue; i.e., vulnerability and adaptation. Some examples of vulnerability include coastal infrastructure, land use strategy, urban environment, and human health.

Adaptation to changes can be through passive adjustment, reactive response, or proactive action. Passive adjustment is a “survival of the fittest” approach. Adaptation is based on how well the system will adjust to changes after they become the new normal frame of reference. Reactive response is a “wait and see” approach.

Adaptation measures are not adopted until after the alteration occurs. While the response is measured by the magnitude of change, it is often implemented too late to help the system cope with the consequences. A proactive measure focuses on preparations in advance of the event to help mitigate the impact on the system. The desired adaptation strategy involves proactive measures through long-term planning to mitigate the negative effects of changing climate conditions and to take advantage of the new opportunities of positive effects. However, in order to anticipate and respond to alterations in climate, a thorough understanding of the regional ecosystems is necessary. This section focuses specifically on the vulnerability of agriculture and forestry to climate variability and climate change in North America.

2. Agriculture in North America

The United States is the world's fourth largest country. Nearly 30% of its territory (approximately 260 million hectares) is covered by forests. Over 25% (approximately 240 million hectares) is permanent grassland and other non-forested pasture and rangeland. Approximately 20% of the area (185 million hectares) in the United States is devoted to cropland. The latter category includes land used for crops, land left idle, and land rotated into pasture. Thus, agriculture, including grazing land and forestry represent nearly 75% of the total expanse of the highly industrialized United States (National Assessment Synthesis Team, 2000).

Some interesting trends in agriculture in the United States have been documented. In the past decade, the area of U.S. cropland has declined over 10% as conservation efforts for the most environment-sensitive lands and highly erodible lands have removed about 15 million hectares from the cropping systems (U.S. Department of State, 1997). While there have been declines in area devoted to production, U.S. harvests feed a population that has grown two and a half times in the last century, and its food exports have expanded considerably.

Canada is the second largest country in the world and extends over 997 million hectares in total of which 921.5 million hectares is land area. But the country is sparsely populated, with most of its population concentrated along its southern border. Most of the land area is forested, and only 5% is suitable for farming, mostly in two zones – the Prairies and the mixed Wood Plains of the St. Lawrence River and Great Lakes regions. The Prairies alone account for about 80% of Canada's 68 million hectares of farmland. Two-thirds of all farmland is used for crops and improved pastures (those are seeded, drained, fertilized, or weeded); the rest is occupied by "unimproved" pastures and other land covers. The relative areas devoted to annual crops and animal husbandry vary widely across the country. For example, large areas of the Prairies are used almost exclusively for cropland, whereas small pockets of concentrated livestock production exist in areas of British Columbia and the southern regions of Alberta, Ontario, and Quebec. (Janzen et al., 1998).

Temperate and boreal forests cover nearly half of Canada's land mass. Of the 417.6 million hectares of forests, 234.5 million hectares are considered "commercial forests" – capable of producing commercial species of trees as well as other non-timber benefits. The non-commercial forest area (183.1 million hectares) is made up of open forests comprising natural areas of small trees, shrubs, and muskegs. With about 10% of the world's forests and nearly 25% of the planet's fresh water (much of it in forested areas), Canada's forests play critical roles in moderating climate and filtering air and water (Canadian Forest Service, 2001).

3. Climate of North America

North America has a wide variety of climate conditions, representative of nearly all the major regions of the world. The characteristics of the climatic regimes range from the polar ice cap in the far north of Canada to subtropical conditions in the southern United States. It encompasses arid sections of the western United States to humid regions of the eastern United States. The diverse climate zones, topography, and soils support many ecological communities and supply an abundance of renewable resources. Because of this broad diversity, the effects of changing climatic conditions cannot be oversimplified. Consequently, extensive research has definitely sharpened the focus on trends, impacts, vulnerability, and adaptability of agriculture and forestry to these changes.

Observations over the past century have revealed some interesting trends in U.S. climate. National temperatures, on average, have increased by about 0.6°C. Regionally, the coastal Northeast, the upper Midwest, the Southwest, and parts of Alaska have experienced increases in annual average temperature approaching 2°C over the past 100 years. The Southeast and southern Great Plains have actually experienced a slight cooling over the 20th century, but since the 1970s have had increasing temperatures as well, the largest observed warming across the nation has occurred in winter (National Assessment Synthesis Team, 2000).

Focusing on growing season variability in the heart of the Corn Belt, Iowa is the leading corn-producing state in the United States. Figure 1 shows the historical time series of seasonal temperature during the growing season, April to September, during the period 1895–2001. The temperature pattern is quite variable over this time period but there is no clear evidence of warming. However, agriculture was likely impacted by the relatively high degree of temperature variability exhibited throughout the entire period.

One striking feature of temperature records is the influence of urbanization. Studies have documented that urbanization-induced warming can be a full order of magnitude greater than the background trend. While researchers have attempted to remove the urbanization effects, it is a complex issue with spurious urban warming possibly influencing surface-based temperature records. Two methods utilized to

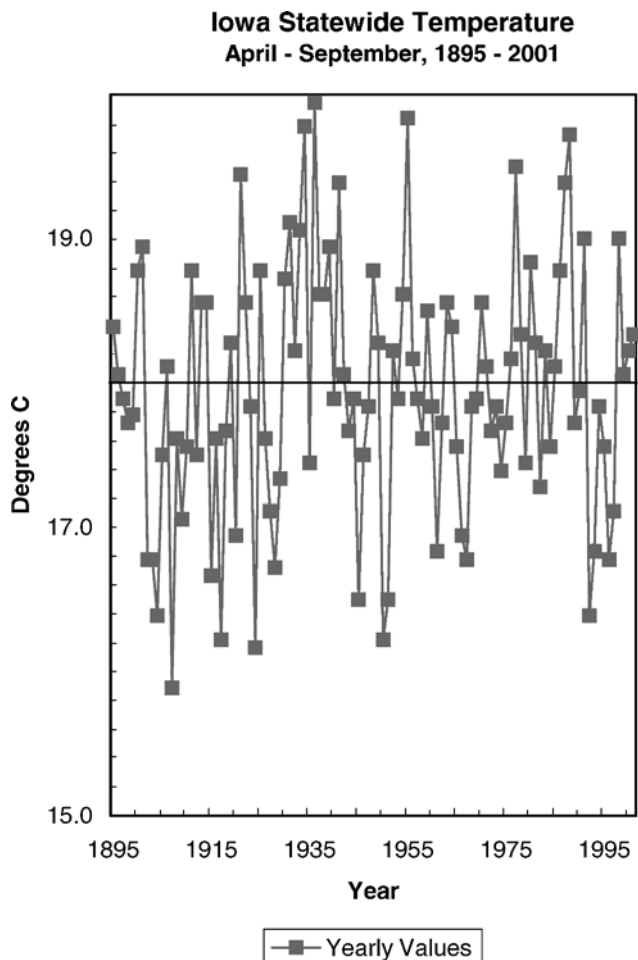


Figure 1. Iowa statewide temperatures ($^{\circ}\text{C}$) during the growing season, April–September, for the period 1895–2001. Filtered values from a smoothing procedure, computed by NOAA National Climatic Data Center, and the long-term mean value also shown. *Source:* National Climatic Data Center/NESDIS/NOAA.

minimize the urbanization effects include the creation of data sets using a minimum population-based threshold, and, analytical comparisons of soil temperature data at totally rural sites with contemporary air temperature records at nearby towns. Both methods are able to discern an urban warming bias in climatic records (Changnon, 1999; Dow and DeWalle, 2000).

Average U.S. precipitation has increased by 5–10% over the last century, attributable mostly to an increase in the frequency and intensity of heavy rainfall. Precipitation increases have been especially noteworthy in the fertile Midwest, southern Great Plains, and parts of the West and Pacific Northwest. Decreases in annual precipitation were evident in the northern Great Plains (National Assessment

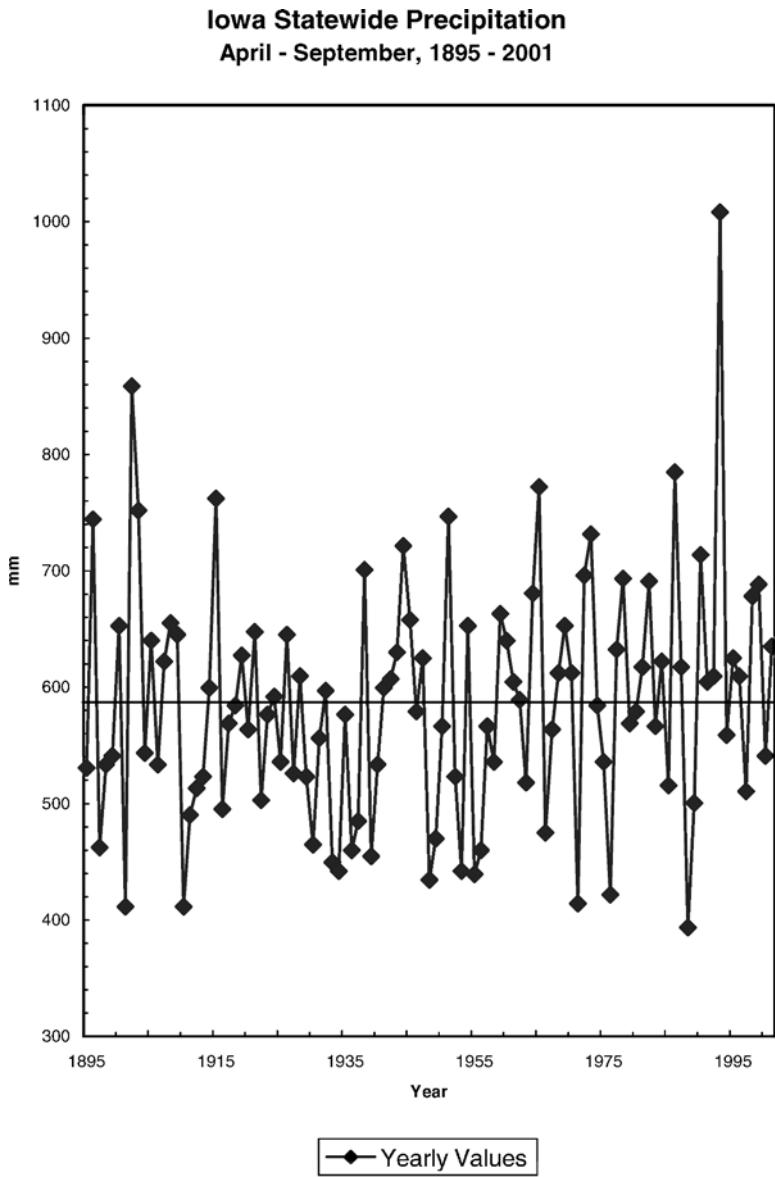


Figure 2. Iowa statewide precipitation (mm) during the growing season, April–September, for the period 1895–2001. Filtered values from a smoothing procedure, computed by NOAA National Climatic Data Center, and the long-term mean value also shown. Source: National Climatic Data Center/NESDIS/NOAA.

Synthesis Team, 2000). Figure 2 shows the growing season (April–September) precipitation for the state of Iowa during the time period 1895–2001. As in Figure 1, this chart shows high degree of variability over the entire period. However, the most extreme events occurred within 5 years of each other. The worst drought

Annual national temperature departures and long-term trend, 1895- 1996

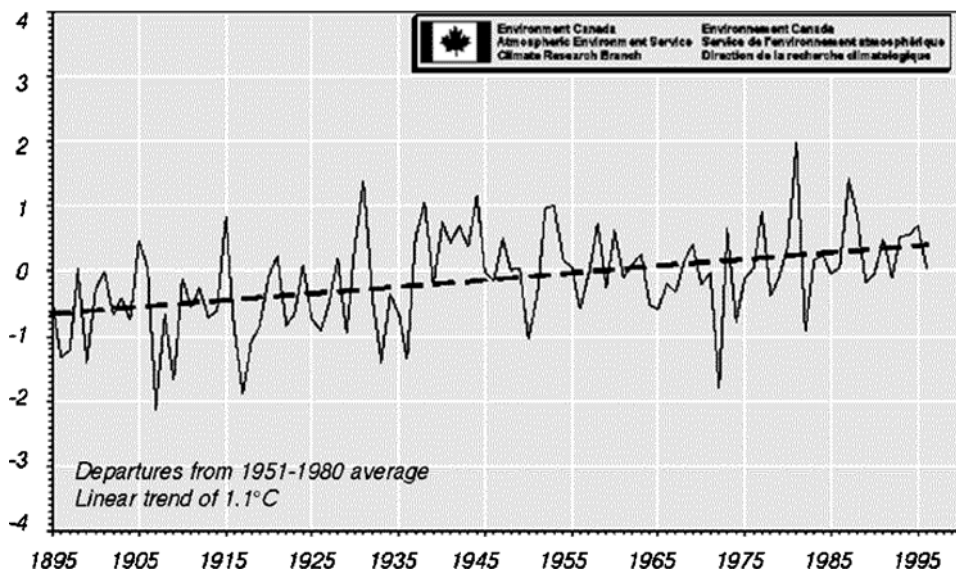


Figure 3. Annual national temperature departures and long-term trend: 1895–1996. Source: Environment Canada 1999, p.3.

in this period of record occurred in 1988. The wettest summer growing season occurred in 1993, a year of record flooding in the U.S. Midwest.

In Canada, the average annual climate has warmed by about 1°C compared to the associated global warming of 0.5°C . Figure 3 shows the annual national temperature departures and long-term trend, 1895–1996 (Environment Canada, 1999). Regional variations range from a warming of about 1.5°C in the Northwestern Territories (N.W.T.), to a warming of less than 1°C over southern Canada, and to a cooling of 0.8°C in extreme eastern N.W.T. (Environment Canada, 1997a). Consistent with the global precipitation trend, Canada as a whole has also experienced increased annual precipitation (Figure 4). Changes in the mean annual temperature regions of the boreal forests between 1895 and 1994 show a general increase ranging from 0.5°C over the Northeastern Forest to 1.4°C over the Northeastern Forest to 1.7°C over the Mackenzie District (Figure 5).

Zhang et al. (2000) analyzed trends in Canadian temperature and precipitation during the 20th century using recently updated and adjusted station data. Six elements, maximum, minimum, and mean temperatures along with diurnal temperature range (DTR), precipitation totals and ratio of snowfall to total precipitation were investigated. Trends were computed for 1900–1998 (period 1) for southern Canada (south of 60°N), and separately for 1950–1998 (period 2) for the entire country.

It is interesting to note that the above results for the longer period 1 for southern Canada corroborate those from the Environment Canada (1999), Canada Country

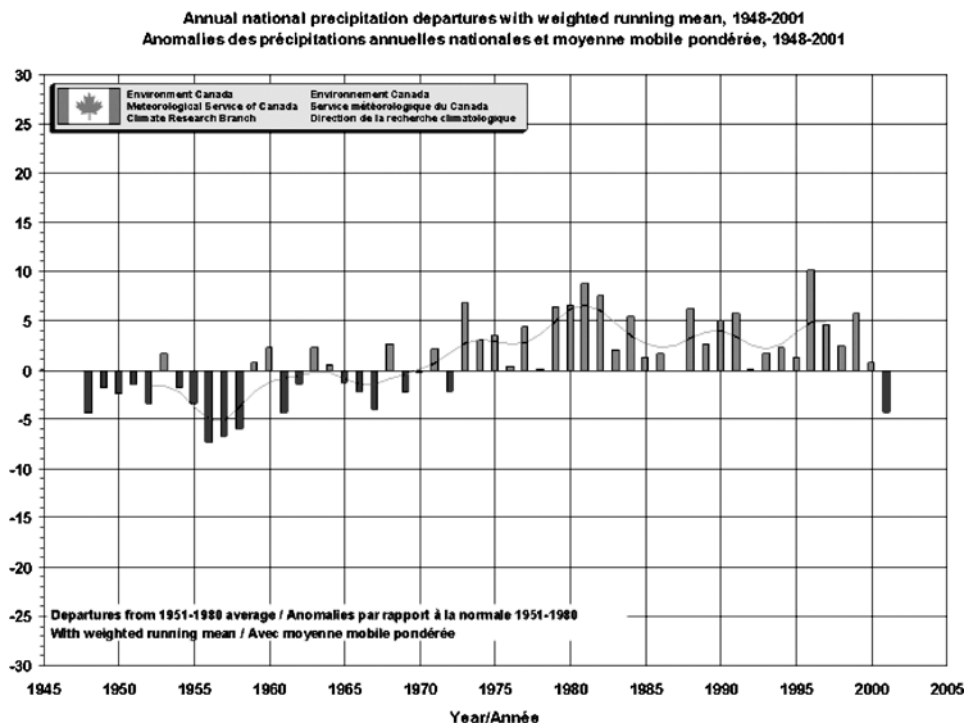
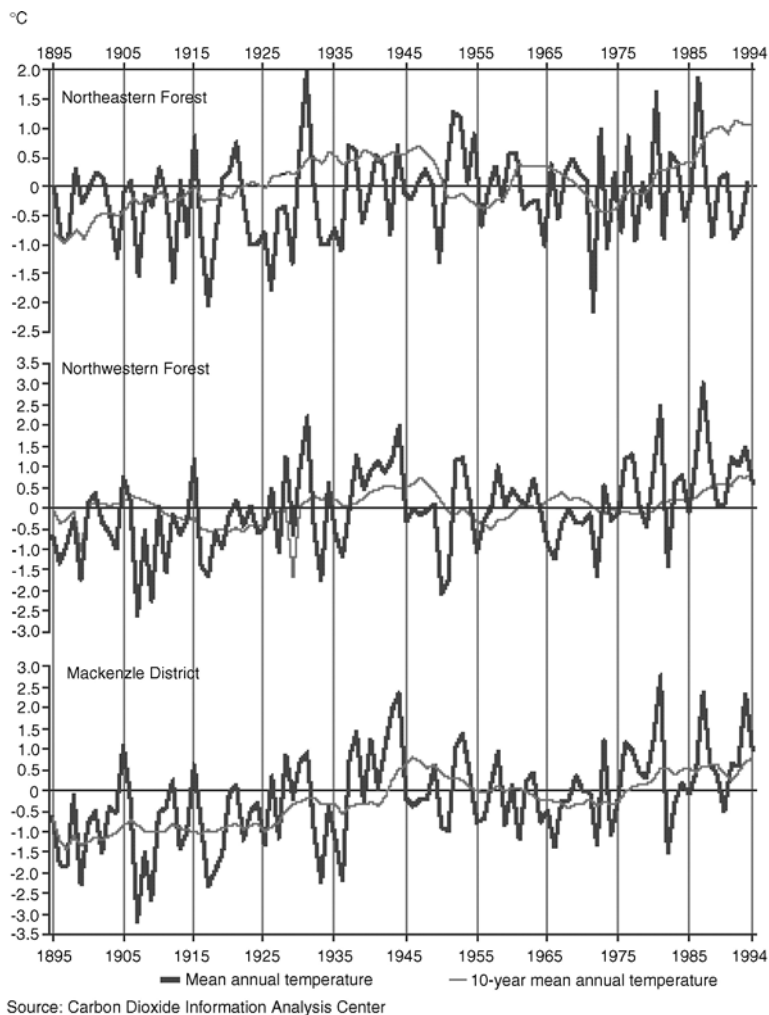


Figure 4. Annual national precipitation with weighted running mean: 1945—2001. (Source: Climate trends and variations bulletin for Canada. Annual 2001 temperature and precipitation in historical perspective. Source: Environment Canada 2002/2003. Climate trends and variations bulletin for Canada, Annual 2001 temperature and precipitation in historical perspective, p.3. Environment Canada, Meteorological Service of Canada, Climate Research Branch.

Study (CCS) for 1895–1996, whereas those for the shorter and more recent period 2 for the entire country show a somewhat different pattern. From 1900–1998, the annual mean temperature increased between 0.5 °C and 1.5 °C in the south. The warming is greater in minimum temperature than in maximum temperature in the first half of the century, resulting in a decrease of DTR. The greatest warming occurred in the west, with statistically significant increases mostly seen during spring and summer periods. Annual precipitation also increased from 5% to 35% in southern Canada over the same period. In general, the ratio of snowfall to total precipitation has been increasing mostly due to the increase in winter precipitation which generally falls as snow and an increase of ratio in autumn. Negative trends were identified in some southern regions during spring.

From 1950–1998, the pattern of temperature change is distinct: warming in the south and west and cooling in the northeast, with similar magnitudes in both maximum and minimum temperatures. This pattern is mostly evident in winter and spring. Across Canada, precipitation increased from 5% to 35%, with significant



◆ Disturbance and stress

◆

◆ Ecosystem condition and productivity

Figure 5. Temperature deviations in three regions of boreal forest: 1985–1994. Source: Criteria and Indicators, Criterion 2: Ecosystem condition and productivity, Element 2.1 Disturbance and Stress, Fig. 2.1n, p.36.

negative trends found in southern regions during winter. Overall, the ratio of snowfall to total precipitation has increased, with significant negative trends occurring mostly in southern Canada during spring. Zhang et al. (2000) concluded that climate has been becoming gradually wetter and warmer in southern Canada throughout the entire century, and in all of Canada during the latter half of the century.

In another study of precipitation characteristics in Canada during the past century, decadal variability was found to be a dominant feature of both the frequency

and intensity of annual precipitation (Zhang et al., 2001). The observed upward trend in precipitation totals was mainly due to increases in the number of small-to-moderate rainfall and snowfall events. There appears to be upward trends over eastern Canada and in the number of heavy snowfall events for autumn and winter over northern Canada.

Similar findings were also reported by Akinremi et al. (1999) from studies on precipitation trends at 37 stations with 75 years of records across the Canadian prairies. The analysis showed that there has been an increase in rainfall amount, an increase in the number of events, and a decrease in the variance of rainfall within the last 75 years. However, snowfall has declined from 1961 to 1995. The difference in trends for snowfall between period 1 (1921–1960) and period 2 (1961–1995), combined with the inverse relationship in the rainfall-snowfall trends, suggests that these trends may be related to climate change.

Precipitation seems to have increased and become more variable over the past 100 years (Bootsma, 1994, 1997). This may have impacted agriculture through reduced drought stress but may have increased problems in coping with excess moisture. Increased variability may have resulted in greater fluctuations in crop yields in recent decades. While long-term changes in precipitation are statistically significant, they are still relatively small in comparison to the year to year variability that growers must contend with (Bootsma, 1997). Soil moisture is critical for both agriculture and natural ecosystems. While observations of soil moisture are wholly inadequate for analysis, there is a good understanding of its relationship to climate. Soil moisture levels are determined by an intricate interaction between precipitation, evaporation, run-off, and soil drainage. Precipitation is the source for soil moisture. However, higher air temperatures increase the rate of evaporation and may remove moisture from the soil faster than it can be added by precipitation. Under this scenario, a region would become drier even though rainfall increases. These conditions have been observed in portions of the Great Plains and eastern seaboard, where precipitation has increased and air temperature has risen. Bootsma's conclusions are substantiated by the trends computed for 1900–1998 for southern Canada reported by Zhang et al. (2000) viz. an annual mean temperature increase between 0.5 °C and 1.5 °C and an annual precipitation increase from 5% to 35%.

Projections of future climate are generally derived from Global Circulation Models (GCMs) which depict scenarios of what is expected under particular assumptions. Scenarios provide a realistic framework to help identify vulnerabilities and plan adaptation strategies. The following scenario analysis of future U.S. climate, discussed in the next several paragraphs, was developed by the National Assessment Synthesis Team (2000) for the United States Global Change Research Program. Average warming in the U.S. is projected to be somewhat greater than for the world as a whole over the 21st century. Seasonal patterns indicate that projected changes will be particularly large in winter, especially at night. In summer, temperature increases in the South will raise the heat index, a measure of discomfort based on temperature and humidity, significantly.

Model projections of precipitation change are in less agreement. Generally, western and northern portions of the nation are projected to receive increased precipitation mainly in the winter. There is divergence of expectation for southern and eastern areas of the nation, however, with some GCMs projecting increases and other indicating decreases. The largest projected decreases are most evident during summer. One very interesting observation can be made from these model projections. There is general agreement that most regions are expected to experience an increase in the frequency of heavy precipitation events. This model projection raises concern over the impact that these extreme precipitation events would have on flooding and erosion which are key issues for agriculture.

In the West, the models generally concur that a warmer Pacific Ocean would pump moisture into the region and cause a southward shift in Pacific Coast storm activity. With projected temperature increases, much of the increased precipitation in winter would fall as rain rather than snow, causing a reduction in mountain snowpacks. Winter snowpack is a major source of water in the West for both summer agriculture and hydroelectric power generation. Thus, while wintertime river flows would tend to increase, diminishing snowpacks would reduce summertime flows creating potentially dangerous water shortages in the heat of summer.

Projections of soil moisture are even more diverse because any differences in change in precipitation and temperature are accentuated in the soil moisture projections. Model projections generally agree that soil moisture increases are likely in the U.S. Southwest. In the models that project both significant increases in temperatures and decreases in precipitation, substantial soil moisture decreases are common, most notably from the central Great Plains to the East. However, models that project more modest warming and precipitation increases generally result in soil moisture increases over these same areas.

Another interesting and important feature of this scenario analysis for agriculture is drought tendencies. Models generally indicate increased incidence of drought, especially east of the Rocky Mountains from the Great Plains to the East. Intense drought tendencies are projected to increase in many agricultural areas of the nation. Both soil moisture availability and drought tendencies will have a significant impact on water supply, the vigor of agriculture, and the health of forests. In Canada, the climate is expected to change with significant regional variations. Long-term (100 years) climatic trends for agriculture were studied for five locations in Canada: Agassiz, B.C., Indian Head, Saskatchewan; Brandon, Manitoba; Ottawa, Ontario; Charlottetown, Prince Edward Island (Bootsma, 1994). A total of 17 agroclimatic parameters were computed on a yearly basis from daily climatic data. The parameters included climatic characteristics of importance to agriculture such as frost dates, growing degree days, temperature, precipitation, potential evapotranspiration and forage aridity index. The climatic attributes were extremely variable, such that detection of warming (greenhouse induced or otherwise) was difficult. Most of the evidence of climatic warming comes from stations located in western Canada. This warming is mainly confined to the growing season and is not apparent in mean

temperatures during winter. The temporal variations are not uniform over space. Stations in western Canada indicated trends of increased frost-free periods, growing degree-days and corn heat units. Stations in eastern Canada did not exhibit the same warming trend.

4. Impacts of Climate Variability and Change on Agriculture in North America

Before discussing future projections, let's return to the state of Iowa and look at agricultural trends over the past century. Figures 1 and 2 presented time series of seasonal growing season temperatures and precipitation during the past century for the state of Iowa. How do they compare with corn yields for Iowa during the same period? Figure 6 presents the time series for corn yields during 1895–2002 for the state of Iowa, revealing some interesting comparisons. First, there are three relatively stable trends in this time series. During the 1895–1940 period, there is no upward trend revealed in the data, with relatively low variability, except in the mid-1930s associated with a prolonged drought. From 1940 to 1970, generally low variability is evident but a substantial increase in trend yields is associated with the introduction of fertilizers, seed hybrids, and better farm management practices. From 1970 to the mid-1990s, the upward trend in yields continues but this period is marked with high variability around the trend yields.

Ironically, the greatest departures from trend yields occur within 5 years of each other due to extreme but contrasting weather events. In 1988, one of the worst droughts in modern history during the growing season (see Figure 2) caused significant agricultural losses. In 1993, even greater yield losses were caused by

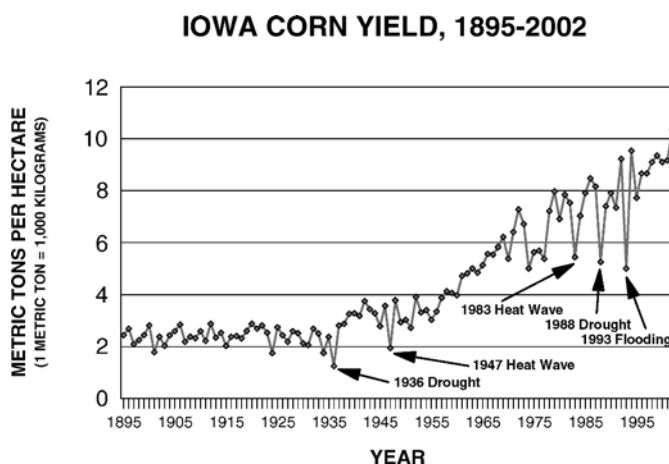


Figure 6. Iowa statewide corn yields (metric tons per hectare) for the period 1895–2002. Years of unusually extreme weather events documented. *Source:* United States Department of Agriculture.

severe and prolonged flooding in the U.S. Midwest. This represents a period of extreme weather variability over a relatively short climatic period.

While drought and flooding cause significant yield losses as illustrated in Figure 6, untimely heat during critical growth phases can also have a significant negative impact on yields. Corn development is especially sensitive to the weather during the crucial reproductive phase of development. Hot, dry weather during silking can inhibit grain development, reducing the yield potential. The large negative departures from trend noted in 1947 and 1983 were caused by untimely heat waves during the crucial reproductive phase. The impact of these extreme weather events are demonstrated in these charts and illustrate how weather and climate variability are major factors affecting the success or failure of crops in the U.S. Midwest.

The potential impact of climate change on agricultural production in the United States and Canada varies mostly by latitude. In the United States, projections based on scenarios from GCM outputs indicate a decrease in yields of all major unirrigated crops based on the premise of increased temperature and reduced crop-water availability. The largest reductions are projected for the South and Southeast. In northern areas, however, where temperature is currently a constraint on growth, yields of unirrigated corn and soybeans could increase as higher temperatures increase the length of the available growing season. When the direct effects of increased CO₂ are considered, yields may increase further in northern areas. Some recent climate models are projecting higher expected precipitation due to feedback mechanisms. However, higher air temperatures will increase the rate of evaporation. In some areas, moisture loss may still be greater than the increased projected precipitation. With the relative increase in productivity in northern areas and decrease in southern areas, a major northward shift in land use is implied for the United States.

The comprehensive Canada Country Study (CCS), Climate Impacts and Adaptation provides a state-of-the-art assessment based on a range of scenarios from five GCMs developed in Canada, United States and United Kingdom (Environment Canada, 1999). The assessment indicates that an important dimension to the relationship between climate change and agriculture is the wide range of conditions for agricultural production between different regions in Canada. There has been considerable research into the possible implications of climate change scenarios for agro-climatic conditions in all regions of Canada. These studies have considered several climatic change scenarios and have examined the implications of altered climates for wide range agro-climatic properties, including the growing and frost free seasons, and seasonal values for temperature, growing degree days, corn heat units, precipitation and moisture deficits. The implications for thermal regimes have been investigated more thoroughly than the implications for moisture regimes.

According to the CCS, all of the global climatic change scenarios and studies suggest warming for most of Canada. Impacts of climate change on agriculture will be most directly reflected through the response of crops, livestock, soils, weeds, and insects and diseases to the elements of climate for which they are most sensitive. Soil moisture and temperature are the climatic factors likely to be most sensitive to

change across large agricultural areas of Canada. Longer frost free seasons more conducive for commercial agriculture are expected under climate change. For the Prairies, Ontario and Quebec, most estimates suggest an extension of 3 to 5 weeks. Results relating to moisture regimes show estimated precipitation changes ranging from decreases of about 30% to increases of 80%.

The CCS further concludes that despite favorable potential impacts in terms of longer and warmer frost-free seasons and of greater precipitation, most climate change scenarios also imply important increases in potential evapotranspiration. This may lead to larger seasonal moisture deficits in many regions of Canada, with the severest situations anticipated for Ontario. Impacts on agricultural land potential north of 60° are generally considered to be insubstantial in nature. However, the Peace River region and northern agricultural areas in Ontario and Québec are expected to see some expansion of the land area suitable for commercial crop production. The physical potential for fruit and vegetables could expand beyond current southern locations in Québec, Ontario and British Columbia, but may be very much limited by lack of suitable soils for agriculture in these regions.

Other results suggest largest changes in soil moisture deficits will likely be in the southern prairie regions of Saskatchewan and Manitoba, but results vary somewhat depending on which GCM is used and how deficits are determined. See for example, the soil moisture maps available on the web site of the Canadian Climate Impact Scenario project (CCIS) at: <http://www.cics.uvic.ca/scenarios/index.cgi>.

Computer simulation models have been extensively used for analysis of the complex climate-crop interactions and the assessments of climate change on agro-climate, agricultural resources and crop production. Such studies are important for national and international resource planning because Canada is identified to become even more prominent as a supplier of food with projected climate change (IIASA, 2001). While the agricultural sector of the economy is highly vulnerable to climate change, it is generally felt that agriculture can readily adapt to the kinds of changes that have occurred over the past 100 years or so (Bootsma, 1997). However, projected changes for the next 100 years by the GCMs are substantially larger by at least an order of magnitude than changes that have occurred over the past 100 years. If these projections are accurate, agriculture may experience increased difficulty in adapting to any negative impacts. On the other hand, projected changes in climate could result in longer and warmer frost-free periods across Canada and, thereby, generally enhance thermal regimes for commercial agriculture. The extent to which these changes might benefit Canada, however, will in all likelihood be diminished by less soil moisture in all regions and under all climate change projections (Environment Canada, 1997b).

Climate variability raises another major concern in Canada. Large tracts of land in the prairies lie unprotected from the wind (McRae et al., 2000). In fact, about two-thirds of the prairie region would be under a moderate to severe risk of wind erosion if soil conservation measures were not taken. Improved tillage practice has reduced the risk of wind erosion in the Prairies by about 30% from 1981 to 1996

(McRae et al., 2000, p. 72). However, higher temperatures, lower precipitation, and higher wind speeds, associated with climate extremes, would have a negative impact on crop productivity potential.

Another important point for consideration of agricultural impacts related to climate variability is the difference between primarily rainfed agriculture and irrigation agriculture. Gadgil et al. (2000) notes that, in rainfed agriculture, yields tend to be lower and there are large fluctuations in yield induced by variations of the environment. In this agricultural system, available resources for input to the system are typically low. In the more mechanized irrigation-based agricultural system, higher-yielding varieties involve large inputs from the farmers in terms of fertilizers and pesticides and from the farmers/government in irrigation of the lands. Consequently, the impact of climate variability typically was reduced by adopting measures such as irrigation.

Irrigated agriculture is common in the western United States, relying heavily on winter snowpack in the Rocky Mountains as the principal source of irrigation supplies. Intensive agriculture has been highly successful but heavily dependent on these irrigation reserves. Extreme climate variability and changing climatic trends may have a profound effect in this production system for two reasons. First, if the tendency is for winter precipitation to diminish during this scenario of more extreme variability or climate change, the available supply of water for agriculture will be reduced. However, some GCMs show increased precipitation over winter in the western U.S. for future climate (see, for example, maps available on the CCIS web site: <http://www.cics.uvic.ca/scenarios/index.cgi>). It is more likely that the winter snow pack may be reduced due to increased melt during winter and more precipitation in the form of rain rather than snow.

At the same time, increasing competition for water due to higher population in urban centers and greater demand for hydroelectric power generation compounds the issue of agricultural water supplies. In the long-term, policymakers need to focus attention on these water management issues as they affect all segments of the economy.

The environmental consequences of agriculture are strongly influenced by climate. Significant problems other than highly variable crop production include substantial loss of fertile topsoil to erosion; spread of desert-like conditions; water logging, salinization, and alkalization of formerly productive areas; and, flooding and silting due to deforestation. Climate variability and associated extreme weather events contribute substantially to agricultural losses caused by these problems. Thus, agriculture is highly vulnerable to the vagaries of climate.

5. Agriculture's Role in Greenhouse Gas Emissions

The complex interactions become even more confusing as noted earlier by the growing concern over greenhouse gases. Warming from the natural phenomenon, characterized by warming from the atmospheric greenhouse effect, is highly beneficial

to life as it exists on earth. The gases causing the warming of the atmosphere are known as greenhouse gases, including water vapor, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). CO_2 is released to the atmosphere when solid waste, fossil fuels, and wood are burned. Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from the decomposition of organic wastes in municipal solid waste landfills, and the raising of livestock. Nitrous oxide is emitted during agricultural and industrial activities, as well as during combustion of solid waste and fossil fuels.

There is growing evidence that the concentrations of CO_2 , CH_4 , and N_2O have been increasing steadily since the Industrial Revolution, associated with more intense human activity. Greenhouse gases may have the desired effect of warming the atmosphere sufficiently to create favorable conditions for biological activity in some areas. Enhanced greenhouse warming due to human activity may, however, lead to uncertain, disruptive consequences to the natural ecosystems.

Agriculture is a relatively minor source of gases that contribute directly to changing climate conditions. However, agriculture is especially sensitive to climate and atmospheric composition. Agriculture can play a contributing role in slowing the buildup of greenhouse gases. Changes in land use and forestry activities can emit CO_2 to the atmosphere through the conversion of forest land to agricultural or urban use. Forests are a major terrestrial sink for CO_2 . Approximately half the dry weight of wood is carbon and, as trees add mass to trunks, limbs, and roots, carbon is stored in relatively long-lived biomass instead of being released to the atmosphere. Soils and vegetative cover also provide potential sinks for carbon emission. Soils and trees act as natural sinks for carbon, with hundreds of billions of tons of carbon in the form of CO_2 absorbed by oceans, soils, and trees each year. Thus, removal of forests and changes in land use, associated with the conversion from rural to urban domains, alters this natural sink for carbon and increases the potential for atmospheric CO_2 .

The agricultural sector produces a significant amount of methane emission (Desjardins et al., 2001). Animal digestion in domestic livestock is the leading contributor to agricultural methane emission (McRae et al., 2000). Enteric fermentation, the process in which microbes that reside in animal digestive systems, breaks down the feed consumed by the animal and releases methane. The decomposition of organic animal waste in an anaerobic environment also produces methane. Rice cultivation is another source of methane emission (Lal et al., 1998; Wang et al., 1996). The soil's organic matter decomposes under the anaerobic conditions created by flooded fields, releasing methane to the atmosphere through the rice plants. These are considered major sources of methane in the atmosphere.

The application of synthetic nitrogen and organic fertilizers is a leading contributor to N_2O emissions. Bacterial action on the chemical fertilizers results in the release of N_2O . The gas is released when soil microbes digest the fertilizers. The more inorganic nitrogen-based fertilizers that are applied, the more N_2O goes into

the atmosphere. This potent pollutant is detrimental to the life-preserving ozone layer (Lyman et al., 1990). Soil management practices, such as irrigation, tilling, or laying fallow the land can also affect N_2O fluxes to and from the soil.

Thus, agriculture has a significant role in the inventory of atmospheric greenhouse gases and in mitigation measures to reduce greenhouse gases. CO_2 accounts for 85% of net U.S. greenhouse gas emissions in 1995 (U.S. Department of State, 1997). Lower harvests in old-growth forests help prevent CO_2 emissions. A shift toward ecosystem management also favors timber harvest methods that inflict less damage, and helps retain carbon in forest lands. The conversion from conventional tillage to reduced-tillage systems increases soil organic carbon (SOC) content that amounts to sequestration of atmospheric CO_2 . Removal of erosion-prone land from cropping, and seeding it in perennial grasses, also allows soils to sequester carbon.

Rosenzweig and Hillel (2000) noted that proper land management aimed at enhancing soil organic matter improves soil fertility and soil structure, reduces soil erosion, and helps to mitigate the greenhouse effect. It is estimated that methane comprised about 11% of U.S. greenhouse gas emission in 1995. The improvement in animal breeding and husbandry, the adoption of biotechnology, and the current declining trend in the consumption of milk and red meat could cut methane emission by 20%. Research on ways and means of capturing methane released from manure management systems and using the captured methane as an on-farm energy resource showed that it is technologically feasible (Janzen et al., 1998., p. 55). More efficient animal production through improved grazing management, strategic feed supplementation, genetic characteristics and reproduction, and disease control contributed toward reduced methane emission (U.S. Department of State, 1997). Finally, while nitrous oxide emissions account for only about 3% of U.S. greenhouse emission in 1995, improved management of fertilizers could reduce N_2O emissions from the soil.

In Canada, the effect of agriculture on the atmosphere has been documented in a national report entitled: *The Health of Our Air* (Janzen et al., 1998), which is a companion report to *The Health of Our Soils* and *The Health of Our Water*. *The Health of Our Air* provides first comprehensive estimates of GHG emissions from Canadian agriculture with reference to the global concepts. It addresses in detail the amounts of the various greenhouse gas emissions and possible ways of reducing them. Many of the findings presented were obtained from a national research program initiated by Agriculture and Agri-Food Canada in 1992.

The three most important three greenhouse gases (CO_2 , CH_4 , and N_2O) of current concern differ in their warming effects. To compare their relative effects, therefore, their emissions are usually expressed as “ CO_2 equivalents.” One kilogram of N_2O has the warming effect of about 310 kg of CO_2 (when considered over 100 years), so it represents 310 CO_2 equivalents. Similarly, 1 kg of CH_4 represents 21 CO_2 equivalents. According to best estimates, using the approaches described for each gas, farm management practices contributed about 10% of Canada’s GHG emissions or 67 T.g. (million tonnes) of CO_2 equivalents in 1996 (Table I). Of this

TABLE I
Estimates of total greenhouse gas emissions from Canada's agroecosystems

	(T.g. CO ₂ equivalents)						
	1981	1986	1991	1996	2000 ^a	2005 ^a	2010 ^a
CO ₂	9	7	5	3	1	0	0
CH ₄	22	20	20	23	23	24	25
N ₂ O	32	33	34	41	43	45	48
Total	63	60	59	67	67	69	73

^aPredicted using a scenario of medium growth from Canadian Regional Agricultural Model (CRAM) to 2007. All 2010 data follow a best-fit trend using data from 1993 to 2007 from the CRAM (Kulshreshtha et al., 2000). All fertilizer data were predicted using a best-fit trend from 1981, 1986, 1991, and 1996 Census data. All sheep, chicken, and turkey populations were predicted using a best-fit trend from Census data. (From: Janzen et al., 1998, Table 14.)

amount, about two-thirds was as N₂O and about one-third as CH₄. Livestock and Manure account for about 58% of these emissions, cropping practices for 37%. By comparison, net emissions as CO₂ were almost negligible. The estimates of CO₂ emission, however, exclude most of the CO₂ from fossil fuels used to produce inputs, power farm machinery, and transport products. These sources emitted about 25 T.g. (million tonnes) of CO₂ in 1996. With these emissions from all other agricultural practices included, the agriculture sector's contributions were about 15% of Canada's emissions.

The emissions of greenhouse gases from Canadian agriculture are increasing, according to current estimates (Table I). By 2010, emissions may be about 9% higher than those in 1996, unless producers adopt better management practices. These projected increases stem largely from predicted increases in livestock numbers and N inputs as fertilizer and manure. Emissions of CO₂ are expected to decline, but not nearly fast enough to compensate for predicted increases in the other gases.

The above Canadian statistics are not without uncertainties, N₂O has the highest and CO₂ lowest uncertainty. Nevertheless they serve as a reference point for showing trends. Future emissions will depend on changes in farming practices that are hard to predict. Livestock numbers, crops that are grown, fertilization patterns, and manure management techniques can all change quickly, throwing off the current best projections (Janzen et al., 1998).

At one time, agriculture was also an important source of CO₂ because of the substantial loss in soil carbon that has occurred since cultivation began through conversion of forest and rangeland to arable land, fertilizer manufacture, and fossil fuel use. However, these emissions have decreased to almost negligible levels. Smith et al. (2000), using the Century model for the period 1970–2010, simulated

changes in SOC in agricultural soils of Canada. Changes in SOC in agricultural soils influence soil quality and greenhouse gas concentrations in the atmosphere. The simulation changes indicate that the agricultural soils in Canada, whose SOC are currently very close to equilibrium, may stop being a net source of CO₂ and will become a sink by the year 2000. The rates of carbon change for the years 1970, 1990, and 2010 were estimated to be -67, -39 and 11 kg C ha⁻¹. These changes are the result of an increase in the adoption of no-tillage management, a reduction in the use of summer fallowing, and an increase in fertilizer application.

6. Scenarios of CO₂, Climate, and Agriculture

As the CO₂ content of air rises, many plants exhibit increased rates of net photosynthesis and biomass production. Plant water use efficiency is defined as the amount of carbon gained per unit water lost per unit leaf area. Plant water use efficiency among many field crops and grasses is directly related with atmospheric CO₂ enrichment. Thus, from agriculture's perspective, as CO₂ content of air continues to rise, plant life in general should exhibit increases in water use efficiency and biomass production. In Canada, Rosenzweig et al. (1993) analyzed model scenarios and found that a 2 °C increase in temperature with no precipitation change resulted in wheat yield increases with the direct effect of CO₂ taken into account.

The productive capacity of a plant is the net resultant of two processes, photosynthetic fixation of carbon dioxide and its release by respiration (Rosenberg, 1974). Crop species vary in their response to CO₂. Wheat, rice, soybeans, cotton, oats, barley, and alfalfa belong to a physiological class called C3 plants that respond readily to increased CO₂ levels. Corn, sorghum, sugarcane, millet, and other tropical grasses are C4 plants, though more efficient photosynthetically than C3 plants at present levels of CO₂, tend to be less responsive to enriched concentrations. C3 crops show an average increase in net primary production of approximately 33% for a doubling of atmospheric CO₂ (Koch and Mooney, 1996). Some field studies show C4 plants responded to elevated CO₂ due to increased water use efficiency (Owensby et al., 1993).

Elevated atmospheric CO₂ concentrations tend to reduce the size of open stomatal pore space on leaf surfaces. Thus, plants tend to display lower stomatal conductances which effectively reduces the amount of water lost to the atmosphere via transpiration. As a result, the soil moisture content would likely rise with increased atmospheric CO₂ content, given no change in precipitation trend.

However, the reduced transpiration may be offset by higher evaporation at higher temperatures. While water use efficiency may increase under this scenario, the effects of higher temperatures may negate any beneficial effects. For example, increased temperatures may accelerate the rate at which plants release CO₂ through respiration, resulting in less than optimal conditions for net growth (Rosenzweig and Hillel, 1995).

Highly productive forest ecosystems have the greatest potential for absolute increases in productivity due to CO₂ effects. Studies have shown a stimulation of photosynthesis of about 60% for a doubling of CO₂ (Saxe et al., 1998; Norby et al., 1999). A fast growing young pine forest showed an increase in 25% in net primary production for an increase in atmospheric CO₂ to 560 ppm (DeLucia et al., 1999). Slowing deforestation and promoting natural forest regeneration and afforestation could increase CO₂ storage.

The direct biological effects of atmospheric CO₂ enrichment tend to mimic a warming and moistening of the environment. This is expected because plant optimum temperatures and water use efficiencies both rise. Studies have shown that woody species, such as oak trees, will gradually expand onto arid and semi-arid grasslands due to increased precipitation patterns, especially during the summer growing season. This is a likely scenario in the southwestern United States where climate models generally predict a tendency toward increasing precipitation.

The rise in atmospheric CO₂ should also have a significant positive effect upon pasture and rangeland productivity, based on research studies. CO₂ enrichments appear to slightly augment the legume content of grasslands, providing more nitrogen to the ecosystem which promotes the nutritive quality of the forage. Increases in the air's CO₂ content should enable pasture and rangeland plants to better cope with water deficits.

Experiments have also shown that elevated CO₂ consistently enhanced rates of net photosynthesis in upland cotton (Ready et al., 1999). These studies indicated that although elevated CO₂ did not significantly impact boll size or maturation, it did increase boll numbers by about 40% regardless of temperatures, without changing fiber properties. The results infer that if air temperatures in cotton-growing areas of the United States increase in future years, the predicted rise in the air's CO₂ content will enhance cotton photosynthesis rates, boll production, and fiber yields without altering fiber quality. It remains unclear, however, if the enhanced photosynthesis due to the direct effect of higher CO₂ will be offset at least partially by projected higher moisture stress in some areas.

7. Vulnerability of the Agricultural Sector

Rosenzweig et al. (1993) presented some interesting results based on current production and change in simulated wheat yields under GCM climate change scenarios. For the GCM doubled CO₂ climate change scenario, simulated yield increases in mid- to high-latitudes were caused by the positive physiological effects of CO₂ and the lengthened growing season. In contrast, decreases in simulated yields were caused by shortening of optimum growth periods due to higher temperatures, decreases moisture availability and poor vernalization.

As mentioned earlier, increased concentrations of greenhouse gases in the atmosphere are a major factor in contributing to enhanced natural climate variability. Climate extremes are becoming more pronounced and the impact on agriculture

can be catastrophic in terms of productivity declines and economic losses. Rapid geographical shifts in the agricultural land base, brought about by very rapid climate changes, could disrupt rural communities and associated infrastructures.

McCracken et al. (1990) reviewed the critical issues in agricultural impact assessment. Agricultural crops and livestock are extremely vulnerable to extreme events, such as droughts, heat waves, and severe storms. The frequency, intensity, and duration of extreme climatic events can be more consequential to crop yields than changes in mean values. Another important aspect of this analysis is that next to climate, technology is the most critical factor affecting agricultural productivity. Projecting the impact of future climate change requires a projection of future technological improvements.

Even in the highly industrialized United States, agriculture is highly vulnerable to the vagaries of climate and the complex interactions between farming and the environment. Farming has successfully produced food and fiber but it also caused environmental degradation. Worldwide degradation of agricultural land causing irreversible loss of productivity is estimated to be 6 million hectares per year (Lal et al., 1998). Soil erosion by wind and water has been significant, but any decline in yields has been largely offset by greater use of fertilizers. However, off-farm pollution due to runoff of fertilizer and agrichemicals has increased. As a result of these issues, an alternative approach to conventional farming practices has evolved. This approach focuses on the reduction of environmentally damaging use of fertilizers and chemical pesticides through processes that directly or indirectly (by reducing waste) affect fertilizer and pesticide consumption. These processes include improved efficiency of fertilizer uptake by a plant; biological pest control practices; production of plants more resistant to stress; and reduction of post-harvest losses through better storage, handling, and distribution (Bugliarello, 1989).

8. Adaptation Strategies

Agriculture in the United States and Canada has many strong points in its favor to permit successful adaptation to climate variability and climate change. The overall production system is technically advanced and can adopt new technology rather quickly. It is regionally diverse, making adaptation to a wide range of conditions quite feasible (IPCC, 2001). The agricultural sector is highly productive, intensively managed, and market based. Further, agriculture accounts for less than 5% of the national gross national product (GNP), allowing considerable flexibility to adapt to changes required in the production system. At the same time, it would be prudent for agriculture to take advantage of any positive opportunities offered by climate change in order to maximize production efficiency and remain competitive in the international marketplace.

U.S. agriculture is vulnerable to rapidly changing climate conditions. The range over which major crops are planted could eventually shift hundreds of kilometers to the north. The availability of fresh water and the distribution of pests and diseases

may have significant impacts on production potential. The goals of adaptation strategies are to improve the knowledge and skills of farmers, to encourage adoption of new technologies, and to expand the array of options available to farmers.

One option of the research community is to continue to develop new ways for certain crops to adapt to climatic constraints, such as warmer or colder temperatures, and drier conditions. More recent innovations in biotechnology offer promising new techniques. New tissue-culturing and genetic-engineering tools, combined with traditional agricultural breeding methods, alter plants to incorporate greater disease, insect, and weed resistance, and to better withstand environmental stresses such as drought, heat, and frost. Efficient water resource planning is also an essential aspect of adaptation strategies for agriculture.

Erosion in the Great Plains was reduced after devastating losses of valuable topsoil during the dust bowl years of the 1930s by planting shelterbelts of trees to reduce wind erosion. Reduction of summer fallow practice and move to minimum or zero tillage are management practices which have reduced erosion and promoted higher soil organic matter (McRay et al., 2000, Chapter 7). Other means of alternative agriculture included systematically incorporating natural processes, such as nutrient cycles, nitrogen fixation, and pest-predator relationships into the agricultural production process; reducing the use of chemicals and fertilizers; making greater use of the biological and genetic potential of plant and animal species; improving the match between cropping patterns and the productive potential and physical limitations of agricultural lands in order to ensure the long-term sustainability of the land; and, emphasizing improved farm management and conservation of the soil, water, and biological resources (World Resources, 1992).

U.S. agriculture is vulnerable to rapidly changing climate conditions. The range over which major crops are planted could eventually shift hundreds of kilometers to the north. The availability of fresh water and the distribution of pests and diseases may have significant impacts on production potential. The goals of adaptation strategies are to improve the knowledge and skills of farmers, to encourage adoption of new technologies, and to expand the array of options available to farmers.

Having noted this, however, it must also be said that given the uncertainties and serious consequences of potentially inaccurate assessments, a prudent course of action is to aggressively study and research how best to limit and mitigate the impacts of climate change on agriculture. Complacency poses great risk. A vigorous effort is needed to understand and prepare for potentially serious impacts on agriculture by developing strategic adaptation strategies.

Crop yields and variability under climate change (historic baseline and $2 \times \text{CO}_2$ scenario) and adaptive crop management scenarios (planting dates; harvest dates; fertilizer applications; tillage practices) were assessed for the major agricultural regions across Canada, using the EPIC simulation model (De Jong et al., 2001). EPIC (version 5300) integrates the major processes that occur in the soil-crop-atmosphere management system, including hydrology, weather, wind and water erosion, nutrient cycling, plant growth, soil temperature, tillage, plant environmental control

TABLE II

Summary of crop yields and standard deviations as simulated by EPIC for baseline (1966–1995 period) and a future climate scenario (2041–2060 period) for selected locations in Canada

Crop	# sites	Yields (Mg/ha)			
		Average		Std. Dev.	
		Baseline	2 × CO ₂	Baseline	2 × CO ₂
Barley	29	3.5	3.5	0.77	0.94
Spring wheat	25	2.8	2.7	0.85	0.91
Canola	12	2.5	2.6	0.89	1.03
Corn	6	5.7	5.0	1.73	1.99
Soyabeans	6	2.0	2.2	0.56	0.83
Potatoes	5	6.7	7.9	0.81	1.01
Winter wheat	3	3.5	4.2	0.67	0.77

Source: Results were taken by A. Bootsma from: De Jong, R., Li, K. Y., Bootsma, A., Huffman, T., Roloff, G., and Gameda, S. 2001. Crop yield and variability under climate change and adaptive crop management scenarios. Agriculture and Agri-Food Canada, Eastern Cereal and Oilseed Research Centre, Ottawa, Ontario, Climate Change Action Fund Project A080, Final Report. 49 pp.

and economics. Under a warmer and slightly wetter 2 × CO₂ climate scenario, the planting dates advanced 1 to 2 weeks in eastern and central Canada and by approximately 3 weeks in western Canada. Yields of spring planted barley, wheat and canola (prairie region only) did not change significantly (Table II). Corn yields in central Canada decreased significantly by 11%, although with increased nitrogen fertility the yield decrease was reduced to less than 5%. With the projected longer growing season, higher yielding corn hybrids with higher heat unit regimes may also negate the projected yield declines. Soybean, potato and winter wheat yields increased by approximately 12%, 16% and 18% respectively. The temporal yield variability of all crops increased under the 2CO₂ scenario from 6% for spring wheat to 50% for soybeans. The reduction in corn yields predicted by the EPIC model is probably the result of water stress, as other studies have suggested that even many areas in central Canada (Ontario/Quebec) may, like soybeans, have increased corn yields as a result of being able to grow longer season, higher yielding hybrids with the higher heat units regimes.

Based on the assumption that at least 2400–2500 crop heat units must be available for the crop to mature, corn and soybeans could be grown under the 2 × CO₂ climate scenario at all locations (29 climate stations in 17 ecoregions selected across Canada) – except some of the most northern ones. When water stress was not a limiting factor, corn and soybean yields were comparable to those simulated in central Canada where these crops are currently grown.

McGinn et al. (2001) generated regional climate change scenarios for the Canadian Prairies using historic weather data and daily data from two Canadian Climate Centre Global Circulation Models. The climate change scenario data included daily maximum and minimum air temperature and precipitation data generated using the Canadian Centre for Climate Modelling and Analysis second generation Global Circulation Model (GCMII) and their newer coupled (linking ocean and atmospheric processes) GCM with atmospheric aerosols (CGCMI-A). In addition, a combination of each GCM temperature and the historic precipitation (HP) amount and frequency were used to generate a third (GCMII_HP) and fourth (CGCMI-A_HP) climate change scenario.

All scenarios were used to drive the modified Versatile Soil Moisture Budget model that assesses soil moisture, aridity and other agroclimatic indices. The results from the four climate change scenarios were compared to those using the historic climate data. With spring warming occurring earlier the provincially averaged advancement of seeding dates varied between 16 and 29 days depending on the chosen scenario – in more southern regions an additional 2–3 days compared to the provincial averages. All four climate change scenarios predicted increases in the number of degree-days between 3% and 22% (provincial averages). Greatest warming during the growing season was anticipated in Alberta. Soil moisture was predicted to increase between 22% and 34% using GCMII scenario, coinciding with the large predicted increase in precipitation. However, little change in soil moisture was predicted under a CGCMI-A scenario.

Climate change with warming but no change in precipitation (GCMII_HP and CGCMI-A_HP) resulted in a 10% decrease in soil moisture in Alberta and no change in Saskatchewan and Manitoba. Aridity during the growing season was predicted to decrease dramatically under a GCMII scenario (wetter conditions) to only slight changes with the remaining scenarios. Both GCM output data resulted in a shift to earlier seeding dates and an improvement in soil moisture status on the Canadian Prairies. Even under the worst-case scenario (no change in annual precipitation amount or pattern), the shift in seeding dates compensated for increased evaporation during the summer – only. Alberta was predicted to experience a decrease in soil moisture. It should be noted that these projected changes in soil moisture are based on the advancement in the growing season dates and decreased maturity period. The adoption of earlier seeding dates with conventional short-season crops was an adaptive strategy that resulted in water savings.

Without this adaptive strategy, production of cereal crops in the Prairies is expected to drop by up to a third in western areas and increase by up to two-thirds in eastern areas due to changes in available soil moisture. Ontario and Quebec will experience similarly variable results. In both the Atlantic Region and British Columbia increased grain yield potential is foreseen but realization of this potential is likely dependent on the amount of water available for irrigation (Environment Canada, 1997b).

Agroclimatic indices (heat units and water deficits) were determined for the Atlantic region of Canada for the present day climate (1961–1990) and for two future periods (2010–2039 and 2040–2069) using the output from the Canadian GCM (Bootsma et al., 2001). The climatic changes expected to occur within the next 50 years, based on the Canadian GCM model and a “business as usual” scenario for Green House Gases emissions, are likely to have significant impacts on crop production. Crop (Corn) Heat Units (CHU) would increase by 300–500 CHU for 2010–2039 and between 500–700 CHU for 2040–2069 in the main agricultural areas of the Atlantic region. Anticipated changes in water deficits, defined as the amount by which evapotranspiration exceeded precipitation over the growing season, were generally less than 50 mm for both periods, increasing in some areas and decreasing in others. Statistical comparisons of crop yields with climate indices suggest that yields of grain corn and soybeans could increase as much as 3.8 and 1.0 tonnes per hectare, respectively, by the year 2055, mostly as a result of increased availability of heat units. Changes in water deficit are not expected to have a significant impact on crop yields. Yields of barley are likely to change only slightly but the competitive advantage in relation to corn and soybeans will be significantly reduced and likely lead to major shifts in areas seeded to these crops.

Grasslands are an important carbon and methane sink. Mitigation strategies for grasslands focus on small to moderate improvements in soil carbon levels, primarily through the prevention of overgrazing which leads to dramatic changes in plant species, decreased plant growth, and potential desertification. Improved management of grasslands can result in small increases of carbon sequestration per unit of land. In contrast, the biological process of denitrification releases nitrous oxide and enteric fermentation by cattle grazing the forage on grassland releasing methane. The complexity of issues involved can be illustrated by the following interaction. Some of the mitigation strategies that have the potential to increase soil carbon sequestration could result in increased nitrous oxide and methane emissions due to improved soil fertility and increased cattle numbers on the land. For cultivated land, soil carbon sequestration is dependent upon three key factors: land tillage practices, plant species selected, and soil nutrient and water inputs. Minimum or zero tillage initially was recognized as an important tool for reducing soil erosion and improving water conservation. However, low-tillage soil management has also been recognized as an effective means of soil carbon sequestration. There is increasing consensus that summer fallow acreage will also reduce N_2O emissions.

As noted earlier, nitrous oxide occurs as a result of the denitrification processes in the soil. Soil carbon and nitrogen cycles are linked. Therefore, land management strategies directed toward the incorporation of atmospheric CO_2 into soil organic matter must be evaluated relative to the impacts on N_2O emissions. For example, the portion of N_2O that is produced near the soil surface or that is not able to be absorbed at deeper levels through downward diffusion due to an inhibiting layer will result as N_2O flux into the atmosphere. An inhibiting layer is, for example, a frozen

ground layer in the spring. Thus, a greenhouse gas mitigation strategy relative to soil nutrient management is to reduce this soil N_2O flux into the atmosphere.

A major complication to an effective strategy is the complex and rather poorly understood mechanisms that govern conditions for N_2O production and emission from agricultural soils. Seasonal distribution of N_2O emissions have been well characterized; however, the ability to quantify these emissions has been difficult. A number of factors influence nitrification and denitrification processes, the time lag between production and emission of soil N_2O , and the relationship between production and emission rates of N_2O . These include rainfall, snowmelt, temperature, freezing and thawing, fertilizer and manure applications, and tillage.

Although agriculture is a net emitter of green house gases, farmers can adopt several measures to reduce emissions (Desjardins et al., 2001). Some of these are expensive, but some can be used with little cost or even at higher profit. Widespread use of such practices could reduce emissions of all three green house gases, and for CO_2 , even make farms net absorbers (Janzen et al., 1998). Practices that are relevant to GHG emission reduction and sustainable development include: reduced tillage intensity; reduced summer fallow area; improved manure management; improved feeding rations; improved drainage/irrigation. Other considerations that come into play include their practical feasibility, economic cost, effect on soil quality, and influence on the whole environment. The projected effects of the above selected practices on GHG emissions and on other considerations are illustrated in Table 16 of *The Health of Our Air* (Janzen et al., 1998).

Water management practices and trends have a direct impact on greenhouse gases. Soil water content influences the timing, nature, and magnitude of soil microbial processes which are responsible for the production and consumption of CO_2 , CH_4 , and N_2O . Further, wetlands and bogs represent areas of significant carbon accumulation due to high plant productivity, coupled with the inhibition of organic matter oxidation.

Wetlands currently cover 14% of Canada's land mass and are a critical resource providing habitat for species (including some of Canada's rare, threatened, or endangered ones), storage for atmospheric carbon, nutrient and mineral cycling, water purification, and natural flood control. Climate change could result in the conversion of semi-permanent wetlands from open-water dominated basins to vegetated areas (Environment Canada, 1999). Wetlands in Canada's agricultural zones are considered to be product ecosystems and are a net sink for greenhouse gases. In some areas, a promising mitigation strategy would be to return those lands that are marginally producing or that are increasingly subject to salinization to either permanent grass cover or to wetlands.

Opportunities for reducing emissions through increasing C sequestration exist by using improved farming practices and thereby modifying the soil climate and other physical soil properties, but the net effect is complicated. For example, the increase in soil moisture associated with no-till or reduced tillage leads to more soil decomposition, whereas the cooler temperatures and less soil aeration lead

to less soil composition. But no-till has also other benefits such as minimizing C loss associated with soil erosion and savings in fossil fuel emissions because of reduced machinery use. In fact, no-till is the most efficient management practice for sequestering C in cropland, when compared to cover crops, crop rotation, fertilizer strategies and manure applications (Desjardins et al., 2001).

Large expanses of Canada's land base is forested land. It has already been noted that trees have the potential to trap atmospheric CO₂ and sequester carbon. Planting shelterbelts have traditionally been an effective means of protecting agricultural or grazing land from strong winds. Plants and livestock can be subjected to severe stresses associated with excessive chilling, high temperatures, dessication, or direct wind injury. Windbreaks can, by reducing these stresses, be profoundly beneficial to the growth of plants and health of livestock. Thus, an effective mitigation strategy is the planting of trees on the landscape that is normally devoted exclusively to agricultural production. In addition to sequestering carbon, shelterbelts have the potential to reduce N₂O emissions. There would be less fertilizer nitrogen applied to the land. More trees would mean less nitrogen moving out from the root zone to surface or groundwater resources (i.e., less denitrification). Finally, nitrogen would be recycled from the tree leaves that fall to the ground, reducing the need for nitrogen application to the soil.

9. Summary and Conclusion

Increased weather variability likely resulted in greater fluctuations in crop yields in recent decades. Key issues for agriculture are extreme weather events, such as drought, flooding, and heat waves. Changes in drought tendencies, soil moisture availability, and frost-free growing seasons are also factors that influence agricultural and forest productivity. Agriculture plays a role in the inventory of greenhouse gases and in mitigation measures to reduce these gases.

Rapid shifts in the agricultural land base brought about by extreme climatic variability can have a major disruptive effect on rural communities and associated infrastructures. It is essential that proactive mitigation measures be developed to cope with these changes and preserve the all-important agricultural and forest systems.

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ASSESSING THE CONSEQUENCES OF CLIMATE CHANGE FOR FOOD AND FOREST RESOURCES: A VIEW FROM THE IPCC

WILLIAM EASTERLING¹ and MICHAEL APPS²

¹*Department of Geography, The Pennsylvania State University, University Park, PA 16802 U.S.A.
E-mail: easter@gis.psu.edu*

²*Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC Canada*

Abstract. Important findings on the consequences of climate change for agriculture and forestry from the recently completed Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) are reviewed, with emphasis on new knowledge that emerged since the Second Assessment Report (SAR). The State-Pressure-Response-Adaptation model is used to organize the review. The major findings are:

- Constant or declining food prices are expected for at least the next 25 yr, although food security problems will persist in many developing countries as those countries deal with population increases, political crisis, poor resource endowments, and steady environmental degradation. Most economic model projections suggest that low relative food prices will extend beyond the next 25 yr, although our confidence in these projections erodes farther out into the 21st century.
- Although deforestation rates may have decreased since the early 1990s, degradation with a loss of forest productivity and biomass has occurred at large spatial scales as a result of fragmentation, non-sustainable practices and infrastructure development.
- According to United Nations estimates, approximately 23% of all forest and agricultural lands were classified as degraded over the period since World War II.
- At a worldwide scale, global change pressures (climate change, land-use practices and changes in atmospheric chemistry) are increasingly affecting the supply of goods and services from forests.
- The most realistic experiments to date – free air experiments in an irrigated environment – indicate that C₃ agricultural crops in particular respond favorably to gradually increasing atmospheric CO₂ concentrations (e.g., wheat yield increases by an average of 28%), although extrapolation of experimental results to real world production where several factors (e.g., nutrients, temperature, precipitation, and others) are likely to be limiting at one time or another remains problematic. Moreover, little is known of crop response to elevated CO₂ in the tropics, as most of the research has been conducted in the mid-latitudes.
- Research suggests that for some crops, for example rice, CO₂ benefits may decline quickly as temperatures warm beyond optimum photosynthetic levels. However, crop plant growth may benefit relatively more from CO₂ enrichment in drought conditions than in wet conditions.
- The unambiguous separation of the relative influences of elevated ambient CO₂ levels, climate change responses, and direct human influences (such as present and historical land-use change) on trees at the global and regional scales is still problematic. In some regions such as the temperate and boreal forests, climate change impacts, direct human interventions (including nitrogen-bearing pollution), and the legacy of past human activities (land-use change) appear to be more significant than CO₂ fertilization effects. This subject is, however an area of continuing scientific debate, although there does appear to be consensus that any CO₂ fertilization effect will saturate (disappear) in the coming century.
- Modeling studies suggest that any warming above current temperatures will diminish crop yields in the tropics while up to 2–3 °C of warming in the mid-latitudes may be tolerated by crops, especially if accompanied by increasing precipitation. The preponderance of developing

countries lies in or near the tropics; this finding does not bode well for food production in those countries.

- Where direct human pressures do not mask them, there is increasing evidence of the impacts of climate change on forests associated with changes in natural disturbance regimes, growing season length, and local climatic extremes.
- Recent advances in modeling of vegetation response suggest that transient effects associated with dynamically responding ecosystems to climate change will increasingly dominate over the next century and that during these changes the global forest resource is likely to be adversely affected.
- The ability of livestock producers to adapt their herds to the physiological stress of climate change appears encouraging due to a variety of techniques for dealing with climate stress, but this issue is not well constrained, in part because of the general lack of experimentation and simulations of livestock adaptation to climate change.
- Crop and livestock farmers who have sufficient access to capital and technologies should be able to adapt their farming systems to climate change. Substantial changes in their mix of crops and livestock production may be necessary, however, as considerable costs could be involved in this process because investments in learning and gaining experience with different crops or irrigation.
- Impacts of climate change on agriculture after adaptation are estimated to result in small percentage changes in overall global income. Nations with large resource endowments (i.e., developed countries) will fare better in adapting to climate change than those with poor resource endowments (i.e., developing countries and countries in transition, especially in the tropics and subtropics) which will fare worse. This, in turn, could worsen income disparities between developed and developing countries.
- Although local forest ecosystems will be highly affected, with potentially significant local economic impacts, it is believed that, at regional and global scales, the global supply of timber and non-wood goods and services will adapt through changes in the global market place. However, there will be regional shifts in market share associated with changes in forest productivity with climate change: in contrast to the findings of the SAR, recent studies suggest that the changes will favor producers in developing countries, possibly at the expense of temperate and boreal suppliers.
- Global agricultural vulnerability is assessed by the anticipated effects of climate change on food prices. Based on the accumulated evidence of modeling studies, a global temperature rise of greater than 2.5 °C is likely to reverse the trend of falling real food prices. This would greatly stress food security in many developing countries.

1. Introduction

Considerable progress in the understanding of how global climate change is likely to affect agricultural production and forest resources has been made in recent years. In the recent Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change's (IPCC) Working Group (WG) II (McCarthy et al., 2001), agriculture and forest resources were combined in a chapter with other, less managed, terrestrial and aquatic ecosystems in order to assess their response to climate change. This was intended to facilitate comparison of the impacts of climate change on basic biological and ecological processes across ecosystems (including agro-ecosystems and forest ecosystems) in a consistent manner. However, agro-ecosystems and forest ecosystems are fundamentally different from less managed ecosystems such as

wetlands, tundra, and savannas: they produce economically valuable goods and services within a system of clear and enforceable property rights. Such greatly complicates understanding of their response to climate change because of intense human intervention into climate-ecosystem interactions and because responses of these ecosystems to climate change can have direct and immediate economic impacts. Hence, we focus on agriculture and forest resources together in this paper.

The aim of this paper is to distill important insights into the vulnerability, potential impacts, and adaptation prospects of agriculture and forest resources in response to climate change from the IPCC's WG II TAR¹. The majority of this paper is drawn from material generated for Chapter 5 of the TAR-WG II. The purpose of that chapter was to review and assess scientific progress in the understanding of how ecosystems (including agroecosystems and forest ecosystems) and their coupled social systems may respond and adapt to climate change, and to provide a global perspective on possible agricultural and forest outcomes. The absence of important research published since 2000 dictates caution in the interpretation of earlier studies, which follow below. We adopt a global perspective and although we recognize the importance of regional and local variation of impacts, we leave detailed discussion of such for others to consider.

We follow a modified version of the *State-Pressure-Response* model (to include *Adaptation*) of the Organization for Economic Cooperation and Development (OECD) to report key findings. *State* refers to the status or condition and future trends in food, fiber, fuel, and fodder systems under current climate conditions. *Pressure* refers to environmental and social stresses, including those arising from climate change, on such systems. *Response* refers to the induced changes in these systems arising from the imposed pressures (including climate change). *Adaptation* refers to the managed changes in ecosystems and deliberate human actions aimed at meeting resource supply needs given the ecosystem responses to climate change. This model disciplines our synthesis of the large amount of research on the consequences of climate change by focusing the review on the following questions: What is the current state of the Earth's agricultural and forest ecosystems and how effectively are we meeting the demands for their goods and services? What major challenges confront the world's food and fiber sectors over the next several decades, whether the climate changes or not? What are the likely biophysical and socioeconomic effects of climate change? What are the prospects for successful adaptation by agricultural and forestry systems to those effects? How vulnerable will those systems be after accounting for the potential for adaptation to alleviate adverse outcomes or take advantage of opportunities?

2. State of the Global Agriculture and Forest Sectors

Agriculture and forests account for approximately 41% of the Earth's land covers (Houghton, 1990). According to the United Nation's Food and Agriculture Organization (FAO, <http://www.fao.org/DOCREP/003/X7470E/X7470E00.HTM>), global

exports of their commodities and services were valued at \$440 billion in 1999. As noted above, unlike less managed ecosystems, the products of agriculture and forests are traded as commodities on world markets. Those products possess critical life-giving properties and are part of the Earth's life support system. There is a consensus that the global food and fiber enterprise will be challenged over the coming decades to expand capacity in step with anticipated expansion in global demand (World Bank, 1993; Alexandratos, 1995; Rosegrant et al., 1995; Antle et al., 1999; Johnson, 1999). Furthermore, the severest challenge to the ability of global agricultural capacity to expand apace with demand, with or without climate change, will come in the next 25-40 yr, with the challenge abating after that as population growth is projected to slow and global income elasticity of food demand is projected to decline. That is, the real story of climate change impacts on global agriculture is likely to be played out over the next 25-40 yr, with the rest of the century being anti-climatic. The situation for forest ecosystems and the services they provide may be somewhat different due to the longer lifetime of the species involved. The response of forest ecosystems will play out over longer time frames of a century or more, with reliability of the forecasted change critically tied to the accuracy of the future climate predictions. Here, however, it is expected that economic systems will change more rapidly in response to ecosystem changes in resource supply than those ecosystem responses themselves, and arguably with greater uncertainty attached to them.

2.1. STATE OF AGRICULTURE

Agricultural production in the latter half of the 20th century increased the global food supply outstripping the increase in global demand for food – this was accomplished in spite of increases in global population and incomes. As a result, prices for most major crops declined when adjusted for inflation. Wheat and feed corn declined at an annual average rate of 1-3% over the period (Johnson, 1999; Antle et al., 1999). In the absence of climate change, several analysts (e.g., World Bank, 1993; Rosegrant et al., 1995; Johnson, 1999) expect inflation-adjusted food prices to remain stable or slowly to decline over the next two decades. Confidence in this outcome is high over the next two decades.

Declining food prices will likely ease but not fully erase problems of food security, particularly in low-income countries where lack of access to food, political instability, and inadequate physical and financial resources will remain major challenges. In some instances, especially in the small number of nations with little immediate prospect for a successful transition from agricultural economies to manufacturing or service-based economies, lower global food prices could be stressful. However, the anticipated spread of technology and science-based production practices even to the poorest agricultural economies will likely reduce costs of production to help farmers cope with lower prices. Agricultural trade policies tend to decrease the efficiency of production both in high and low-income countries. In high-income countries, policies tend to subsidize production in order to protect the

agriculture sector while in low-income countries policies tend to tax and discourage production (Schiff and Valdez, 1996).

Much of the optimism for future growth in agricultural production hinges on anticipated technological progress that increases crop yields. Rosegrant and Ringler (1997) argue that considerable unexploited capacity to raise crop yields exists in current crop varieties. Other analysts (e.g., Pingali, 1994; Tweeten, 1998) argue that the declining supply of new agricultural land combined with large-scale degradation of soil and water resources will slow the increase in global agricultural output, which may slow or negate the expected decline in real food prices. Approximately 50% of cereal production in developing countries is irrigated and, although it accounts only for 16% of the world's crop land, irrigated land produces 40% of the world's food. It appears that the rate of expansion of irrigation is slowing and 10 to 15% of irrigated land is degraded to some extent by waterlogging and salinization (Alexandratos, 1995). It is questionable whether or not the irrigation water supplies necessary to meet future irrigation demands will be available. The two conflicting views represented in this paragraph make the future trend in prices beyond the first third of the century highly uncertain.

2.2. STATE OF FOREST RESOURCES

Forests cover nearly 30% (3,500 Mha) of the world's land area (excluding Greenland and Antarctica), of which 60% are located in seven countries (in order): Russia, Brazil, Canada, United States, China, Indonesia and the Democratic Republic of the Congo. Although 57% of the global forest is in developing countries, only 81 Mha of these were classified as plantations in 1995; developed countries account for a further 80–100 Mha (FAO, 1997). Between 50 and 95% of the industrial roundwood production for many countries is met from plantations that cover as little as 1–17% of their total forest area (Sedjo, 1999), and plantations in developing countries typically occur in community woodlots or agro-forestry operations.

FAO (1997) estimated that there was a human-induced net loss of about 5% (180 Mha) in forest area between 1980 and 1995. The estimated 200 Mha conversion of forests to subsistence agriculture, cash crops and ranching was in part offset by an estimated 40 Mha of new plantations and 20 Mha of afforestation and old-farm abandonment in developed nations. Deforestation appears to have accounted for an overall loss of native forest estimated at 65 Mha between 1990 and 1995 (FAO, 1997), while degradation, in the form of fragmentation, non-sustainable logging of mature forests, and infrastructure development, has occurred on large scales, leading to a net loss of forest biomass in existing forest. For example, 1 Mha yr⁻¹ of degraded forests result from damaging logging practices and surface fires in Brazil and effectively account for as much loss of forest areas as the annual deforestation in these same regions (Cochrane et al., 1999, Nepstad et al., 1999). These human encroachments are not limited to the tropical forests: Robinson

et al. (1999) have shown that in boreal Canada, road development, survey lines and wellheads have led to a loss of 54,000 to 81,000 ha yr⁻¹ forest cover.

Forests and woodlands provide many goods and services that society depends upon, including marketable timber and non-timber products (food, fuel, and fiber) as well as a host of environmental, recreational and spiritual values. Changes in the global climate, as well as the direct pressures by human activities, are likely to have an impact on most of these goods and services, with significant socioeconomic impacts (Winnett, 1998). Separation of the influence of climate change on forests and their associated goods and services from other global change factors such as land-use change, land-use practices and changes in atmospheric chemistry (CO₂ and pollution) is difficult. There are, however, strong signals emerging both from carefully controlled experiments (e.g., Luo et al., 2002, Shaver et al., 2000) and from transect studies across strong climatic gradients (e.g., McGuire et al., 2001, Yu et al., 2002, Canadell et al., 2002). These signals appear across a range of scales from responses of individual organisms and species, to changes in landscape patterns associated with a combination of competitive advantage and altered disturbance regimes. Associated changes in carbon stocks (i.e., source-sink relationships), a focus for many of the studies (e.g., Apps et al., 2002), are strongly linked with the global change induced alteration of forest dynamics. Alteration of natural disturbance patterns (such as fire, insect disease and storm damage) and human disturbances (land-use change) appear to be especially important in northern and some temperate forest ecosystems. Not only are there direct effects from the disturbances themselves, but they may also facilitate other ecosystem responses to climate change through altered successional pathways (Overpeck et al., 1990). Because of the importance of this matter to the land use, land-use change and forestry components of the Kyoto protocol (Watson et al., 2000), for example, the IPCC is presently convening an expert task group to factor out direct human-induced changes in carbon stocks from those due to indirect human induced and natural effects.

3. Environmental Pressures on Agriculture and Forest Resources

The degradation of environmental assets, especially soils, air and water, severely challenges the productivity of agriculture and forest resources (Pinstrip-Andersen and Pandya-Lorch, 1998, Price et al., 1999a,b). In the post-World War II period, approximately 23% of the world's agricultural and forest lands were classified as degraded by the United Nation's Environment Programme (Oldeman et al., 1991). Irrigated land is particularly vulnerable, although the expansion of irrigation is slowing.

In forest ecosystems, where the life cycle of the dominant vegetation is measured in decades and centuries, the impacts on ecosystem productivity depends on both the change in regional environmental conditions and the history of those changes over the past century. An asymmetry in the rates of mortality or degradation and the processes of regeneration and renewal (Kurz et al., 1995) strongly influences

the achieved productivity at the landscape scale by introducing an age-class legacy effect (Bhatti et al., 2000) that constrains opportunities for human intervention (Kurz and Apps, 1999). In some regions adverse impacts of climate change on productivity are associated with local climatic extremes, late or early frost (Repo et al., 1996, Ogren et al., 1997, Columbo, 1998), or increases in fire, insect or disease (Hogg and Schwarz 1997; Kurz et al., 1995). Where higher temperatures are associated with increased drought, as appears to be happening in continental parts of the boreal zone, even in the absence of fire, net primary productivity is reduced as a result of lowered photosynthetic rates associated with reduced stomatal conductance (Sellers et al., 1997). Some of these adverse influences may be offset by increases in growing season length (Myneni et al., 1997), nutrient cycling (Tian et al., 1998), and more favorable temperatures (Bugmann, 1997). Although at present the global forests on aggregate appear to have increased productivity (i.e., are acting as a net sink of atmospheric carbon), the changes are not spatially uniform. Moreover on the time dimension, there is a growing consensus that the present net positive increment (Schimel et al., 2001) in the global average in response to global change is not sustainable, and will decline or disappear as global change pressures continue.

Although the economic impacts of the long term environmental degradation of forest and agricultural systems are difficult to determine, the general consensus is that they will eventually begin to undermine the necessary expansion of food and fiber production if allowed to increase at current rates.

4. Response of Agriculture and Forest Resources to Rising Atmospheric CO₂ and Climate Change

4.1. DIRECT EFFECTS OF RISING ATMOSPHERIC CO₂

4.1.1. CO₂ Effects on Crops

Results from experimental studies have established that it is no longer realistic to examine the effects of climate change on crop and forage plants without also accounting for the direct effects of rising atmospheric CO₂ at the same time. The short-term responses to elevated CO₂ of isolated plants grown in artificial conditions remain difficult to extrapolate to crops in the field (Körner, 1995). Even the most realistic free-air carbon dioxide enrichment (FACE) experiments yet undertaken impose an abrupt change in CO₂ concentration and create a modified area (Kimball et al., 1993) analogous to a single irrigated field in a dry environment. Natural ecosystems and croplands are experiencing a gradual increase in atmospheric CO₂. Nonetheless, a cotton crop exposed to FACE increased biomass and harvestable yields by 37 and 48% respectively in elevated (550 ppm) CO₂ (Mauney et al., 1994). At the same CO₂ increase, spring wheat yields increased by 8–10% when water was non-limiting (Pinter et al., 1996). A simple linear extrapolation of spring wheat FACE results to a doubling of CO₂ produces a 28% increase in yields.

Several important breakthroughs in the understanding of CO₂ direct effects on crops were accomplished since the SAR. Most concern improvements in the understanding of how climate interacts with the physiology of CO₂ direct effects. Horie et al. (2000) found that moderate temperatures accompanied by a doubling of CO₂ increases the seed yield of rice by 30%. However, with each 1 °C increase in temperature above 26 °C, rice yield declined by 10% because of shortened growth period and increased spikelet sterility. This raises concerns that CO₂ benefits may decline quickly as temperatures warm (established but incomplete). On the positive side, crop plant growth may benefit more from CO₂ enrichment in drought conditions than in wet soil because photosynthesis would be operating in a more sensitive region of the CO₂ response curve (Samarakoon and Gifford, 1995). Significantly, this effect was observed in C₄ photosynthesis. The most likely explanation for this thus far is that drought-induced stomatal closure causes CO₂ to become limiting in the absence of CO₂ enrichment (established but incomplete). It is not clear how much this effect is likely to offset the overall effect of drought on crop yield. Also, the notable dearth of testing of tropical crops and suboptimal growth conditions (nutrient deficits, weed competition, pathogens) continues from the SAR as a major research gap.

4.1.2. *CO₂ Effects on Forests*

In forests, the influence of increased CO₂ levels at the ecosystem level is not well understood and is, in many regions, masked by other direct and indirect effects of human activity. Most global models of terrestrial ecosystem dynamics include a growth enhancement associated with a CO₂ fertilization effect on photosynthesis (Prentice et al., 2001). At the plant and plot level, Norby et al. (1999) point out that saturation of the CO₂ response due to acclimation of the individual plant to elevated CO₂ or to other environmental limitations (such as water or nutrients) must be examined with long term observations. In their review of existing manipulative experiments, Norby et al., conclude that elevated CO₂ yields continued and consistent stimulation of photosynthesis with little evidence for long-term loss of sensitivity to this stimulation. In contrast, a later study of East coast north-American forest inventory data by Caspersen et al. (2000) concluded that changes in growth enhancement due to environmental factors including post industrial CO₂ increases is much smaller than has previously been reported, accounting for only $2.0 \pm 4.4\%$ of the aboveground net ecosystem production of the last century. They conclude that changes in land use (abandonment of marginal agricultural land), and land-use practices (forest management) have had a far greater impact. Whether CO₂ fertilization presently plays a significant role in forest biomass and fiber accumulation, the general consensus appears to be that its influence will saturate in the coming century and become increasingly insignificant in relation to other global change impacts. Unlike agricultural systems, the turnover time (life cycle) of forest vegetation is long in comparison with the rate of projected environmental change.

4.2. IMPACTS OF CLIMATE CHANGE

4.2.1. *Impacts on Crops and Livestock*

Major advances were made since the SAR in the understanding of how changes in climate elements such as temperature, precipitation, and humidity, are likely to affect crop plants and livestock; CO₂ direct effects were included in much of this new crop research. A review of 43 crop modeling studies performed since the SAR revealed important geographic differences in the predicted impact of climate change on yields (Gitay et al., 2001, Table 5.3²). The studies incorporated a wide range of climate change scenarios, including several different general circulation model experiments, historical climate fluctuations, and simple sensitivity experiments. While change in climate variability, defined as change in the higher moments of climate elements, was not explicitly examined in this part of our review, it is incorporated in many of the scenarios used in the crop modeling experiments. The modeling studies were separated into tropical and temperate regions for comparison. Predicted percentage changes in yields (relative to current yields) in response to climate change from each study were plotted against local temperature increases; the crops were rice and corn in the tropics, and corn and wheat in the temperate regions. All studies accounted for CO₂ direct effects but not for adaptation. Only study results based on local precipitation increase were selected for this comparison. We focused on cases of precipitation increase for three reasons: (i) to permit evaluation of the response of crops to the least stressful expected conditions as a conservative estimate of crop sensitivity; (ii) to be able to report an acceptable number of studies performed with comparable climate change characteristics – there are more modeling studies in important agricultural regions based on positive precipitation change than negative, and, following from ii, (iii) among the more discernable patterns of agreement among climate model projections reported by the TAR-WG II (Carter and LaRovere et al., 2001), are increases in summer precipitation in high northern hemisphere latitudes, tropical southern Africa, and south Asia, with little change in southeast Asia³. The distribution of raw modeled yields versus temperature change was converted to a log normal distribution in order to damp the distorting effect of outlier yield estimates. The logged yield values were then averaged across studies at each degree of temperature change – i.e., yield estimates for all studies reported at, for example, +1 °C were averaged to create a mean value for +1 °C, +2 °C and so on out to +4 °C. The mean log yields were then converted back to their original units (mT^{-ha}) and plotted to produce the line graphs shown in Figures 1 and 2.

Comparison of Figures 1 and 2 demonstrates the relatively greater sensitivity of tropical crops to climate warming than temperate crops. In the tropics, although rice yields increase by approximately 7% above current yields with 1 °C of warming, they decline sharply beginning at 2 °C of warming, falling to 17% below current yields at the maximum of 4 °C of warming. The initial positive response of rice was heavily skewed by a preponderance of studies at the northern edges of the tropics. Rice yields everywhere else in the tropics declined with the initial 1 °C of warming.

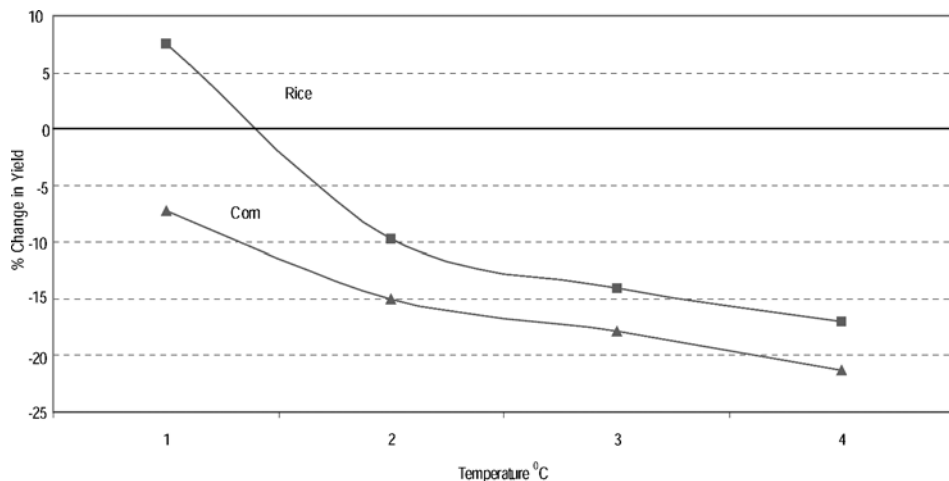


Figure 1. Corn and Rice yields versus temperature increase in the tropics averaged across 13 crop modeling studies. All studies assumed a positive change in precipitation. CO₂ direct effects were included in all studies.

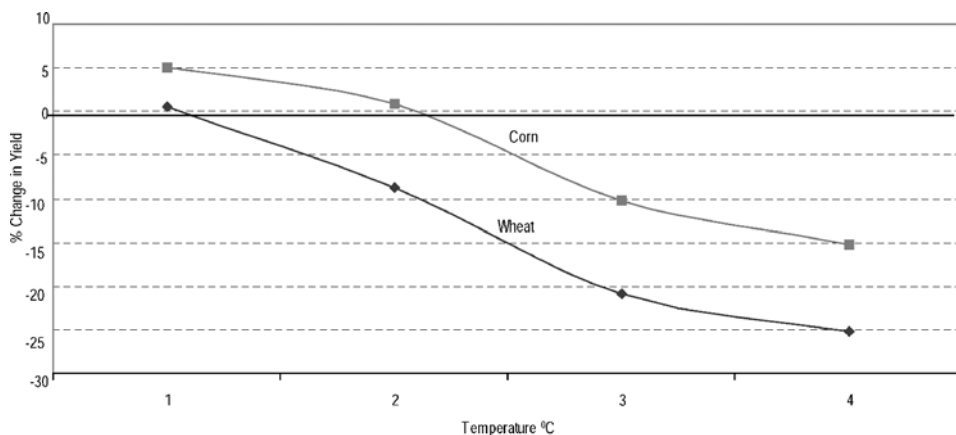


Figure 2. Corn and Wheat yields versus temperature increase in the temperate zone averaged across 30 crop modeling studies. All studies assumed a positive change in precipitation. CO₂ direct effects were included in all studies.

Tropical corn yields decline by nearly 7% with the warming of 1 °C, by more than 20% with warming of 4 °C. This will pose a challenge to adequate food production in a majority of the world's least developed nations.

In temperate regions, corn was slightly benefited by warming of up to 2 °C before slipping below current yields at +3 °C (Figure 2). Wheat yields tended to be less resilient in response to the climate change, slipping below current yields at warming of +2 °C, and declining to -25% below current yields at +4 °C.

The greater sensitivity of crops to warming in the tropical region is partly explained by the fact that crops in this region are grown under normal temperatures

that approach theoretical optima for photosynthesis, and any additional warming is deleterious, even when accompanied by increased precipitation. Temperate crops are normally cold temperature limited, and the early stages of warming, accompanied by increasing precipitation, undoubtedly stimulate higher productivity – for a while. However, as temperate warming proceeds so does evapotranspiration. At temperature increases of $+3^{\circ}\text{C}$ or greater, evapotranspiration appears to overcome the benefits of warming and increased precipitation, leading to increasing aridity and decreasing yields. Hence, all major planetary granaries are likely to require adaptive measures by $+2\text{--}3^{\circ}\text{C}$ of warming no matter what happens to precipitation. It would be reasonable to expect adaptive measures to become necessary at lesser amounts of warming in those regions experiencing precipitation decreases with the warming.

Recent research on the impact of climate change on livestock supports the major conclusions of the SAR. Farm animals experience climate change directly by altered physiology and indirectly by changes in feed supplies. A dearth of physiological models that relate climate to animal physiology limits confidence in predictions of impacts, although model building is underway (Hahn, 1995; Klinedinst et al., 1993). However, there is general consensus from experimental results that climate warming likely will alter heat exchanges between animals and their environment such that mortality, growth, reproduction, and milk and wool production would be affected.

Livestock managers routinely cope with weather and climate stresses on their animals, using techniques such as strategic shading and use of sprinklers. This bodes well for adapting to climate change.

4.2.1.1. Accounting for Climate Variability. Natural climate variability and its changes with mean warming regulate the frequency of extreme events such as drought, excessive moisture, heat waves, and the like, which are critical determinants of crop and livestock production. Carter and LaRovere et al. (2001) list several *likely to very likely* changes in extreme events of importance to agriculture including, for example, higher maximum temperatures over nearly all land areas and increased summer drying over most mid-latitude continental interiors (even in cases of increased precipitation due to increased evapotranspiration). Research has only begun to consider the effect of change in frequency of extremes on agricultural production explicitly. Some analysts find that increased interannual climate variability accompanying mean climate changes disrupts crop yields more than mean climate changes alone (Mearns et al., 1995; Rosenzweig et al., 2000). Stochastic simulations of wheat growth indicated that a greater interannual variation of temperature reduces average grain yield more than a simple change in mean temperature (Semenov and Porter, 1995). The potential of a change in extreme events with climate change to amplify the impact of climate change on crop productivity (both positively and negatively) is established but research is incomplete.

Analysts argue that it is important that the effect of change in climate variability on crops be distinguished from that of the change in mean climate conditions

as a basis for distinguishing the impacts of natural swings in climate variability from those of climate change (Hulme et al., 1999). Hulme et al. (1999) found it difficult to distinguish the impact on modeled wheat yield of simulated natural climate variability from that of simulated changed variability due to climate change. Hulme et al. (1999) compared wheat yields simulated with a multi-century modeled control climate containing realistic natural climate variability with those simulated with a multi-century climate change containing a change in climate variability. They found that yields under the control climate were indistinguishable from yields under climate change in a majority of the modeling sites. Such simulation results emphasize the need for greater efforts to distinguish the 'noise' of natural climate variability from the 'signal' of climate change (Semenov et al., 1996; Pittock, 1999).

4.2.2. *Impacts on Forest Resources*

Since SAR, with the increased availability of transient GCM simulations, much more research has been focused on the transient responses of forest ecosystems to changing climate rather than the assessment of forest resources under an assumed equilibrium climate for a doubling of atmospheric CO₂ forcing. Such equilibrium analyses are now recognized to give valuable insight into the likely sensitivity of forest ecosystems and vulnerability of the goods and services they supply, but are not good predictors for resource management strategies which must deal with changing forest conditions. New dynamic vegetation models (DGVMs) have largely displaced the earlier static biogeographic models (from which many derive). These new models may also be used to examine the sensitivity of global forest ecosystems to climate change, and in broad terms portray the same story as the earlier static models. They add, however, the important time dimension, and combined with increased spatial resolution provided by Regional Climate Models, permit the simulation of more detailed and realistic regional response patterns. Early examples of these new models are provided in the IPCC Special Report on the Regional Impacts of Climate Change (Watson et al., 1998) and in the Vegetation/Ecosystem Modeling and Analyses Project (VEMAP). Neilson et al. (1998) compared output for some of these models using transient climate change scenarios as input and compared the results with those reported in SAR. They concluded that the new transient GCMs produce somewhat cooler climates than the static simulations (primarily because of lag effects) but that significant poleward shifts in temperature limited vegetation types (temperate and boreal forests) are still expected. As pointed out by Gitay et al. (2001), however, these DGVMs are in their infancy, and the timing and actual distributions will be better understood when the models are both fully dynamic and feedbacks into the climate models is completed.

One factor that has emerged in importance has been changes in natural disturbance regimes. In most of the seven countries containing 60% of the global forest resource, controlling fire, insect and disease impacts is already a significant part of the forest resource management portfolio. Both climate change and other global

change pressures are expected to result in changes in the annual rate of areas affected by such disturbances. In the absence of directed management interventions, the changes are likely to be towards increased disturbances and there is some evidence that such increases are already occurring in boreal fire (Kashischke et al., 1995; Kurz and Apps, 1999; Shvidenko 2000) and insect outbreaks (Kurz et al., 1995; Fleming and Tatchell, 1995; Williams and Liebhold, 1997; E. Berg Personal Communication, 2002). A pressing question is whether such environmentally induced increases in disturbance rates can be effectively controlled through increased suppression effort. In the case of wild fire, which accounts for at least 2 Mha annual forest combustion in Canada (average for the 1990s), the probability of reducing this burn rate through increased suppression effort is very low, even with great increases in expenditures. Some 97% of the area annually burned is caused by the 3% of the fires that escape initial effort (which is limited by response time and the vast territories involved).

Increased present rates of disturbance facilitate successional change, providing a mechanism for ecosystem readjustment to altered environmental conditions of the new climate over the long term (Overpeck et al., 1990). In the near term (decades), at some locations there may be a transient loss of resources associated with these increased disturbances as older stands are replaced by juveniles.

In summary, while climate change is proceeding, the global forest resource is likely to be adversely effected due to the transient effects, and because of the relatively long life times of the vegetation, these impacts from changes taking place today will play out over a century or more into the future.

4.3. RESPONSE AND ADAPTATION TO IMPACTS ON CROPS, LIVESTOCK, AND FOREST RESOURCES

4.3.1. *Response and Adaptation of Crops and Livestock*

The impacts of climate change will induce responses from farmers and ranchers aimed at adapting. Initial responses likely will be autonomous adjustments to crop and livestock management such as changes in agronomic practices (e.g., earlier planting, cultivar switching) or microclimate modification to cool animals' environment. They require little government intervention and are likely to be made within the existing policy and technological regimes. Methodologically, there has been little progress since the SAR in modeling agronomic adaptations. On the positive side, the adaptation strategies being modeled are limited to a small sample of the many possibilities open to farmers, which may underestimate adaptive capacity. On the negative side, the adaptations tend unrealistically to be implemented as though farmers possess perfect knowledge about evolving climate changes, which may overstate their effectiveness (Schneider et al., 2000). The preponderance of studies finds agronomic adaptation to be most effective in mid-latitude developed regions and least effective in low-latitude developing regions (Rosenzweig and Iglesias, 1998; Parry et al., 1999). However, differences in assumptions and

modeling methodology among studies often lead to conflicting conclusions in specific regions. For example, in two studies using the same climate change scenarios, Matthews et al. (1997) simulate large increases while Winters et al. (1999) simulate large decreases in rice yield with adaptation across several countries in Asia. This lowers confidence in these simulations.

Like crop producers, livestock managers are likely to implement routinized adaptive techniques that were developed to deal with short-term climate variability during the initial stages of warming. For example, Hahn and Mader (1997) suggest several proactive management countermeasures that can be taken during heat waves (e.g., shades and/or sprinklers) to reduce excessive heat loads. The success livestock producers have had in the past with such countermeasures gives optimism for dealing with future climate change. However, coping can entail significant dislocation costs for certain producers. Confidence in the ability of livestock producers to adapt their herds to the physiological stresses of climate change is difficult to judge. As noted above, the absence of physiologically based animal models with well-developed climate components suggests a major methodological void.

4.3.1.1. *Economic Costs of Agricultural Adaptation*⁴. The agricultural cost (both to producers and consumers) of responding to climate change will mostly be for the implementation of measures to adapt. At the individual farm or ranch level, these costs will reflect changes in revenues, while at national and global levels they will reflect changes in prices paid by the consumer. Crop and livestock producers who possess adequate levels of capital and technology should be capable of adapting to climate change, although changes in types of crops and animals that are grown may be required. Two different studies in the U.S. midwest, demonstrate this point. Doering et al. (1997) used a crop-livestock linear programming model linked to the Century biogeochemistry model to show that climate change may cause substantial shifts in the mix of crops grown in the upper midwest, with much less land planted to a corn-soybean rotation and more land devoted to wheat than now observed. Earlier planting of corn increased returns, hence a more frost resistant corn variety was found to be important to farm-level adaptation. Antle et al. (1999) used an econometric-process simulation model of the dryland grain production system in Montana also linked to the Century model (as reported in Paustian et al., 1999) to assess the economic impacts of climate change in that region. Simulations were conducted for baseline and doubled CO₂ (Canadian Climate model) with the observed production technology, with and without land-use adaptation and with and without CO₂ fertilization. With climate change, CO₂ fertilization and adaptation, mean returns change by -11 to +6% relative to the base climate and variability in returns increases by +7 to +25%, whereas without adaptation mean returns change by -8 to -31% and variability increases by 25 to 83%.

There will be important regional variation in the success of adaptation to climate change. It appears that developed countries will be less challenged than developing countries and countries in transition, especially in the tropics and subtropics.

Winters et al. (1999) examined the impacts of climate change on Africa, Asia and Latin America using a computable general equilibrium model. They focus on the most vulnerable groups in poor countries: poor farmers and urban poor consumers. The results show that impacts on incomes of these vulnerable groups after adaptation would tend to be negative and in the range of 0 to -10% , as compared to the impacts on consumer and producer groups predicted for the U.S. by Adams et al. (1998), which ranged from -0.1 to $+1\%$. Darwin (1999) reports results disaggregated by region, and also concludes that the developing regions are likely to have welfare effects that are less positive or more negative than the more developed regions. These findings provide evidence to support the hypothesis advanced in the SAR that climate change is likely to have its greatest adverse impacts on areas where resource endowments are the poorest and the ability of farmers to respond and adapt is most limited.

At the global level, adaptation is expected to result in small percentage changes in income. These changes are expected to be generally positive for small to moderate amounts of warming, account taken for CO_2 effects. The price of agricultural commodities is a good all-around quantity to reflect the net consequences of climate change for the regional or global supply-demand balance and on food security. A global economic model used by Darwin et al. (1995) and a U.S. model developed by Adams et al. (1998) predict that, with the rate of average warming expected by the IPCC scenarios over the next century, agricultural production and prices are likely to continue to follow the downward path observed in the 20th Century. As a result, the impact on aggregate welfare comprises a small percentage of Gross Domestic Product, and tends to be positive, especially when the effects of CO_2 fertilization are incorporated. The only study that predicts real price increases with only modest amounts of climate change is Parry et al. (1999).

Is there a threshold of climate change below which the global food production system is unimpaired, but above which is clearly impaired? The question can only be answered with very low confidence at this time. Response of prices to climate change provides insight into the question because prices determine the accessibility of a majority of the world's population to an adequate diet. Two of three recent global economic studies project real agricultural output prices to decline with a mean global temperature increase of up to 2.5°C , especially if accompanied by modest increase in precipitation (Darwin et al., 1995; Adams et al., 1998). Another study (Parry et al., 1999) projects output prices to rise with or without climate change and even a global mean temperature increase of $\sim 1^\circ\text{C}$ (projected by 2020) causes prices to rise relative to the case of no climate change. When studies from the SAR are combined with the recent ones, there is general agreement that a mean global temperature rise of more than 2.5°C could increase prices (Reilly et al., 1996; Adams et al., 1998; Parry et al., 1999), with one exception (Darwin et al., 1995). Thus, with very low confidence, it is concluded from these studies that a global temperature rise of greater than 2.5°C will exceed the capacity of the global food production system to adapt without price increases.

A note on environmental damage from adaptation to climate change

Degradation of the natural resource base for agriculture, especially soil and water quality, is one of the major future challenges for global food security. Those processes are likely to be intensified by adverse changes in temperature and precipitation. Land use and management have been shown to have a greater impact on soil conditions than the direct effects of climate change, thus adaptation has the potential to significantly mitigate but may, in some cases, intensify degradation. Such environmental damage may raise the costs of adaptation. Lewandrowski and Schimmelpfennig (1999) suggest that the increased demand for irrigation predicted by a suite of studies of land and water resources, wild species, and natural ecosystems likely will increase the opportunity cost of water and possibly reduce water availability for wildlife and natural ecosystems. Strzepek et al. (1999) show that some scenarios of climate change may reduce irrigation system reliability in the lower Missouri River in the U.S. Cornbelt, which may induce instream environmental stress. In many developing countries, current irrigation efficiencies are very low by developed country standards. Irrigation efficiency in the Philippines in 1990 was 18% compared to the global average of 43% (ADB, 1998). Some 3,480 to 5,000 L of water are currently used to produce 1.0 kg rough rice (equivalent to 640 g milled rice) in the Philippines (Baradas, 1999) and some neighboring countries. At those irrigation efficiencies, increased irrigation demand caused by climate change would strain irrigation supplies. Hence, one adaptation strategy is to increase irrigation efficiency.

4.3.2. Response and Adaptation of Forest Resources

Managers of forest resources face a somewhat different problem than those managing shorter-lived crops. In the absence of spatially explicit and transient models of changes in climate, present-day forest management activities – whether it be forest plantation scheduling, silvicultural treatments or any other resource investment activity – are, to many, a speculative proposition because the result of those activities is so dependent on what happens over many decades into the future, at the specific sites being managed. This dependence on future conditions is not new to forest management, of course, but the new factor is the increased certainty of climate change at the global scale with uncertainty about the magnitude, direction and details at the local scale. Increases in locally extreme events (outside the historical norm to which the forest ecosystem and the management infrastructure has adapted) are of particular concern as they are often triggers or exacerbating factors for subtle ecosystem changes that influence successional pathways (e.g., changes in regeneration success and failure) that are beyond the present capability of management.

On the other hand, at the regional and global scales, it is believed that timber and non-wood goods and services will adapt to the changes in forest ecosystems through adjustments in the global market place. At these larger scales, the extent and nature of this adaptation will depend primarily on prices, the relative value of

substitute products, the costs of management and advances in technology (Joyce et al., 1995; Binkley et al., 1997; Sohngen and Mendelsohn, 1998). In contrast to the findings in SAR (Solomon et al 1996), more recent studies suggest that climate change will tend to favor rising market share in developing countries (Sohngen et al., 2000). Some suggest that this could happen at the expense of producers in temperate and boreal countries where short-term dieback effects and lower prices may prevail, despite a potential long-term (>50 yr) increase in supply from these regions under some climate response scenarios (Sohngen et al., 2000; Solomon and Leemans, 1997).

5. Summary and Conclusions

A clearer picture of the manner in which climate change likely will affect agriculture and forestry has taken shape over the past few years. Some important generalizations are now possible. Levels of uncertainty indicated in the text above are not repeated in the list that follows, although we urge the reader to keep these in mind. We state these as major findings from the TAR under the headings of the *State-Pressure-Response-Adaptation* framework. They include the following:

State

- Constant or declining food prices are expected for at least the next 25 yr, although food security problems will persist in many developing countries as those countries deal with population increases, political crisis, poor resource endowments, and steady environmental degradation. Most economic model projections suggest that low relative food prices will extend beyond the next 25 yr, although our confidence in these projections erodes further out into the 21st century.
- According to United Nations estimates, approximately 23% of all forest and agricultural lands were classified as degraded over the period since World War II.

Pressure

- Although deforestation rates may have decreased since the early 1990s, degradation with a loss of forest productivity and biomass has occurred at large spatial scales as a result of fragmentation, non-sustainable practices and infrastructure development.
- At a worldwide scale, global change pressures (climate change, land-use practices and changes in atmospheric chemistry) are increasingly affecting the supply of goods and services from forests. At present, it appears that the impacts of direct human pressures on forest ecosystems are greater than those directly attributable to climate change, but how the balance of these pressures will develop over the coming century is still to be determined with certainty.

Response

- The most realistic experiments to date – free air experiments in an irrigated environment – indicate that C₃ agricultural crops particularly respond favorably to the gradual rise of atmospheric CO₂ concentrations over current levels (e.g., wheat yield increases by an average of 28%), although extrapolation of experimental results to real world production where several factors (e.g., nutrients, temperature, precipitation, and others) are likely to be limiting at one time or another remains problematic. Moreover, little is known of crop response to elevated CO₂ in the tropics, as most of the research has been conducted in the mid-latitudes.
- Research suggests that for some crops, for example rice, CO₂ benefits from a doubling of atmospheric CO₂ concentrations over current concentrations may decline quickly as temperatures warm beyond optimum photosynthetic levels. However, crop plant growth may benefit relatively more from CO₂ enrichment in drought conditions than in wet conditions.
- The unambiguous separation of the relative influences of elevated ambient CO₂ levels, climate change responses, and direct human influences (such as present and historical land-use change) on trees at the global and regional scales is still problematic. In some regions such as the temperate and boreal forests, the legacy of past human activities (land-use change), direct human interventions (including nitrogen-bearing pollution), and climate change impacts, appear to be more significant than CO₂ fertilization effects. There appears to be consensus that, whatever its magnitude, any CO₂ fertilization effect will saturate (disappear) in the coming century.
- Modeling studies suggest that any warming above current temperatures will diminish crop yields in the tropics while up to 2–3 °C of warming in the mid-latitudes may be tolerated by crops, especially if accompanied by increasing precipitation. The preponderance of developing countries lies in or near the tropics; this finding does not bode well for food production in those countries.
- Where direct human pressures do not mask them, there is increasing evidence of the impacts of climate change on forests associated with changes in natural disturbance regimes, growing season length, and local climatic extremes.
- Recent advances in modeling of vegetation response suggest that transient effects associated with dynamically responding ecosystems to climate change will increasingly dominate over the next century and that during these changes the global forest resource is likely to be adversely affected.

Adaptation

- The ability of livestock producers to adapt their herds to the physiological stress of climate change appears encouraging due to a variety of techniques

for dealing with climate stress, but this issue is not well constrained, in part because of the general lack of experimentation and simulations of livestock adaptation to climate change.

- Crop and livestock farmers who have sufficient access to capital and technologies should be able to adapt their farming systems to magnitudes of climate change common in the agricultural literature. Substantial changes in their mix of crops and livestock production may be necessary, however, as considerable costs could be involved in this process because of investments in learning and gaining experience with different crops or irrigation.
- Impacts of climate change on agriculture after adaptation are estimated to result in small percentage changes in overall global income. Nations with large resource endowments (i.e., developed countries) will fare better in adapting to climate change than those with poor resource endowments (i.e., developing countries and countries in transition, especially in the tropics and subtropics) which will fare worse. This, in turn, could worsen income disparities between developed and developing countries.
- Although local forest ecosystems will be highly affected, with potentially significant local economic impacts, it is believed that, at regional and global scales, the global supply of timber and non-wood goods and services will adapt through changes in the global market place. However, there will be regional shifts in market share associated with changes in forest productivity with climate change: in contrast to the findings of the SAR, recent studies suggest that the changes will favor producers in developing countries, possibly at the expense of temperate and boreal suppliers.
- Global agricultural vulnerability to climate change is assessed by the anticipated effects such change will have on food prices. Based on the accumulated evidence of modeling studies, a global temperature rise of greater than 2.5 °C is likely to reverse the trend of falling real food prices. This would greatly stress food security in many developing countries.

Notes

¹Easterling and Apps were lead authors on Chapter 5 from which much of the material for this paper was drawn. We acknowledge the co-authors of Chapter 5, including J. Antle, S. Brown, H. Bugmann, L. Erda, R. Fleming, L. Hahn, E. Schulze, O. Sirotenko, B. Sohngen, J. Soussana, G. Takle, J. van Minnen and T. Williamson.

²Specific information about features of these studies, including climate scenarios used, is reported in Gitay et al., 2001, Table 5.3.

³Continental drying can be expected even when warming is accompanied by increased precipitation due to the effects of higher evapotranspiration.

⁴The reader is referred to Gitay et al., 2001, Table 5.3 for details of climate scenarios used in model simulations reported in this section.

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ACHIEVING ADEQUATE ADAPTATION IN AGRICULTURE

IAN BURTON¹ and BO LIM²

¹*Meteorological Service of Canada, Canada*

E-mail: ian.burton@ec.gc.ca

²*UNDP-GEF, New York, U.S.A.*

E-mail: bo.lim@undp.org

Abstract. This paper reviews the prospects for adaptation in world agriculture in the face of climate change. The record of experience from previous decades demonstrates a considerable capacity to adapt and there is general optimism that successful adaptation will be maintained. There are some grounds for concern because of the uncertainty surrounding global climate projections and the probability of considerable regional variation in impacts. While world production may not be adversely affected, the prospects are not so encouraging for low latitude agricultural regions, in part because of lower capacity to adapt. Attention has focused on the farming community itself as the place where adaptation takes place, but now the processes of globalization are placing adaptation more in the hands of agri-business, national policy makers, and the international political economy. The continued success of adaptation rests more heavily on actions at the national level in the context of changing technology and world trade liberalization. An adaptation policy framework is suggested as a vehicle to help understand and facilitate adaptation in this changing context.

1. Adaptation in the Agricultural Sector

For most of the decade since the United Nations Framework Convention on Climate Change (UNFCCC) was opened for signature in Rio de Janeiro in 1992, the emphasis in research, research assessments, and negotiations has been placed heavily on mitigation rather than adaptation. Mitigation refers to actions that reduce greenhouse gas emissions or sequester carbon in soils and biomass, and has been addressed by the Kyoto Protocol. More recently the negotiations at meetings of the Conference of the Parties are beginning to focus attention on adaptation. Adaptation refers to “adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. It refers to changes in processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change.” (IPCC, 2001, p. 879).

As a result of the increased interest in adaptation a new set of questions is now being directed from the policy makers to the research and expert communities at both national and international levels. Some of these questions have not yet been strongly articulated, but it is not difficult to see them coming. Many of them can be related to agriculture. To what extent can agricultural systems be adapted to rapid anthropogenic climate change? By how much can the estimated adverse impacts be reduced by adaptation? What are the costs and benefits of adaptation likely to be and how will they be distributed? What new opportunities might become available

under new climate regimes? Where and when is adaptation likely to be most and least effective? Where and why do farmers have or lack the capacity to adapt? What should be done to assess and then enhance adaptive capacity? What are the obstacles to effective adaptation and how can they be addressed? Is world food supply in danger from climate change? In any given place what new risks does agriculture face? How can these risks best be managed? What places, and what people are especially vulnerable? What policies and measures should governments and the private sector promote or facilitate? What kind of international cooperation would be helpful?

It has to be admitted that fully satisfying answers to these questions are generally not available. Nevertheless recent summaries of the scientific literature do offer some relevant information for preliminary conclusions. These partial answers are summarized as a prelude to a discussion of some of the current problems of climate and agriculture today, and some suggestions for a research agenda. We conclude with a proposed framework for the development of more appropriate policies and measures.

2. Some Good News and Some Bad News

The second synthesis of the scientific literature (IPCC, 1996) concluded that, "On the whole, these studies support the evidence presented in the first intergovernmental panel on climate change (IPCC) assessment that global agricultural production can be maintained relative to baseline production in the face of climate changes likely to occur over the next century (i.e. in the range of 1–4.5 degrees celcius) but that regional effects will vary widely." (IPCC, 1996, p. 23). A more recent IPCC assessment (IPCC, 2001) goes further and asserts that "Most global and regional economic studies – with and without climate change – indicate that the downward trend in real commodity prices in the 20th century is likely to continue into the 21st century, although confidence in these predictions decreases further into the future." (IPCC, 2001, p. 237).

The good news is that scientists and economic experts participating in the IPCC assessments appear confident that global agricultural production can be maintained in the face of climate change. The bad news includes the facts that there is considerable uncertainty in the climate projections themselves; that assumptions have been made about the likely success of adaptation on the basis of very little research, and that the prospect of relative success at the global level even if fully justified, probably masks considerable regional variation in impacts and adaptive response capacity. In short there will be winners and losers.

Research by Parry and others (Parry et al., 1999) has concluded that the adverse effects of climate change on agricultural production are likely to be felt more in the lower latitude countries even though the amount of temperature change there is projected to be less than in higher latitudes. Some of this higher vulnerability may be ascribed to environmental conditions where crops are grown close to their limits

of heat tolerance or moisture availability. Mostly it is supposed to reflect a lower adaptive capacity in socio-economic systems.

In reaching their positive conclusions about the future of world agriculture the IPCC authors note that agriculture is subject to a wide range of multiple stresses and impacts and that climate change is just one factor among many that the sector has routinely to contend with. Among these factors climate change is often considered to be a relatively minor, or a distant threat. The high degree of confidence reported about global agriculture probably stems also from the commonly accepted view that farmers and the agricultural sector have, up to now, demonstrated remarkable resilience in the face of all kinds of change, and that sufficient adaptive capacity to cope with climate and other risks has been demonstrated in the past and will continue. But adaptive capacity is not equally distributed. And the climate changes threaten to be of an unprecedented magnitude and are likely to occur at a rate not previously experienced in human history.

At the same time it is recognized that the uncertainty associated with the threat of climate change is less than the uncertainty which surrounds changes in technology; in competitive markets and trade regulations; changes in relative efficiency and comparative advantage, and consumer demand. In the climate community it is commonly asserted that agriculture is one of the sectors most vulnerable to climate change. Perhaps it would be more accurate to say that in the face of the great uncertainties that agriculture faces from changes in technology, economic and social forces, we have little or no understanding of what the added stress of climate change will do.

The output from global climate models (GCMs) is not only uncertain (a wide range of temperature increases is projected), but is also on a coarse scale and is commonly expressed in terms of changes in mean temperature and precipitation. Thus the scale and the variables are not those most relevant to choices in the agricultural sector. To make informed decisions farmers require information on short-term seasonal and inter-annual variability for very specific localities. This circumstance contributes to a general sense that long-term climate change is not, and should not be high on the farming agenda.

3. Climate and Agriculture Today

A broad perspective on world agriculture today recognizes that along with a remarkable success story in production, a number of major problems remain and more are looming on the horizon. These threats are more due to the economics of demand and distribution than simple production. There are still many hungry and malnourished people on the planet, mostly in developing countries and in low latitude climates. Trade barriers, including massive subsidies in the US and the EU, obstruct the logical and reasonable exploitation of the comparative advantages that varied climate regimes offer. The same tropical agricultural producer countries that are failing to meet the food requirements of their own populations find that their

commercial products are excluded or subjected to tariff barriers in the world's most affluent markets. This applies especially to those "temperate climate" food staples that can be produced in the cooler regions of low latitude countries.

New technologies, among which genetically modified organisms (GMOs) are currently a salient example, threaten dislocation and possible new environmental and health risks as well as substantial production benefits to those who are able and willing to use them. Highly commercialized capital intensive farming systems dependent upon scientific knowledge from veterinary science to plant genetics, meteorology, hydrology, soil physics and chemistry, are displacing the traditional diversity of farming systems and their associated social and community structures. The whole notion of adaptive capacity is taking on a new meaning. What can and will be done to adapt to changes is less and less in the hands of the farmers themselves, and more and more dependent upon agri-business, and the global political economy.

The threat of climate change comes as a new and additional concern on top of these current concerns. The adaptation of agriculture to climate change has to be seen in this larger context.

The agro-meteorological community has a strong record of contributions to the resilience of agriculture including in developed countries. Sophisticated experiments and modeling have provided new knowledge that can be applied in cultivar design and selection, and in farm management. The success of this work depends on finding a receptive audience in the shape of an innovative and modernizing farming community eager to increase productivity and efficiency. In the face of climate change the same approach is being advocated and implemented in developing countries. There is currently much excitement about the improvements being made in seasonal forecasting, and efforts to improve and disseminate better weather information to farmers are being energetically pursued. Evaluation studies show that the benefits to farmers and the economy in terms of increased productivity considerably outweigh the costs of producing and disseminating the information. With experience the service is being improved by the incorporation of greater knowledge of the type of information required, timely delivery, and the design of information packages targeted more precisely to specific needs. There is no doubt that this work is valuable and should be vigorously supported. But by themselves these advances in technology will not be sufficient to deal with the new threats of climate change.

In the context of these developments, and the multiple stresses that the farming communities are exposed to, what more might be done to enhance resilience in the face of climate change? If better answers are to be found to the opening questions a more sophisticated understanding of adaptation is required.

4. Levels and Types of Adaptation

Several typologies of adaptation to natural hazards, climate change and variability have been developed. (Burton et al., 1993; Smit et al., 2000; Smit and Pilifosova, 2001). Adaptation in a narrow sense refers only to those measures that are taken

at the farm level. But in fact adaptation is a much wider concept involving choices at national and international levels as well as local. Adaptation involves more than measures, it is also a matter for national agricultural and development policy.

Most of the literature on climate change and agriculture deals with adaptation at the local level. Many lists have been published showing the wide range of adaptation options theoretically available. Numerous examples may be found in the first national communications submitted by developing country governments under the UNFCCC. Typically these include changes in seasonality of production; dates of sowing; choice of crop varieties or species; development of new varieties including GMOs; improved water supply and irrigation systems including efficiency in use; tillage practices; other inputs and management adjustments and improved short-term weather and seasonal climate forecasting. As noted above efforts are now being made to strengthen the role of national governments in facilitating the dissemination and adoption of technical adaptation at the farm level. This is usually presented as the need to incorporate climate change considerations into farm management. Unless this can be linked to short-term considerations and climate variability and extremes it seems to generate little response in farming communities. Under the UNFCCC very little attention has been given so far to technical adaptation. The debate has centered on the need for technology transfer but adaptation technology has been virtually ignored in the rush to explore tech-transfer for greenhouse gas emission reductions. There is, of course, a great deal of international attention to such agricultural issues as the protection and use of genetic resources, and the spread of GMOs, but so far the climate dimension has figured little in these issues.

There is also a concern in the development assistance agencies to foster the incorporation of climate adaptation into national economic development policy and associated development assistance (Burton and van Aalst, 1999). A new generation of impact and adaptation studies is now beginning to address this need, but the research is only now getting started. A key question here is the danger that agricultural policies may serve to increase vulnerability. National agricultural policy is developed in the context of local risks, needs, and capacities, as well as international markets, tariffs, subsidies and trade agreements. It is often claimed that the international context imposes a straightjacket on national policies and choices, and that policies are insufficiently responsive to local needs. Stakeholder participation in policy development is frequently recommended as a measure that can help to reduce the distance between national policy processes and the farm and community level.

At the same time it is acknowledged that in both developed and developing countries agricultural policies are among the most difficult to change. That farming is so often regarded as a "way of life" and not just a matter of efficient production, helps to strengthen conservatism and widespread resistance to change. This conservatism, strongly advocated by a significant proportion of the farmers themselves, is asserted to be essential for the maintenance of stable rural communities and the quality of food produced. Vocal resistance to change helps to keep farm subsidies

high in developed countries and does not facilitate positive attitudes to innovation and adaptation. Confident forecasts about adaptation in agriculture have often neglected this situation and have assumed that adaptation will occur up to, or close to, the limits of technical feasibility.

The fact that agriculture can be described on one hand as highly adaptable and resilient, and on the other as resistant to change, is related to the diffusion and success of technical innovations at the farm level. Successful adaptation over decades and centuries at this level goes a long way towards explaining the confidence now being expressed in the ability of agriculture to cope with the potential impacts of climate change. On the other hand there are concerns that improvements in the efficiency of agricultural production are having serious environmental and social consequences. It is paradoxical that while apparently advocating trade liberalization, and export-led development, the developed countries effectively discourage modernization and adaptation in tropical agriculture by their own farm subsidies. Successful adaptation to climate change in developing countries will depend upon more than assistance in the adoption of adaptation measures. It will require a broader and more consistent global approach that facilitates policy change in developed as well as developing countries.

Despite such obstacles the record so far seems to suggest that the prospects for agriculture in the face of climate change are good at the global level, but that severe local disruptions and inequalities are possible, even likely. This diagnosis suggests the need to pay more attention to national policy and global negotiations in order to alleviate inequalities between and within nations. The very success of technical adaptation at the local level in some places is creating problems that need to be addressed by national governments acting in their own areas of jurisdiction, and by international agreements directed towards the stability of the global system. To date adaptation has been treated largely as a matter of measures to be adopted at the local level. There is also a global dimension to adaptation which we neglect at some risk. From the perspective of climate change and development the place where local and global converge is at the level of national policy.

5. The Adaptation Policy Framework

Partially in response to this diagnosis some new approaches to national policy for climate change adaptation are now being developed and applied. These include the national adaptation programmes of action (NAPAs) agreed in October 2001 in Marrakesh at the 7th meeting of the Conference of the Parties to the Framework Convention on Climate Change (COP 7). The preparation of these plans of action, and other studies being supported with funds from the global environment facility (GEF) draw upon the concepts developed in the adaptation policy framework (Burton and Lim, 2000).

The adaptation policy framework (APF) is now being further elaborated building upon past work and experience, especially that conducted in line with the IPCC

technical guidelines for assessing climate change impacts and adaptations (Parry and Carter, 1998). It also takes into account the recent findings of the IPCC third assessment (IPCC, 2001). In elaborating the APF, seven principles have emerged which deserve particular mention. As the work advances, and as the framework is developed for application in specific sectors this list may be modified or expanded:

- Assess policy and measures for adaptation in a development context. This is at the same time the most important and the most difficult part of the APF exercise. The importance is related to the need to integrate adaptation into national development strategies and to take account of socio-economic scenarios, national and global. There are inevitable difficulties related to the very concept of policy. Policy-making is by its nature a complex process in which a wide range of interests and ideas compete for attention. How climate change is weighted in the policy process necessarily depends upon national and local circumstances.
- Start with recent climate experience; current impacts from climate variability and extreme events; and current or baseline adaptation in order to provide an empirical foundation for the choice of future adaptation.
- Explicitly include adaptation to current climate variability and extremes as a step towards reducing vulnerability to longer-term climate change.
- Adopt a stronger focus on vulnerability than has been the practice in previous work. This attention to vulnerability in the present helps to guide policy and measures towards priority development needs such as those identified in the UN. Millenium development goals, and poverty reduction strategy papers.
- Give specific consideration to current development policies and proposed future activities and investments, paying particular attention to those activities that may tend to increase vulnerability to climate change or which are maladaptive.
- As part of the development of national policy, include a “bottom-up” or vulnerability-driven risk assessment approach to adaptation in which the actual adaptation measures in place, and vulnerability is assessed at the local and community level. Ensure to the extent possible that national policies and international agreements are designed to facilitate adaptation and enhance adaptive capacity.
- Engage stakeholders in the process at all stages.

The APF (Lim et al., 2004), includes a simple five-step framework to help guide studies of vulnerability and adaptation, and to help in the formulation of adaptation policy responses and measures (Figure 1), (Springer-Siegfried and Dougherty, 2003)

Step 1. Project scope and design

The purpose of Step 1 is to ensure that a study of adaptation is well designed and integrated into the national policy process for planning and development. This

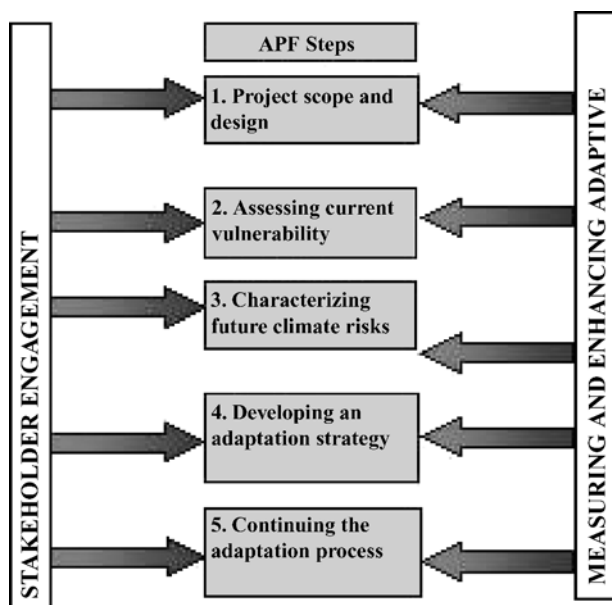


Figure 1. The APF steps (Spanger-Siegfried and Dougherty, 2004).

involves an understanding of the policy process itself, and choices about the sector(s) to be studied. Step 1 also includes the initial formulation of ideas for an adaptation strategy so that this may be tested and elaborated throughout the study.

Step 2. Assessing current vulnerability

The purpose of Step 2 is to make a thorough assessment of the present situation. It essentially asks the question, “Where do we now stand with respect to our vulnerability to climate risks; what are the factors generating vulnerability, and how successful is current adaptation?” This analysis gives rise to ideas and suggestions for ways in which current vulnerability can be reduced and adaptation made more effective.

Step 3. Characterizing future climate risks

While the improvement of adaptation policies and measures to current climate variability and extremes can be a step in the right direction, it is not likely to be sufficient to deal with all the risks of climate change. Potential future conditions have to be taken into account. This includes likely future vulnerability, which itself depends upon climate change and socio-economic conditions locally, nationally and globally, as well as trends in related areas of natural resource and environmental management.

Step 4. Developing an adaptation strategy

The major task of Step 4 is to synthesize the results of Steps 1–3 of the project together with any prior information, and to create a coherent set of adaptation

policy suggestions and associated measures. Step 4 also involves working with stakeholders and policy makers to ensure that a set of proposals are brought forward for further assessment.

Step 5. Continuing the adaptation process

The completion of Step 4 may mark the conclusion of a particular policy study. But this is only the beginning of the adaptation process. Provision must be made for the ongoing monitoring and evaluation of adaptation. New institutional arrangements may be required and further opportunities for specific capacity building identified. If the project has been limited in coverage of sectors, regions, or risks, further work may be required.

The APF is being developed by UNDP at a generic level. More specific guidelines are needed sector by sector. The World Health Organization (Rome office) is developing a set of guidelines for the assessment of adaptation to climate change in the health sector. Perhaps a similar activity led by WMO with partners such as FAO and CGIAR would be useful and timely.

6. Conclusions

At the world level, agriculture has a strong record of adaptability and the prospects are good that this can be maintained in face of the threat from global climate change. This optimistic scenario is qualified by concern about uncertainty in the climate forecasts, and the prospect of regional variation in impacts. It is expected that the impacts of climate change will be greatest in low latitude regions where crops are often grown close to their limits of heat tolerance and moisture availability. Even more significant is the lower adaptive capacity of farming communities especially the poor.

Attention has focused heavily upon the capacity for adaptation at the farm level. Strengthening adaptive capacity at this level is not likely to be sufficient without changes in national policy and the international political economy of the agricultural sector. The future continued success of adaptation in global agriculture requires changes at the national policy level and this in turn depends on the future pattern of world trade. The threat posed to world agriculture by long-term global climate change has to be understood in the context of shorter term changes in weather and the terms of trade.

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THE DEVELOPMENT OF SEASONAL AND INTER-ANNUAL CLIMATE FORECASTING

MIKE HARRISON

Hadley Centre, Met Office, London Road, Bracknell, Berks RG12 2SY

E-mail: mike.harrison@metoffice.com

Abstract. A review of the development and status of seasonal to inter-annual climate forecasting up until 2001 is presented covering not only the successes but also identifying some of the major challenges remaining. Included is discussion on the history of the enterprise; the scientific basis of modern seasonal to inter-annual prediction and its background of predictability theory; the current status of predictions and the measurement of their skill; the experiences and consequences of the 1997–1998 El Niño event; approaches to linking forecasts with applications; and a view to the future.

1. Introduction

Climate forecasting is probably one of the oldest professions in the world. A Babylonian scroll dated to about 3000 BC may well be the oldest-known example of an attempt to predict the weather that would affect the following season's crops. Later attempts are listed in Holy Scriptures, such as in the story of Joseph in the Bible, while phenological approaches based on perceived behaviours of flora and fauna, or on the sun, moon and stars, have developed throughout the world across many succeeding centuries. Not surprisingly there are many similarities amongst these phenological approaches between countries and continents. Interest in phenology remains strong, and has prompted new investigation by the World Meteorological Organisation's Commission for Climatology, although rigorous examination does not always provide succour to the acolytes (Marriott, 1981).

Society has been exposed to the vagaries of climate variability throughout the millennia, but resilience to and protection from these variations as they affect food supplies, water availability and comfort levels has been gained only in some countries. It is hardly surprising therefore that people have long looked to phenology and to beliefs for ways of knowing the severity of the coming winter and the beneficence of the next summer well ahead in order to prepare. Phenological and belief approaches are still used in many countries, including developed ones, and it is likely that they will continue to be employed long after modern scientific approaches have matured well past their current stage.

It is not a simple task to identify the initial breakthrough that led to the current stage of development of modern scientific seasonal to inter-annual forecasts, although the work of Gilbert Walker¹ is certainly recognised as one of the prime inputs, even though its import was not fully appreciated at the time. Working in

India in the early 20th Century, and tasked as Director-General of the Indian Meteorological Department to find a method of predicting the monsoon rain total, Walker set out to examine statistical relationships in the global atmosphere. There were already clues that climate variations in different parts of the globe may be associated and Walker examined all data available to him in an attempt to identify predictive links for the monsoon rains. His work uncovered the North Pacific Oscillation and the North Atlantic Oscillation, apparent latitudinal “seesaws” in pressure across these basins. Neither aided the monsoon problem. However it was the third seesaw, the “Southern Oscillation”, which imparted the stimulus to further study, and continues to provide one input to the prediction methods used by the Indian Meteorological Department today. It was many years, however, before the importance of the Southern Oscillation was comprehended in terms of its inherent global-scale atmosphere/ocean dynamics, and its links to El Niño recognised.

2. A Review of Modern Short-Range Climate Forecasting

The principles of modern short-range climate forecasting are straightforward. The atmosphere works on many spatial and temporal scales, the shortest of which only possess predictability out for a limited time period provided the current state of the system is adequately known. For synoptic scales, those associated with local day-to-day weather variations, this translates to predictability for no more than a few days, given rigorous observation of the state of the atmosphere around the globe. But underlying the atmosphere are the continents and oceans, surface conditions across which change only relatively slowly. Transfers of heat and momentum between these underlying surfaces and the atmosphere can, in appropriate circumstances, act as a slowly varying regulator for the atmosphere, providing a memory which limits the range of weather in affected areas, thus creating a predominant climate anomaly over a period of a season or more.

The best-known example of boundary layer changes forcing climate anomalies on scales up to the global is the El Niño/Southern Oscillation (ENSO),² of which Walker’s work uncovered only part of the atmospheric component. Many texts outline the dynamics of ENSO,³ and here it may suffice that when cold water upwelling off the equatorial west coast of South America is replaced by warmer waters from the west, then an El Niño occurs. At the same time the mass of tropical convection that is typically found in the South-East Asian/Indonesian region migrates into the central tropical Pacific Ocean, close to the date line, bringing drier conditions in the west and heavy rainfall to normally-dry islands. There is close linking between the change in sea surface temperatures, the location of the equatorial convective mass, and the changes referred to as the Southern Oscillation by Walker. Other changes in the global circulation accompany the movement of the equatorial convective mass (Glantz et al., 1991), which is the atmosphere’s main heat source, and impacts on temperatures and rainfall occur over a season or more as a consequence in regions across, around and remote from the Pacific basin.

Sea surface temperature variations in other tropical oceans additionally affect countries around those basins (e.g. Hastenrath, 1991), although these influences appear to be less spatially extensive than those related to the Pacific and as well act predominantly on decadal time scales (Latif and Barnett, 1994). Mid and high latitude oceanic changes have lesser seasonal scale impacts than those in the tropics (e.g. Rodwell and Folland, 2002). Evidence is growing that changes in land surface conditions, particular the soil moisture content, can also affect atmospheric circulation on seasonal time scales.⁴ Perhaps the best known example relates to the Indian monsoon, changes in which are linked to soil moisture deficits in the Himalayan region resulting from melt of winter snowfall (Ferranti and Molteni, 1999).

Seasonal to interannual prediction in general presently uses knowledge of sea surface temperature variations on which to base a forecast of temperature and rainfall conditions in teleconnected parts of the globe. Several prediction approaches are possible. Relationships between recent sea surface temperature anomalies and future climate conditions may be estimated empirically using historical data. Alternatively current sea surface temperature conditions may be persisted into the future as a proxy prediction, or future anomalies themselves predicted using empirical or dynamical methods, and in either case concurrent or additional dynamical methods then used to make the required climate prediction. Other predictors are used at times, such as the Himalayan snow cover mentioned above or various proxy indicators, but the principles remain the same and the focus in the remainder of this paper will stay with the oceanic anomalies.

A complete review of all types of models used in prediction is beyond the scope of this paper,⁵ but these may be divided into two main groups. Empirical models are developed using historical data and attempt to represent statistical links between one or more predictors, usually sea surface temperature anomalies averaged across specific regions, and rainfall or temperature anomalies across the area of concern. Typically linear regression is used to derive the associations, but other methods have been employed. Computer-based dynamical models of the ocean and/or atmosphere, often similar to, or even the same as, the models used for weather or climate change prediction, form the other group. In between are a number of approaches that use simplified statistical or statistical/dynamical models for one of the components, either the atmosphere or the ocean. Fledgling coupled models of both the atmosphere and the ocean, recently introduced into operational short-period climate forecasting at a small number of leading centres, represent the most technically advanced approach.

In all cases the objective is to produce a prediction of the average climatic conditions throughout a season across a region measuring several hundred kilometres along each side (Goddard et al., 2001). In general the main predictands of concern to applications are rainfall and temperature, although others, such as numbers of tropical storms and start/end dates of rainfall seasons, have also been attempted. This is such an extensive area of activity that the focus in this paper will be on rainfall prediction, the central concern of agriculture and many other activities including

energy conservation, water and fire management. Rainfall is a natural predictand for seasonal forecasts, as it is the changes in oceanic rainfall, forced by modified sea surface temperatures, that result in adjustments to the atmospheric circulation that lead to the variations in rainfall over the continents.⁶ Nevertheless rainfall is variable in both space and time and many applications are more sensitive to the timing and amounts of rainfall through a season than they are to the total amount. For this reason users of seasonal forecasts have often requested both more temporal and spatial detail in predictions than is available directly from the global models. These requests, for example, have driven attempts over a number of years to predict local start dates of rainfall seasons using empirical techniques. However the modern approach to obtaining increased detail of information is to use regional climate models (RCMs) (Goddard et al., 2001). RCMs are the higher resolution brothers of the global atmospheric models. Covering areas perhaps the size of Europe, and using controlling information from runs of global models, RCMs provide more detail on both temporal and, particularly, spatial scales than is available from the global models themselves. In particular RCMs have the more detailed underlying topography and so in principle can provide information on rainfall differences associated with mountains and valleys, although it must be noted that development of these models is at an early stage and the practical utility of the information produced remains to be demonstrated.

3. Predictability

Were the links between oceanic sea surface temperatures and continental rainfall directly linear then seasonal prediction would be straightforward. In practice most empirical models make the underlying assumption of linearity and this provides a reasonable starting point. Nevertheless rainfall over land may be influenced by sea surface temperature variations across several parts of an ocean, by variations across more than one ocean, by adjustments in land surface moisture, and by a number of other factors which may have no clear predictability and which are often dismissed as noise. An excellent example of the complexity of the situation related to sea surface temperature changes alone was given during the 1997/98 El Niño event, as will be discussed later, but because of this complexity it is inevitable that even the best-calibrated empirical model will fail at times. Unfortunately, few, if any, empirical models can claim to be well calibrated, as insufficient historical data are normally available from which to develop the models and, additionally, evidence exists that the empirical relationships forming the foundations of the models may in any case change slowly in time (e.g. Kumar et al., 1999).

There is, however, a more key aspect of predictability than the basic complexity of the links, and that is 'chaos'. A chaotic system is one that, if perturbed by a small amount (in meteorology these 'small amounts' can be below normal measurement capabilities), may end up in a different state than it would have had the perturbation not been present. In fact the perturbation may not exist as such but

may, and usually is, a consequence of a limited global observing system leading to errors in information provided to the model. Such sensitivity to small changes is not present at all times at a given location in chaotic systems, but in the more complex chaotic systems, including that of the atmosphere, special techniques are required to determine what sensitivities are present and what their consequences are. In meteorology the ensemble approach is used to assess the level of sensitivity of a forecast to perturbations, the impacts on a prediction of which can be substantial even over only a few days. The standard way of producing an ensemble, of which there are a number of variants, is to run the model from a number of slightly different starting points, differences between which being consistent with the errors that can occur in measuring the starting point. Ensembles with over 50 members are now run operationally at some leading centres for periods out to ten days (Mullen and Buizza, 2002), with smaller ensembles generally used for seasonal predictions (Goddard et al., 2001). A further issue is that the models themselves are not perfect and errors developing in the models can provide additional sensitivities. One of the best approaches to encompassing model sensitivities is to use more than one model in an ensemble (Graham et al., 2000). On seasonal time scales the underlying sea surface temperatures tend to constrain the atmospheric circulation to a restricted set of options and so provide the sought-after predictability, but even in the ocean chaotic influences are important. Only a few systems take this oceanic chaos into account at present.

Because of computer processor restrictions operational seasonal forecast ensembles often have less than 10 members, but one system⁷ has 40, a figure recently doubled to 80 with the incorporation of a second model from the Met Office in a multi-model configuration. Larger ensembles can be expected in the future. The range of rainfall predictions for a specific location across an ensemble of forecasts, whether from a single model or from multiple models, can be, but need not be, substantial, and from the applications perspective may be daunting. There are two fundamental approaches to presenting ensemble output. The first is to average across all ensemble members and to base the forecast on that average. In theory this is supposed to eliminate the less predictable, smaller-scale, details of the forecast, and certainly produces information easier to use from the applications side, but in practice it has all the limitations of any deterministic prediction, including the possibility of being entirely wrong. The second approach, and the one consistent with chaos theory, is to treat all members of an ensemble as equally likely (or weighted in some manner) and to produce a probability distribution. Although many users, and even some meteorologists, balk at the prospect of using probability forecasts, this approach has many advantages, expanded further later, not least of which is the possibility of providing information on less likely, but nonetheless possible, outcomes. Forecasts of the more extreme events also become more achievable through use of distributions.

Empirical methods can be used to assess chaotic impacts on a prediction, but models currently in practical use do not do so. However a common method used

to develop a probability distribution from a deterministic empirical model is to examine the historical performance of the model and to develop a distribution from that information using occasions when the model was providing similar forecasts to a current one (Folland et al., 2001). When this approach is adopted it becomes possible to build consensus forecasts from both numerical and empirical models, a technique often used in Regional Climate Outlook Forums (RCOFs—see below), and thought to produce the best prediction possible (Basher et al., 2001).

4. The Current Status of Seasonal and Inter-Annual Climate Forecasts

When confronted with any form of seasonal prediction the first question usually asked by potential users is “How good are your forecasts?”. Often this is followed by the deterministically-based query “How often is your forecast correct?”. These are two questions the climatological community has difficulty in responding to in a manner that satisfies most users.

Amongst the numerous issues confronting climate scientists when attempting to validate their models and verify their rainfall forecasts is the problem of data homogeneity when the model is providing spot information at scales of a few hundred kilometres. These spot values are typically averaged to produce a single figure for each model cell, averages which then need to be compared with observations from a set of points somewhat randomly scattered around the cell, data records with inevitable missed observations, and reflecting topography not resolved by the model. Undoubtedly the noise introduced by this process impacts on validation and verification results. The difficulties are compounded when there is a need to compare not a series of single deterministic predictions but a sequence of probabilistic ones. A further important consideration is that there are relatively few realisations of seasonal predictions with which to work. As far as is known to the author no empirical technique employs a data series that exceeds 100 years in length, and most are based on much shorter series, some perhaps no more than 30 years in length. Often with only one prediction per year in the series, these are statistically seriously limited data sets for assessing deterministic systems; for probabilistic systems they are undoubtedly inadequate. Numerical modelling studies, because of data problems and of computing costs, have fewer realisations still. One of the most extensive currently-available series is that from the PROVOST experiment, that reached across 15 years.⁸ The succeeding DEMETER project is planned to cover 40 years,⁹ bountiful by any current measure of numerical seasonal prediction experimentation, inadequate by any statistical measure.

Even accepting the caveats above, it still remains difficult to provide specific information on the quality of forecasts. Probably the major difficulty is that the diagnostics used are often based on those developed for short-range predictions and for informing modellers. Diagnostics that specifically inform users are thin on the ground, although some exist. Probably the most common diagnostic used in seasonal prediction is the correlation between predicted and observed, an approach

particularly used for sea surface temperatures, including those measuring ENSO, and for predictions from empirical models. There is an argument, often discussed by meteorologists, that the minimum correlation required for 'skill' is $(\pm)0.6$, but many seasonal forecast systems fail to reach this level, although in some favoured areas far higher values have been obtained. Correlation, however, has many drawbacks as a diagnostic, and, while useful as a first indicator, it is not one that supplies value to the user question "What decisions can I base on these forecasts"?

Numerous other diagnostics are available, but most forecast centres tend to have in-house preferences that often differ from those of other centres. Thus it is difficult to cross-compare quality of forecasts between centres. Several standardisation activities are now underway in various areas of WMO, with one in particular being designed to assist intercomparison of operational predictions.¹⁰ Three diagnostics are being used, the first of which, Mean Square Skill Score (MSSS), is an extension to the Mean Square Error (MSE) commonly used by meteorologists. MSE, the averaged sum of the squares of differences between forecasts and observations, provides an indication of improvements in forecasts as its value hopefully reduces in time, the ideal being zero. Beyond that its interpretation is difficult, particularly from the perspective of applications. In MSSS MSE values from the forecasts are compared with MSE values of a standard simple forecast in such a way that a zero value means both are identical by this measure. A positive MSSS value indicates that the forecast is an improvement compared to the standard; this improvement is measured in a linear sense so that perfect forecasts (those with an MSE of zero) give an MSSS of 100%. The standard forecast normally used is climatology or persistence, and MSSS at least gives the forecast user an indication of the extent to which the forecast improves on the chosen standard. It applies only to deterministic predictions.

The second diagnostic, Relative Operating Characteristics (ROC) (Mason and Graham, 2002), is of more use to applications, and has the advantage of being applicable to both deterministic and probabilistic predictions. ROC works through events that can be defined in any way consistent with the capabilities of the prediction system and preferably of interest to applications. For example, a specific event might be 'above-average rainfall', or 'temperatures in the lowest 20% of historic events', or any other definable binary value. Then for a deterministic prediction the hit rate (HR) is the proportion of observed events that were correctly predicted. Similarly the false alarm rate (FAR) is the proportion of occasions that the event did *not* happen but on which the event was predicted to occur. The extension to probability forecasts is achieved by calculating HR and FAR for a sequence of cases in which the event is taken to be predicted when the forecast probability equals or exceeds a specific value. Often this is done in 10% steps and when values of HR and FAR are then plotted against each other the ROC curve emerges. Provided the event is chosen to reflect the interest of applications, then the combination of HR and FAR is readily interpreted in terms of user actions, although it is immediately clear from the curve that attempts to maximise HR will also lead to increases in FAR.

The third diagnostic, reliability, is inherent in ROC and is applicable to probability forecasts only. Stated directly, a forecast is said to be reliable if across all occasions on which an event is predicted to occur with, say, 40% probability then it does indeed occur on 40% of occasions. The reliability curve is normally plotted with pairs of values at 10% probability intervals in order to give an overall view of reliability.

Given the range of diagnostics used, and the inadequate time to achieve results as yet from the standardisation activities, it is difficult to create an overarching statement on the quality of the predictions. Nevertheless a number of generalisations may be made. Probably the first statement to be made from the meteorological perspective (the applications perspective is treated below) is that, whilst variable both spatially and between seasons, skill over and above climatology does exist across much of the globe. For example, early results indicating that skill over Europe was marginal and amongst the lowest on the planet have been overturned in the PROVOST project, in which some remarkably skilful predictions were achieved (Graham et al., 2000). Nevertheless high levels of skill are not available over Europe in all years. Projects such as PROVOST have permitted consistent assessment of skill on a global scale.

The variety of models targeted on predicting ENSO-related tropical sea surface temperature variations in the Pacific Ocean all have measurable skill out to perhaps nine months to a year, in some cases perhaps a little longer. Attempts have been made to predict these variations for even longer. A number of estimates from numerical models for Pacific sea surface temperature predictions outside the tropical belt and for predictions across the other ocean basins have been made, and there are indications of some skill, although this varies by region. Empirical prediction models designed for the Atlantic and Indian Ocean basins also give some skill, but overall highest skill levels are clearly achieved for the tropical Pacific. The creation of an array of moored data buoys across this basin, an outcome of the TOGA project, has underpinned this ability. Some moored buoys are present across the other two basins but these arrays are not yet suitable for use in operational prediction. A new global array of drifting buoys, ARGO, is expected to provide useful information for seasonal prediction in the near future.

Regarding the atmosphere, predictions of spatially relatively homogeneous variables, such as temperature, are more skilful than those for the more heterogeneous variables such as rainfall. Nevertheless rainfall can be predicted with a high level of skill in some regions, predictions for the Nordeste of Brazil having a correlation approaching 0.9. It is likely that the high skill for this region results from strongly linear influences from both the Pacific and Atlantic oceans, although rainfall predictions for some tropical Pacific Rim areas approach similar levels of skill. Highest levels of skill in general are in those regions where variations are strongly linked to sea surface temperature variations, and these tend to be at tropical latitudes, particularly close to the Pacific Ocean. In general skill tends to fall off as distance from the equator increases, although regions such as parts of North America are

favoured with relatively high levels of skill for their latitude because of the specific manner in which the global atmosphere responds to changes in the tropical Pacific. Results from the PROVOST experiment appear to indicate that predictability for Europe is mainly restricted to El Niño and La Niña periods.

Skill is also dependent on two further considerations. The highest skills are found in general for the shortest range predictions. As the forecast range and/or the lead time increases so skill tends to decline. The effect has been well demonstrated for sea surface predictions in the Pacific, but is less fully documented for temperature and rainfall predictions. Some empirical methods have been assessed for forecast lead periods exceeding a year, and apparently retain some skill over limited regions, but few statistics are available as yet for numerical models beyond four months. DEMETER is one project that will provide extensive statistics out to six months.

Seasonality is the second consideration, and again statistics are limited, but it is clear that skill varies in a seasonal manner that is difficult to generalise. In the middle northern latitudes skill in general is highest in winter and spring and lowest in autumn. Elsewhere skill for both temperature and rainfall predictions tends to maximise when linear links with sea surface temperatures are strongest. Predictions for Pacific Ocean sea surface temperatures tend to have lowest skill when projected through the April/May period, but skill recovers quickly in June. Known as the predictability barrier, the effect inhibits predictions of the build-up of El Niño events until the later part of the year.

Whilst projects such as DEMETER will provide substantial information concerning the quality of predictions from numerical models there is as yet no equivalent project for detailing the efficacy of empirical models. It is anticipated that the standardisation exercises will facilitate intercomparison of skill levels achievable through the various modelling approaches. At present it is probably fair to state that, in general, the empirical and numerical approaches provide forecasts of comparable skill, although there certainly are regions and/or seasons where one approach demonstrably outperforms the other. Numerical approaches have many potential advantages over empirical methods and are likely to become increasingly predominant. Empirical methods, on the other hand, will continue to play a fundamental role in exploration, in providing performance benchmarks for the numerical models, and in offering opportunities for developing prediction systems available to all.

5. The 1997/98 El Niño Event

Depending on the manner in which it is assessed, the El Niño event of 1997–1998 might be the strongest recorded. Certainly it was of comparable magnitude to the event of 1982–1983 which brought drought to many areas surrounding the Indian Ocean and heavy rainfall to continental areas adjoining the eastern Pacific Ocean. Without doubt the 1997–1998 event was the most heralded in history, as it offered

the first opportunity for modellers to test their El Niño predictions using data from the then newly completed Pacific tropical buoy array. Discussion continues, though, over whether or not the event was predicted ahead of its presence being detected by the observing systems (Barnston et al., 1999).

There is a standard diagram (Ropelewski and Halpert, 1987) that details climate anomalies likely (but not certain) to occur during El Niño events, and countries threatened with drought or flood according to this diagram took some considered actions through the latter months of 1997, which certainly mitigated negative impacts in places (World Meteorological Organisation, 1999; Glantz, 2001). In hindsight, however, some actions were inappropriate to the climate conditions experienced and the event provides an object lesson in many of the issues surrounding prediction on seasonal to interannual time scales. Examples from southern Africa will be used to illustrate the point.

Coincidentally a major new initiative was planned for the period of the 1997–1998 El Niño event, the world's first Regional Climate Outlook Forum (RCOF). Entitled SARCOF, with SA standing for Southern Africa, this was a pilot for the 30+ RCOFs that have subsequently been held around the globe. RCOFs have proven to be a prime instrument through which climate services based on seasonal to interannual predictions have been introduced to the developing world. Forums bring together regional climatologists, intermediaries, end users, policy makers, the media, and various experts in an assembly at which presentations are made in a capacity building context, a consensus forecast is created using all available empirical and numerical inputs, and the forecast is discussed and interpreted in actions appropriate to the forthcoming rainfall season. The standard output product from a Forum is a map on which are given probabilities for rainfall terciles in individual parts of a region (Basher et al., 2001). A text prediction is also provided.

The first meeting in the 1997–1998 SARCOF series was held in Kadoma, Zimbabwe, during September 1997. The concept of probability forecasts was new to most attendees and there were consequent difficulties in defining the interpretation of the forecast, which placed highest probabilities in the driest tercile in most areas likely to experience drought during an El Niño but retained modest probabilities in the other two terciles, including the wettest. Against a media and an Internet barrage (a medium being widely exploited for the first time in delivering seasonal forecasts) calling for a severe drought in line with the canonical El Niño response in southern Africa, the carefully-placed Forum forecast apparently carried little weight. The text accompanying the Forum forecast accepted that drought, possibly severe, might occur but also pointed out that, historically, drought does not necessarily accompany an El Niño event. At a Forum update meeting in Windhoek, Namibia, in December, several of the numerical model predictions had reduced likelihoods of drought as compared to the September situation, a change reflected in the Forum forecast. Despite these activities it is probably fair to state that the general perception across southern Africa, and the frequent planning position, was that a drought was inevitable.

In reality seasonal rainfall over southern Africa was generally around the long-term climatological normal, but with somewhat above-normal totals in favoured places. Certain areas experienced localised flooding. Departures from the canonical response also occurred elsewhere. Rainfall in East Africa was above average, as would be expected from the canonical response, but by an excessive amount. As in southern Africa, the droughts anticipated in India and Australia did not occur. However an unusually severe drought did happen in parts of South East Asia, and was responsible for creating suitable conditions for the haze that developed there.

Almost certainly one reason why these responses did not match the canonical expectation was due to the influence of sea surface temperature anomalies in the Indian Ocean, which were perhaps larger than any previously observed. While the El Niño was taking place in the Pacific Ocean, temperatures across the Indian Ocean resembled the equivalent of a La Niña event with warm anomalies in the west, a distribution that might have been linked with the El Niño itself (Yu and Rienecker, 1999). The warm waters in the western Indian Ocean probably assisted in increasing the rainfall across the whole of the eastern part of Africa. Most of the empirical forecast models used in Africa focused on Pacific Ocean sea surface temperatures as the main predictor, hence failing to incorporate any information from the Indian Ocean. Certain numerical models may have been picking up information from the Indian Ocean given their predicted reduced probabilities of dry conditions by December.

The credibility of seasonal forecasting suffered initially as a result of the 1997–1998 episode. In the view of the author the issue was one of understanding and of recognising the probabilistic nature of the forecasts. This message has been passed continually through ensuing Forums, although it is still probably fair to say that many are not yet comfortable with probabilities. Confidence returned to a certain extent in following years as an extended La Niña event occurred that was associated with generally canonical impacts. But in 2001 the possibility of a new El Niño event developing by the end of the year caused ripples in some parts of the Pacific region. No El Niño developed. At the time of drafting the original version of this paper a similar scenario to that of 2001 was being played out in early 2002, although against the background of El Niño signals certainly stronger than those during 2001. It is now clear, in late 2002, that an El Niño event has developed.

No final solution has yet been obtained in the creation of a general understanding of the limitations of seasonal to interannual forecasting. Many users meetings continue to call for improved forecast accuracy, which will certainly come as the models and understanding improves but which will not meet deterministic expectations. Education initiatives, together with clearer statements from climatologists on the limitations of the prediction systems, plus a willingness amongst users to examine how current predictions might be best used in particular applications, are amongst the requirements at the present time.

6. Interfaces to Applications

The work of Gilbert Walker was driven not by the need to understand the climate of India but by the need to plan for droughts in a largely self-dependent agricultural country. Much of the solution to the food problem in India was ultimately obtained through improved management of food stocks rather than through climate prediction, but India has the distinction of having the longest sequence of operational seasonal predictions using modern empirical techniques anywhere in the world. Elsewhere the long-term drought of the 1980's in the Sahel brought increased attention to the impact of sea surface temperature variations on rainfall and lead, at the UK Met Office, to the development of an empirical forecast model for rainfall over the region (Ward et al., 1989), and then to experiments with numerical models (Folland et al., 1991). A second area subsequently considered by the Met Office team was the Nordeste of Brazil (Ward and Folland, 1991), and the Met Office has provided forecasts regularly for this region since 1987. The Nordeste is subject to El Niño-related severe droughts that impact on both food and local industrial production. Such is the level of predictability that the Nordeste is favoured by having numerous prediction models available created by various research groups.

Applications of seasonal forecasts go back many years and a review of estimates of value obtained through use of the predictions has been published by Nicholls (1996). However as the science has reached a level of maturity over the past few years so the number of projects in which forecasts are fed into decision making in applications has increased and the question of value has become more critical. In the following discussion agricultural applications will provide the focus, although activities are underway in many other applications sectors including water management, energy planning and trading, manufacturing, insurance and health.

One of the longest consistent research projects studying the use of seasonal prediction to agriculture has been that focussed on corn production in the US Mid West (e.g. Mjelde et al., 1997). This series of studies has illustrated the potential value of predictions provided these are designed to fit directly into the needs of the farmer. The basic concept of "designed to fit" was taken as perfect deterministic predictions of temperature and rainfall anomalies delivered at a lead sufficient for decisions to be taken and acted upon. In later studies the concept of partially unreliable predictions was introduced. Substantial benefits were to be gained should prediction quality attain the levels assumed. However experience in the US and elsewhere has indicated that, despite the positive theoretical position established, multiple impediments to the use of seasonal to interannual predictions exist. These impediments lie both on the forecast producer side – including the provision of imperfect forecasts, in probabilistic terms, using non-intuitive presentation formats, at too short leads, in insufficient detail, and through limited-access delivery methods – and on the user side – including misinterpretation of

probabilistic information, lack of full understanding of the limitations of forecasting, and want of optimal methods of incorporating real forecast information into decision processes.

Measurements of forecast quality, and its interpretation as value ultimately obtained in applications, remain amongst the key issues linking and offering at least partial solutions to many of the impediments. The issue of measurement of forecast quality has already been covered in brief. Most currently-used quality measures have been derived from the perspective of the forecaster, with consideration for the needs of the user often attached only as an add-on. A noteworthy sequence of studies in which theoretical attempts were made to link forecast quality with ensuing value was provided by Alan Murphy and collaborators (e.g. Ehrendorfer and Murphy, 1992). One central methodology used in these studies was the Cost/Loss model, in which value for a particular binary event (as defined above under ROC) was calculated for the four combinations of event predicted/not predicted with event observed/not observed. Attempts to relate quality and value were not entirely successful, however, until the introduction of ROC, as the approach used by ROC for examining quality permits transfer directly into the Cost/Loss model without transformation of data. This ROC-Cost/Loss approach was first used at a practical level within a seasonal forecasting context during the first SARCOF and produced results that illustrated the potential value in southern Africa of forecasts of then-existing quality (Harrison and Graham, 2001). Other studies of ROC and its use in estimating value have been made (e.g. Richardson, 2001).

One important result that appears consistent across all studies to date relates to the fact that ROC can be used to measure quality in both deterministic and probabilistic systems in a common manner. As far as is known highest value always results, at least in theory, from use of probability forecasts according to the ROC approach.⁸ This theoretical result is a consequence of the balance between value gained from correct decisions against value lost in incorrect ones. No forecast system can consistently guide perfect decision making, and the evidence suggests that the management and consequences of those occasions on which incorrect decisions are taken determine the final overall value obtained across many years. In the view of the author no quality measure approach that fails to provide detail on prediction limitations sufficient to satisfy value estimates through the range of potential outcomes is adequate for applications needs. One rider to this is that deterministic forecasts, despite offering lower value, can be used provided adequate recognition of the possibilities and consequences of an erroneous prediction is taken. However, as the consequences as far as an application is concerned may depend on the magnitude of the error, a distribution of outcomes is still desirable even in this case for planning purposes. Despite their potential importance few studies of approaches to contingencies in decision making within the context of seasonal forecasts have yet been undertaken. These, plus additional theoretical and practical value studies, are needed in order to design improved decision

processes in applications. While the ROC approach to value is a useful starting point, it handles only limited aspects of issues related to individual decisions, it implicitly assumes certain vital aspects of the decision process, and it ignores socio-economic interactions on both the micro and macro scales. ROC's merit in providing guidance in the use of seasonal forecasts in agriculture has, nonetheless, been established.

One additional benefit of using ROC illustrated in the SARCOF project is that it can be employed to indicate optimal strategies for forecast use by helping identify the selection of model parameters that maximises benefit (Harrison and Graham, 2001). However this carries the vital rider that it is quite possible to use a given set of forecasts in a way that would provide negative value rather than extracting the available positive value, a point that is frequently not considered in planning applications. The benefit gained from the use of seasonal to interannual predictions is therefore not dependent upon the quality of the predictions alone but also relies on the manner in which decisions are made based upon the predictions. Limited research attention has so far been focussed on this latter aspect by comparison with the forecast quality issue.

Relative Operating Characteristics provided much of the basis for a 2000–2001 project in the United Kingdom in which the value of forecasts on a wide range of time scales for the complete food chain, from production to retail, was examined.¹¹ Despite the relatively low level of seasonal predictability over the United Kingdom, certainly by comparison with many tropical regions, substantial benefit was shown to be achievable, and confirmed through a calibration process using ROC. One key ingredient in the project's success was the close collaboration undertaken between meteorologists and all those involved on the agricultural/food side in each of the four sub-projects (dealing with field vegetables, sugar beet, apples and tomatoes), and this stands as a prime example of the type of integrated approach needed. One important project conclusion was that optimal benefits were obtained by coordination of responses to predictions throughout the food chain rather than as a series of separate decisions.

A number of other approaches to the decision process have been examined in both theory and practice, although it is not currently clear what level of benefit is achievable through most. The simplest, and probably the most common, is the straightforward treatment of a deterministic prediction in terms of experience. The benefits and hazards of this approach were illustrated during the 1997–1998 El Niño event. A second approach, the use of analogues, is basically a development of the deterministic approach in that it identifies historical sequences similar to those recently observed and/or predicted that provide appropriate analogues to guide decision making. The technique can be extended to probabilistic predictions through the development of analogues across the full range of possibilities that can then be interpreted as a group of weighted decision options. Analogues require substantial historical data and resource to develop, and so are not appropriate in all situations. A third alternative is the approach of 'least regret'. Following careful

examination of the needs, perceptions and restrictions upon the end user, a decision based on forecast information is created that will provide least future regret should it turn out to be incorrect. By this approach a buffer against the more risky decisions, often those with greater rewards if correct but at greater costs if incorrect, is created. This approach also acknowledges that some agricultural forecast users, particularly in developing countries, do not have the scope to accept incorrect decisions or the flexibility to develop contingencies in the manners that probability forecasts inevitably impose.

In recent years research projects have been developed to provide more direct approaches to decision making through use of climate model outputs to drive agricultural models in a variety of manners. It is expected in these projects that these methods will provide the types of direct information required by agriculture. Further it is hoped that these methods will handle the issue that agricultural responses depend as much, if not more, on the detailed sequence of weather events during a season than on the averages across the season. Statistical weather generators have been used as one method of providing realistic daily weather sequences to feed crop models, as have daily outputs from the climate models. There is insufficient knowledge as yet about the statistics of climate models on a daily basis to be certain that this option is an improvement over the statistical generators, and results will be awaited with interest. Major activities in this area include CLIMAG,¹² PROMISE¹³ and DEMETER.¹⁴ As discussed earlier, regional climate models (RCMs) are also being examined as a means of providing climate information on spatial and temporal scales below those provided by the climate models and to provide information for agricultural decision making.

Most of the above discussion has focused on the use of forecast information alone, with limited reference to the pertinence of historical information in guiding the decision process. The substantial benefit that can be obtained, even by use of information alone without forecast input, has been well demonstrated for agriculture by the work in Australia at BoM¹⁵ and APSRU,¹⁶ both organisations having developed extensive information systems based on historical data to assist in decision making. These systems cover not only climate information but also pertinent agricultural, economic and financial information. A basic approach developed at APSRU, and based in part on observed phases of ENSO in recent months, has been successfully adopted in countries outside Australia (Meinke and Stone, 2004).

7. The Future

Seasonal to interannual prediction is no longer the marginal activity that it was only a few years ago. With the ability to observe the tropical Pacific Ocean both at the surface and at depth in real time, to observe the other oceans in increasing detail through satellites and moored buoys and through the ARGO system coming on stream, and with the rapidly increasing computing power available, global seasonal

to interannual prediction has become an operational activity at a number of major meteorological centres. Workstations and powerful Personal Computers now allow the smallest research groups the opportunities to run RCMs, and even the global models. Empirical models can be developed and run by all. In the future further developments will continue along similar lines. Assimilation of ocean data into the coupled models, lead by the GODAE project, will improve with the implementation of ARGO and further moored buoys systems. Increasingly complex coupled models will be run in larger ensembles. The benefits of RCMs will be examined in detail. And improved empirical models will be developed within a framework that permits contrast of forecast skill with the numerical models and optimal consensus forecast building.

Nevertheless, substantial leaps in skill are unlikely to be gained. Rather a steady improvement in forecast quality will be achieved. Gains will be obtained through the use of improved quality models, through improved oceanic observations and related improved assimilation of ocean data, and perhaps through the use of land surface initialisation of models following results from the GEWEX project. RCMs may prove to provide additional valuable information for some parts of the world.

Predictability gains will be limited by the chaotic nature of the atmosphere-ocean system. The gains listed above will contribute to improvements in predicted probability distributions, with the larger ensembles providing more detail on the outlying parts of these distributions. These outlying parts contain information on the more extreme events and so are key to agricultural decision making. RCMs may be incorporated to help provide probability distributions on reduced spatial and temporal scales.

Alongside the developments in prediction science will be a marked intensification of activities related to decision making processes in agriculture, and it is in this area that the major advances are likely to come in the short term. The use of crop models will be developed and should become integrated into the ensemble outputs of the dynamical models. If necessary, weather generators will be used to obtain crop model output from empirical predictions. A focus in research will be on the integration of all prediction and historical information and its optimal use in agriculture. In support of these activities will be increased and imaginative use of existing information, both climatological and agricultural. This in turn will lead to development of the improved, coordinated climatological/agricultural data bases necessary to provide the information required. Further experiments of the type run in Algeria whereby crop patches were treated with or without use of forecast information will be used widely to assess the value of the forecasts.¹⁷

All evidence to date suggests that the potential benefits of the science are substantial, to both agriculture and to many other economic sectors, but that the effort involved in extracting optimum benefit is equally substantial and requires coordinated multidisciplinary research. Further activities towards development of such co-ordination will continue under the umbrella of the various multinational

organisations in the United Nations system. These will cover not only climate science, but also all involved areas through to the social sciences. Activities such as the current Regional Climate Outlook Forums will provide a model for part of this coordination, but this will be extended through initiatives such as the Regional Climate Centres (Nicholls, 2002) and Res Agricola (Meinke and Stone, 2004). Over and above all of this will be an integrated capacity building activity designed to introduce all concerned to the opportunities and potential pitfalls of the developing science.

8. Conclusions

Seasonal to interannual prediction has a long history in a variety of guises, but it is in the five years during and since the 1997/98 El Niño event that it has become a major research and application issue. It has been demonstrated unequivocally that short-range climate prediction is achievable with skill in many parts of the world. The level of skill available varies geographically and with season, highest levels tending to be found in the tropics, and in some places may only be useable during windows of opportunity. In all cases predictability is available only over large temporal and spatial scales as well as in probabilistic terms, and it is these facts that create difficulties in applications. Attempts through the use of downscaling via RCMs are amongst those being made to overcome the scale problem. Addressing the probability problem is an issue that requires improved methods of interpreting forecast information into applications actions.

An increasing number of projects are being run to assess the opportunities of the predictions in agriculture in numerous crops and disparate regions of the world. Across the range of projects have been initiatives to understand how climate information is used in agriculture, to provide detailed historical information to guide decision making, and to interpret forecasts through a variety of approaches involving crop models and other analysis tools. There is little doubt that benefit has been gained by agriculture and that the potential for increasing this benefit in the future exists. However the optimal approach for using the predictions in a consistent manner remains to be assessed.

Climate variability sits at the lower end of the temporal spectrum occupied at longer scales by climate change. Insofar as climate change deals with trends, so within those trends lie the climate variations that have formed the subject matter of this paper. Adaptation to climate change incorporates adaptation not only to impacts of trends but also to impacts of changes in variability. A new multidisciplinary project, GECaFS,¹⁸ is examining the adaptation needs of agricultural under a changing climate. As such many of GECaFS' considerations are directly equivalent to those required for handling climate variations. The synergies and opportunities for integration of climate and agricultural sciences will continue to grow, and it is likely that we will see a cascading of similar benefits to other climate sensitive industries and activities.

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Notes

1. There are numerous references, amongst which is The Halley Lecture delivered on 31 May 1929 and entitled 'Some Problems of Indian Meteorology'.
2. Numerous texts cover ENSO, including Glantz et al. (1991).
3. An authoritative overview is given in: Anderson et al. (1998).
4. See details on the Global Energy and Water Cycle Experiment web site-<http://www.gewex.org/>.
5. However see: Goddard L., et al.(2001).
6. For a more detailed explanation see Glantz et al. (1991).
7. See: <http://www.ecmwf.int/products/forecasts/seasonal/documentation/index.html>.
8. See Graham R.J. et al. (2000), and other articles in the same Special Edition on PROVOST of the *Quart. J. R. Meteor. Soc.*
9. See: <http://www.ecmwf.int/research/demeter/>.
10. For details see the Global Data-processing System pages, in the World Weather Watch area of the World Meteorological Organisation web pages at www.wmo.ch – follow 'Verification systems for Long-range forecasts'.
11. On <http://www.foresight.gov.uk/default1024ns.htm>, follow → Foresight 1999-2002 → Food Chain & Crops for Industry, for details. Copies of the report are also available from World Meteorological Organisation WCP CLIPS Project Office.
12. See: <http://www.start.org/Projects/Climag/climag.html>.
13. See: <http://ugamp.nerc.ac.uk/promise/>.
14. See: <http://www.ecmwf.int/research/demeter/>.
15. See: <http://www.bom.gov.au/silo/>.
16. See: <http://www.apsru.gov.au/>.
17. See: Report by Galem,O., to the CLIPS Working Group, March 2001. Available from the World Meteorological Office WCP CLIPS Project Office.
18. See: <http://www.gecafs.org/>.

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SEASONAL AND INTER-ANNUAL CLIMATE FORECASTING: THE NEW TOOL FOR INCREASING PREPAREDNESS TO CLIMATE VARIABILITY AND CHANGE IN AGRICULTURAL PLANNING AND OPERATIONS

HOLGER MEINKE and ROGER C. STONE

*Department of Primary Industries and Fisheries,
P.O. Box 102, Toowoomba, Queensland 4350, Australia
E-mail: holger.meinke@dpi.qld.gov.au*

Abstract. Climate variability and change affects individuals and societies. Within agricultural systems, seasonal climate forecasting can increase preparedness and lead to better social, economic and environmental outcomes. However, climate forecasting is not the panacea to all our problems in agriculture. Instead, it is one of many risk management tools that sometimes play an important role in decision-making. Understanding *when*, *where* and *how* to use this tool is a complex and multi-dimensional problem. To do this effectively, we suggest a participatory, cross-disciplinary research approach that brings together institutions (partnerships), disciplines (e.g., climate science, agricultural systems science, rural sociology and many other disciplines) and people (scientist, policy makers and direct beneficiaries) as equal partners to reap the benefits from climate knowledge. Climate science can provide insights into climatic processes, agricultural systems science can translate these insights into management options and rural sociology can help determine the options that are most feasible or desirable from a socio-economic perspective. Any scientific breakthroughs in climate forecasting capabilities are much more likely to have an immediate and positive impact if they are conducted and delivered within such a framework. While knowledge and understanding of the socio-economic circumstances is important and must be taken into account, the general approach of integrated systems science is generic and applicable in developed as well as in developing countries. Examples of decisions aided by simulation output ranges from tactical crop management options, commodity marketing to policy decisions about future land use. We also highlight the need to better understand temporal- and spatial-scale variability and argue that only a probabilistic approach to outcome dissemination should be considered. We demonstrated how knowledge of climatic variability (CV), can lead to better decisions in agriculture, regardless of geographical location and socio-economic conditions.

1. Introduction

Climatic variability (CV) occurs at widely varying temporal and spatial scales. This variability often impacts negatively on agricultural and natural ecosystems. Although floods and droughts have always been an integral part of human existence, our collective coping strategies have so far been limited by the complexity of systems responses to climate, environment and management and our inability to predict such systems dynamics. This has led to the development of conservative management approaches that usually fail to capitalise on the up-sides of CV and often only poorly buffer against the severe downsides.

The emerging ability to probabilistically forecast future seasons *in terms of climate and its consequences on agricultural systems* has started to influence decision-making at many levels. The potential benefits are substantial, but unfortunately adoption of new insights occurs more slowly and in a more haphazard way than was envisaged and is desirable. This is a consequence of the multi-faceted, multi-dimensional and cross-disciplinary nature of the problems.

It is our aim to outline the multi-dimensionality of the problems in order to assist in the process of establishing an operational framework to conduct what is sometimes referred to as 'end-to-end' applications (Basher, 2000; Manton et al., 2000). Such a framework might help us in achieving a better integration of the disciplinary components and hence better outcomes *via* improved management of agricultural systems. Much has been written about individual aspects of this subject and we would like to draw attention to some of the key publications on these issues, such as the books by Muchow and Bellamy (1991), Hammer et al. (2000), IRI (2000) and Sivakumar (2000). Further, and in addition to this special issue of Climatic Change, the following special journal issues of (i) *Agriculture and Forest Meteorology* (vol. 103, 2000) on *Agrometeorology in the 21st century*, (ii) *Agricultural Systems* (vol. 70, 2001) on *Advances in systems approaches for agricultural development* and (iii) *Agricultural Systems* (vol. 74, 2002) on *Applying seasonal climate prediction to agricultural production* need to be mentioned explicitly. We will draw on this material and cite individual contributions where appropriate.

It is important to point out that we do not explicitly distinguish between CV and climate change (CC). Instead, for the purpose of this paper, we regard CC as a low-frequency component of CV that can be managed using the same quantitative tools and approaches. This point will be made more clearly in the relevant sections, but needs to be stressed from the outset to avoid confusion.

2. Setting the Scene

In the tropics and sub-tropics, CV is a major source of agricultural production variability (e.g., Hammer et al., 1987; Dilley, 2000). Although most dramatic at the farm level, this effect of CV is apparent throughout entire economies and can even affect macroeconomic indicators such as international wheat prices, employment statistics or currency exchange rates (Chapman et al., 2000b; White, 2000a). In October 2002, media reports in Australia attributed half of the reported inflation rate to the effects of the El-Niño-induced drought.

Since humans began farming, climate variability has influenced people's experiences, which in turn resulted in agricultural systems that are somewhat resilient, i.e., systems that are capable of absorbing some of that variability without immediate disastrous results. An example is dryland winter and summer cropping in the northeastern region of Australia where water is stored in the heavy clay soils over fallow periods. This water is then used by the next crop grown and acts as a buffer

against possible low, in-season rain (similar practices exist throughout the semi-arid tropics and sub-tropics). Other examples are the wheat/pasture rotations in Southern Australia that remain productive even under adverse climatic conditions (i.e., prolonged droughts or water-logging).

Issues that we have not addressed here are the longer-term implications of CC on enterprise profitability. For instance, some horticultural enterprises, where the set-up cost is substantial and returns are realised on longer time scales, are extremely susceptible to CC. Producers making decisions on introducing such enterprises need to consider not only CV, but also the combined impact of CC and CV.

Although current systems have been developed to cope with the variable climate, they are not necessarily optimally adapted. For instance, relying on fixed fallow lengths can leave fields prone to erosion and drainage below the root zone. Production systems developed during a run of wetter seasons may not be as resilient in drier seasons. Peanut production in Southern Queensland, Australia, for instance, started during the above average summer rainfall conditions of the 1950–1970s but resulted in unrealistically high yield expectations for the changed climate patterns of the 1980s and 1990s (Meinke and Hammer, 1995).

It is important to acknowledge that, although important (and sometimes even dominant), CV is only one of many risk factors impacting on agriculture. From a decision-maker's perspective, it is the consequences of CV and/or CC on possible management responses that are of interest, rather than CV or CC *per se*. This highlights that forecasts must be appropriately 'contextualised' before they can positively influence decision-making. In other words, causes, choices and consequences must be clearly outlined and quantified (Hayman, 2001). This requires effective cross-disciplinary research and we argue here that such contextualised delivery can only be achieved through an integrated, systems analytical approach (cf. Hammer, 2000). While forecasts in terms of a seasonal rainfall or temperature outlook are often followed with interest, they ultimately may not result in subsequent action (i.e., changed practice). However, the same forecast provided, for instance, in terms of crop or pasture yields has the potential for much stronger impact by influencing the decision-making *via* the quantification and discussion of decision options (Hayman, 2001).

The picture gets even murkier when we consider that particularly policy decisions relating to agriculture are not made in isolation from other topics such as issues relating to markets, political environment and lobby groups. In this paper, we deliberately excluded this aspect and concentrated entirely on issues within the realm of agricultural production systems. We refer readers interested in these broader societal issues to publications by Buizer et al. (2000), Agrawala and Broad (2002), Agrawala et al. (2001) and IRI (2000).

At the highest level, the problem appears simple: it is about better risk management and our ability to produce food and fibre products economically and in a socially and environmentally desirable fashion.

This is where the complexity starts and differences based on socio-economic conditions emerge: effective risk management in developed countries is about profitability and the tensions associated with economic production and consequent social and environmental risks (i.e., sustainability). In developing countries, sustainability issues are often, from a farmer's perspective, secondary and only deserve attention after the most pressing needs for survival are met. We need to break the vicious cycle of poverty and hunger before we can successfully promote sustainable development in these countries.

Profitably applying climate information requires the identification of the key decision points in agricultural production systems. We must not assume that these decision points are the same in developing and developed countries. The prime need from climate forecasting in developing countries may simply be disaster management, i.e., to protect the system against the extremes of CV. For example, in Indo-China the fundamental issue related to CV is the capacity to *protect* local people, to *protect* natural ecosystems, and to *protect* national economies. The current ability to provide protection against the impacts of El Niño and La Niña in many Southeast Asian countries remains limited. This is because both effective climate forecasting systems and linkages to decision systems for this region are still in various stages of development (CERED, 2000; Hansen, 2002). There is a fundamental and urgent need to capitalise on our climate knowledge. We may achieve this by translating that knowledge into meaningful, locally relevant decision options.

Decision makers, who must prepare for the range of possible outcomes, often use conservative risk management strategies that reduce negative impacts of climatic extremes. In favourable seasons, however, this can be at the expense of reduced productivity and profitability, inefficient use of resources, and accelerated natural resource degradation (e.g., under-investment in soil fertility inputs or soil conservation measures). Improvements in our understanding of interactions between the atmosphere and sea and land surfaces, advances in modelling the global climate, and substantial investment in monitoring the tropical oceans now provide some degree of predictability of climate fluctuations months in advance in many parts of the world (Goddard et al., 2001).

Broad and Agrawala (2000) showed how climate forecasting can contribute to elevating vulnerability but caution against seeing it as a panacea for solving future food crises. Clearly, 'risk management' must be seen within the context of the actual risk posed (individual survival, economic and environmental risks) and requires a clear analysis of all contributing factors. The role of climate and climate-related risk management tools must then be established and the chosen strategies must take this into account appropriately. This also requires a careful analysis and understanding of the existing policy framework. Often policies have been developed with the aim to alleviate consequences of high climate variability. Such policies (e.g., income subsidies) can act as disincentives for the adoption of better climate-related risk management strategies.

This fact needs to be considered when evaluating the potential of climate forecasting.

Even under homogenous socio-economic conditions, the requirements of potential users of climate forecast information will differ. Firstly, as the title of this paper already implies, there are at least two major stakeholder groups, namely those involved in agricultural planning (mostly policy makers, regulators and large agribusinesses including financial institutions) and those involved directly in agricultural production, i.e., farmers, farm managers, some rural businesses and consultants. Information needs for these groups differ, but even more importantly, their needs vary with on-going changes in socio-economic and market conditions. Tactical as well as strategic decisions must be made all the time and while climate-related information might be highly relevant for some of these decisions, it will be irrelevant for others. Hence, it is no surprise that we generally fail to measure a notable impact of non-contextualised climate forecasts.

When climate forecasting is discussed there is often an implicit assumption that perfect knowledge of, for instance, future rainfall would change the way agriculture is practised. This assumption is rarely challenged, but it touches on two issues that are fundamental when considering the value of climate information in decision-making:

The first issue is the notion that such ‘perfect knowledge’ might be – at least theoretically – achievable. Although we still have much to learn about the underlying physical processes, we now appreciate that climate has many chaotic and non-deterministic features, which will prevent us from ever achieving complete certainty in climate forecasting. Any deterministic forecasting system is therefore either wrong or misleading and should not be endorsed (Meinke et al., 2003).

The second issue is the implicit assumption that a forecast will be useful and lead to improved outcomes. Although many examples can be found where this is the case, others show either negative outcomes or identify decisions that are insensitive to such information. Several conditions must be met before a seasonal forecast will result in an improved outcome: a forecast

- must have some skill (see later);
- must honestly convey the inherent uncertainty (i.e., the information must be presented in a probabilistic form);
- must be relevant (neither trivial nor obvious; timely);
- must be able to be ‘tracked’ in terms of how well the forecasts are representing the actual climate;
- must be inclusive of provision of histories of previous forecasts (Pulwarty and Redmond, 1997);
- must be of value (see later);
- the information content must be applied (see also Glantz, 1977; Lamb, 1981; Nicholls, 2000).

3. Forecasting for a Purpose (Contextualised Forecasting)

As this workshop showed, climate forecasting and its applications have matured considerably over the last few decades. There is excitement about the potential benefits our societies might reap from further research and development. Hence, this paper is titled 'Seasonal and inter-annual climate forecasting: The *new* tool for increasing preparedness to climate variability and change in agricultural planning and operations'. We asked ourselves: how 'new' are climate applications? To answer this question, we will quote from one of the most significant books in Brazilian literature, 'Os Sertões', first published by Euclides da Cunha in 1902. Our quotations are taken from the English translation (*Rebellion in the Backlands*) published by University of Chicago Press, 1995 edition:

... the drought cycles ... follow a rhythm in the opening and closing of their periods that is so obvious as to lead one to think that there must be some natural law behind it all, of which we are as yet in ignorance.

... And then, of a sudden, there comes a tragic break in the monotony of their days. The drought is approaching. Thanks to the singular rhythm with which the scourge comes on, the sertanejo is able to foresee and foretell it. He does not, however, take refuge in flight, by abandoning the region, which is being little by little invaded by the glowing inferno that radiates from Ceará. ... And he confronts them [the droughts] stoically. Although this grievous ordeal has occurred times without number ... he is nonetheless sustained by the impossible hope of being able to hold out against it.

... he has studied this affliction as best he could, in order that he might understand it and be able to bear or to avert it. ... Two or three months before the summer solstice, he props and strengthens the walls of the dams or cleans out the water pits. He looks after his fields and plows up in furrows the narrow strips of arable land on the river's edge, by way of preparing these diminutive plantations for the coking of the first rains. Then he endeavours to make out what the future holds in store. Turning his eyes upward, he gazes for a long time in all directions, in an effort to discover the faintest hints, which the landscape may have to offer him. The symptoms of the drought are not long in appearing; they come in a series, one after another, inexorably, like those of some cyclic disease, some terrifying intermittent fever on the part of the earth.

... This is the traditional experiment of Santa Luzia. On December 12, at nightfall, he sets out six lumps of salt in a row, where they will be exposed to the action of the dew; they represent, respectively, from left to right, the six coming months, from January to June. At daybreak the next morning, he observes them. If they are intact, it presages drought; if the first has dissolved

somewhat, has been transformed into a soggy mass, he is certain of rain in January; if this happens to the second, it will rain in February; if it happens to the majority of the lumps, the winter¹ will be a kindly disposed one.

This experiment is a most interesting one. Despite the stigma of superstition which attaches to it, it has a positive basis and is acceptable when one stops to consider that from it may be gathered the greater or less amount of vaporized moisture in the air and, by deduction, the greater or less probability of barometric depression capable of bringing rain.

This was written over 100 years ago, and it is only the language that gives its age away, not the content. Have we really advanced that much? Graziers and small-holder farmers in the Nordeste region of Brazil are still suffering from droughts and are hoping for divine intervention while the scientific debate about causes and predictability of droughts continues (Moura and Shukla, 1981; Ward and Folland, 1991; Kane, 1997; Folland et al., 2000).

3.1. CLIMATE VARIES AT A RANGE OF SCALES

Research and experience over recent decades has shown that the El Niño–Southern Oscillation phenomenon (ENSO) plays a critical role in partially explaining rainfall variability in many countries, particularly in the tropics and sub-tropics. However, ENSO is not the only source of rainfall variability. The Austral-Asia region is particularly strongly impacted by ENSO and we will use this region as a case study for many of the arguments presented here.

In addition to ENSO and an inherently unpredictable chaotic component there are a range of other climate phenomena varying at a wide range of time scales that determine what manifests itself as ‘climate variability’. Much of the current research concentrates on the development of credible global circulation models (GCM), with the expectation that the emerging dynamics of all these interacting phenomena, including CC, can be captured adequately. In Australia, effort is being directed towards investigating high-frequency phenomena such as the Madden-Julian Oscillation (MJO, also known as the intra-seasonal oscillation or ‘ISO’), to ENSO-related information (e.g., SOI- or SST-based forecasting systems) and to low-frequency phenomena such as decadal and multi-decadal climate variability and CC (Table I).

At the highest frequency, the MJO involves variations in wind, sea surface temperature, cloudiness and rainfall that occur regularly every 30–50 days. Although the MJO is a tropical phenomenon (Wheeler and Weickmann, 2001), it can, *via* teleconnections, influence rain events over large parts of Australia, India and the Maritime Continent. The MJO consists of cloud clusters that originate in the Indian Ocean and move eastward with speeds of 5–10 m s⁻¹. The MJO particularly affects the

TABLE I

Known climatic phenomena and their return intervals (frequency, in years) that contribute to rainfall variability in Australia

Name and/or type of climate phenomena	Reference	Frequency (approximate, in years)
Madden-Julian oscillation, intra-seasonal (MJO or ISO)	Madden and Julian (1972)	0.1–0.2
SOI phases based on El Niño–Southern oscillation (ENSO), seasonal to inter-annual	Stone et al. (1996)	0.5–7
Quasi-biennial oscillation (QBO)	Lindesay (1988)	1–2
Antarctic circumpolar wave (ACW), inter-annual	White (2000b)	3–5
Latitude of sub-tropical ridge, inter-annual to decadal	Pittock (1975)	10–11
Inter-decadal pacific oscillation (IPO) or decadal pacific oscillation (DPO)	Zhang et al. (1997); Power et al. (1999); Meinke et al. (2005); Mantua et al. (1997); Allan (2000)	13+ 13–18
Multi-decadal rainfall variability	Allan (2000)	18–39
Interhemispheric thermal contrast (secular climate signal)	Folland et al. (1998)	50–80
Climate change (CC)	Timmermann et al. (1999); Kumar et al. (1999)	???

intensity and break periods of the Australian and Indian monsoons and also interacts with ENSO. Many farmers in northeastern Australia routinely follow the passage of the MJO for some of their tactical decision making.

ENSO is a quasi-periodic, inter-annual variation in global atmospheric and oceanic circulation patterns that causes local, seasonal rainfall to vary at many locations throughout the world. It is the best researched of all these phenomena and has attracted considerable media attention over the last decade.

The physical causes of lower-frequency rainfall fluctuations are still being investigated, but our understanding of these processes is steadily increasing (Power et al., 1999; Allan, 2000; White, 2000b). It appears that most of these low-frequency phenomena result in modifications of ENSO-related variability (Kleeman and Power, 2000; Meehl et al., 2001). Predictability of low-frequency variability is still questionable and the possibility of stochastic resonance (i.e., the phenomenon whereby noise amplifies the effect a weak signal has on its surroundings) cannot be dismissed

(Ganopolski and Rahmstorf, 2002). However, teleconnections of ENSO with rainfall patterns are clearly affected at these decadal to multi-decadal time scales (e.g., Australia: Power et al., 1999; USA: Hu and Feng, 2001).

Although anthropogenically induced CC does not oscillate, it needs to be included in this list because it (a) interacts with the ‘oscillating’ phenomena of CV and has a tendency to increase the amount of CV we already experience (Kumar et al., 1999; Timmermann et al., 1999; Salinger et al., 2000) and (b) potential management response to CC – and the tools to quantify them – do not fundamentally differ from responses to low-frequency climate variability (Howden et al., 1999, 2001, 2003).

Although Table I lists the most important known phenomena influencing Austral-Asia region, it is by no means complete. Further, we do not wish to imply that all of these phenomena might be – even theoretically – predictable (e.g., see the critical note by Storch and Zwiers, 1999, on the danger of ‘identifying’ periodicity in stochastic time series). Table I is an example of phenomena currently featured in scientific debate and we acknowledge the difficulties of clearly distinguishing between some of these phenomena. Further, other parts of the globe are affected differently and for the northern hemisphere, for instance, the North Atlantic Oscillation (NAO) is one of the most important contributor to inter-annual CV (Salinger et al., 2000).

Table I only considers time scales that are relevant from an agricultural management perspective and thus ignores known fluctuations at the scale of centuries and beyond (e.g., Dansgaard-Oeschger events at 1500 years, or multiples thereof, Milankovitch forcing fluctuations or ice ages at time scales of more than 100,000 years).

The enhanced scientific understanding of the causes and consequences of rainfall variability at a range of time scales and our increasing ability to predict some of these cycles has made ‘managing for climate variability’ an important feature of Australian farming systems. Similar developments can be observed elsewhere (Meinke et al., 2001).

3.2. THE ROLE OF SIMULATION MODELLING IN AGRICULTURAL SYSTEMS MANAGEMENT

All major agricultural decisions are made under uncertainty caused by variability in some of the key parameters (e.g., economic conditions, physical environment and many more). Decision makers need to be cognisant of the time scales that determine this variability and the possible consequences of such variability for their business. By providing new, quantitative information about the environment within which they operate and about the likely outcome of alternative management options, this uncertainty can be reduced (Byerlee and Anderson, 1982). Computer simulations can provide such information and are particularly useful to quantitatively compare alternative management options in areas where seasonal CV is high, such as

Australia, Southeast Asia, Africa, parts of the US and South America (Meinke et al., 2001; Gadgil et al., 2002; Hansen, 2002; Jones et al., 2000; Jagtap et al., 2002).

Economic outcomes are important, but decisions are also based on many other factors such as environmental consequences (on- and off-farm), weed and disease impact, lifestyle and the existing policy framework. At the farm level, most management decisions have to fit within a whole farm strategic plan such that many decisions are planned months ahead and their consequences seen months afterwards. This requirement for a certain lead-time between deciding on a course of action and realising its results is a characteristic of managing cropping and grazing systems (Carberry et al., 2000; Carter et al., 2000). Pannell et al. (2000) stressed the importance of getting the big decisions right, such as land purchase, machinery investment and resource improvement. They pointed out that farmers are usually better off, if they solve the whole problem roughly, rather than to attempt to solve part of the problem extremely well. Or, as one of our colleagues puts it: it is better to be roughly right than precisely wrong (P.T. Hayman, personal communication). This reinforces the importance to consider CV and CC across the spectrum of temporal scales.

Decisions that could benefit from targeted forecasts are also made at a range of temporal and spatial scales. These range from tactical decisions regarding the scheduling of planting or harvest operations to policy decisions regarding land use allocation (e.g., grazing systems *versus* cropping systems). Table II gives a few examples of these types of decisions at similar time scales to those seen in climatic patterns as presented in Table I.

In water-limited environments such as the semi-arid tropics and sub-tropics, rainfall variability represents the predominant force determining production variability and environmental risk. However, factors such as starting soil moisture, soil type, soil fertility, temperature, planting dates, rainfall intensity and timeliness

TABLE II

Agricultural decisions at a range of temporal and spatial scales that could benefit from targeted climate forecasts

Example of decision types	Frequency (years)
Logistics (e.g., scheduling of planting/harvest operations)	Intra-seasonal (<0.2)
Tactical crop management (e.g., fertiliser/pesticide use)	Intra-seasonal (0.2–0.5)
Crop type (e.g., wheat or chickpeas) or herd management	Seasonal (0.5–1.0)
Crop sequence (e.g., long or short fallows) or stocking rates	Inter-annual (0.5–2.0)
Crop rotations (e.g., winter or summer crops)	Annual/bi-annual (1–2)
Crop industry (e.g., grain or cotton; native or improved pastures)	Decadal (~10)
Agricultural industry (e.g., crops or pastures)	Inter-decadal (10–20)
Landuse (e.g., agriculture or natural systems)	Multi-decadal (>20)
Landuse and adaptation of current systems	Climate change

of rainfall also strongly influence the final outcomes. Although rainfall and plant growth are strongly correlated, consequences of rainfall variability will differ from season to season due to these other influences on growth. In livestock systems, these factors not only have an impact on fodder growth and availability, but also on the animals themselves, further complicating the situation. Simulation models can integrate all these effects in a physiologically meaningful way. Sivakumar et al. (2000) stressed that the development of sustainable food production strategies requires a more complete understanding of the ecosystem and the inter-relationships between crops, trees and livestock. We suggest adding 'management' to this list of interacting elements and propose that simulation modelling is the only tool available that allows easy quantification of these inter-relationships in probabilistic terms.

Further, analysing agricultural systems and their alternative management options experimentally and in real time is generally not feasible because of the length of time and amount of resources required. Well-tested simulation approaches offer a time and cost-efficient alternative to experimentation on the physical system and results can be obtained in hours or days rather than years or decades. This provides the capacity to assess a large number of combinations. Today simulation analyses have become a legitimate means of evaluating policy and resource management issues (e.g., Nelson et al., 1998; Howden et al., 1999; Meinke et al., 2001), but they also provide valuable information for on-farm decision-making (Meinke and Hochman, 2000; Gadgil et al., 2002; Nelson et al., 2002; Podestá et al., 2002). This is strongly endorsed by Sivakumar et al. (2000) who identified agricultural modelling as a priority to address sustainable agricultural development in the 21st century.

Traditionally scientists have used simulation models as 'knowledge depositories' in order to describe an area of interest. Once models became available, interest quickly shifted from curiosity about the underlying principles to using models in a predictive capacity (e.g., to develop scenarios or as a decision support tool) or in an explanatory capacity to investigate interactions between processes usually only studied in isolation. This diverse use of models has started a debate about the appropriate way of mathematically describing biological relationships, and the level of detail needed for a 'good' model. Arguments about the 'right' way of modelling have largely concentrated on the level of empiricism acceptable when representing biological, chemical and physical processes. This debate has not been very helpful, since it has been conducted by groups interested in using models for different purposes, namely to either explain how a system operates or to predict the system's behaviour. The former objective requires detailed descriptions of the underlying physiological processes and parameters values that are often difficult, if not impossible, to obtain experimentally. This parameter uncertainty results in low predictive ability. On the other hand, models developed explicitly to predict management responses often use phenomenological descriptions of groups of processes with easily derived parameter values but fewer process details (Meinke, 1996). Some of the emerging challenges relating to genetic research and the establishment of gene

functions (G) and their interactions with environment (E) and management (M) ($G \times E \times M$) require a more balanced emphasis on all attributes and might show a way forward (Hammer et al., 2002).

Biological as well as climate models are useful because they reduce the complexity of the real system to a level that allows us to predict the consequences of manipulating the system. They also allow scientists to test whether the systems approach adequately describes the system they are dealing with. The amount of process detail contained within a model must match its intended application. However, care needs to be taken whenever the level of process detail is reduced that this simplification is based on a sound understanding of the underlying processes. To reduce number and uncertainty of parameters in simulating biological systems, a process-based approach can be replaced by a phenomenological description of that process without sacrificing scientific principles. This requires that (a) the process is already understood at the more basic level and (b) the phenomenological description is general across a wide range of conditions and of low complexity with easily derived parameter values. This will increase the predictive ability of the model and may eventually lead to a more advanced, formal framework for dealing with holistic concepts and emergent systems properties (Gell-Mann, 1995). In situations where multiple hypotheses are possible, one can discriminate amongst them based on their plausibility (Peng and Reggia, 1990). This plausibility is given by the parsimony principle, or Occam's razor, whereby the most plausible explanation is that which contains the simplest ideas and least number of assumptions (Davies, 1990).

Biological models can never be completely validated. At best, we can present case studies and examples of the models' performance and argue that this is sufficient evidence to use model output for decision-making. To illustrate this point, consider the following example:

As part of a research project we tested the APSIM-Wheat model (Keating et al., 2003) on data from 100 plant breeding experiments across 23 experimental sites and several years. We deemed the model's performance adequate ($R^2 = 0.6$) to characterise the environmental component of $G \times E$ interactions (Figure 1a, unpublished data, Cooper, personal communication; Chapman et al., 2000a). These experiments were not specifically conducted for model testing and while some information regarding soil type, soil water and nutrient status were available, the experimental data set still contained a considerable amount of parameter uncertainty. Using data from a long-term soil fertility trial (Strong et al., 1996), where all the necessary input parameters and starting conditions were measured and available, a R^2 value of 0.8 was obtained (Figure 1b). Clearly, measured and simulated data were in better agreement when the input parameter uncertainty was reduced. However, the same data set also highlighted the deficiencies of using R^2 values as an indicator of model performance (Oreskes et al., 1994): When only a sub-set (i.e., data from 1 dry year) was used for testing, the R^2 was zero (Figure 1c), in spite of the model's obvious ability to capture the climate related year-to-year variation in yield (Figure 1b).

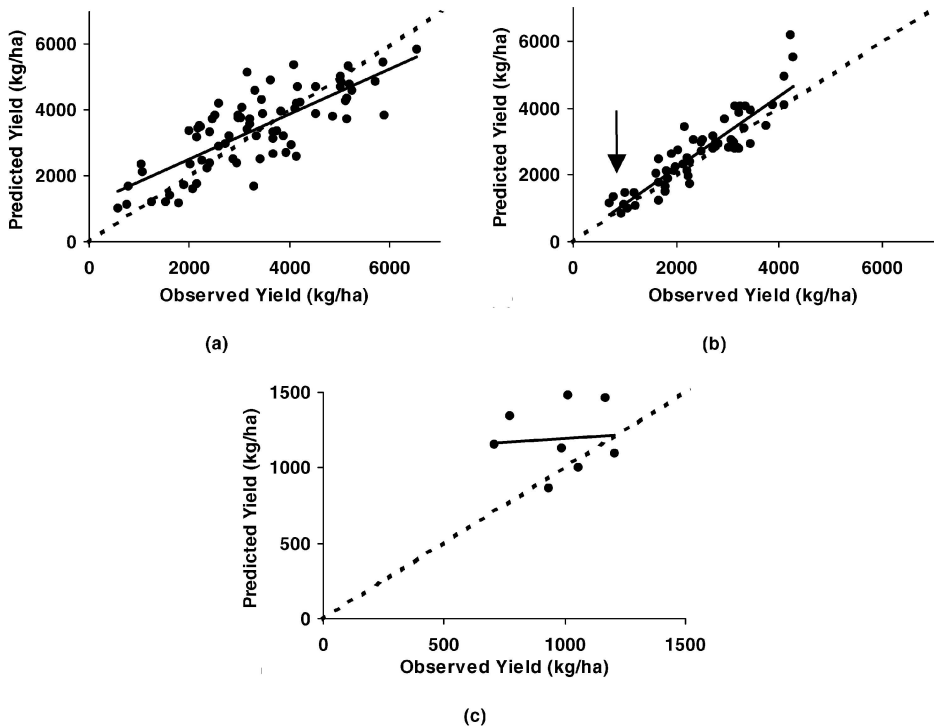


Figure 1. Performance of APSIM-wheat against yield data from (a) 100 plant breeding experiments from 23 locations over several seasons ($R^2 = 0.6$); (b) experimental results from soil fertility studies at a single site in Queensland over 8 years, 5 N levels and 2 surface management regimes ($R^2 = 0.8$) and (c) results from (b) in a dry year ($R^2 = 0$; data presented are included in (b), see arrow).

Obvious ‘over-predictions’ at high yield levels ($>4000 \text{ kg ha}^{-1}$) are generally the result of biotic stresses (i.e., pests and diseases) that are not accounted for by the model (Figure 1b).

The example shows that the validity of a biological model does not depend on a correlation coefficient (or any other, single-value performance measure) but rather on whether the inevitable difference between predicted and observed values are acceptable for the decision maker. This is analogous to Murphy (1994) and Potgieter et al. (2003), who found that there is no single statistical measure to determine ‘forecast skill’ adequately (see Section 4.4). Model performance does not only depend on scientific and technical aspects of the model, but also on the user’s experience and skill. The development of high-performance agricultural simulation platforms such as DSSAT (Jones et al., 1998), CropSyst (Stöckle et al., 2003) or APSIM (Keating et al., 2003) is costly and time-consuming. Due to modern user interfaces these modelling platforms are easy to use and it is therefore tempting to assume that the conduct of agricultural simulation analyses is a low-cost and straightforward exercise. Nothing could be further from the truth. All models require a substantial learning curve for individual users, before they can be applied appropriately.

Unfortunately, we encounter evidence of inappropriate model use far too frequently, which highlights the need for substantial and adequate user training. Further, many climate applications do not rely on straightforward simulations, but require modifications to the model that can only be implemented by highly skilled staff who are intimately familiar with the development pathway of the model in question.

Very similar issues arise in relation to General Circulation Models (GCMs). It is understandable why the most rigorous and successful climate applications are usually achieved by cross-disciplinary teams containing experts from each of the key scientific areas using mature simulation platforms. We should not expect agronomists to develop and run GCMs, nor should we expect climate scientists to become experts in biological model development and applications (there are, however, some rare, but notable exceptions!). Not only must the degree of detail considered in a model be congruent with the intended application, we must also ensure that the level of attention given to the climatic component of an application is of similar resolution and quality as the effort that goes into the agricultural modelling. Unfortunately, donors and funding bodies frequently fail to recognise the importance of such balance and generally provide support for either one or the other, very rarely for both.

3.3. OPERATIONAL ASPECTS – CLIMATE FORECASTS, AGRICULTURAL MODELS AND PROBABILITIES

There is an emerging consensus amongst many climate scientists that statistical, ENSO-based forecasting methods are approaching their limits of predictability. Hence, there is increased emphasis on the development and application of GCMs and regional climate models (RCMs). Connecting GCMs with agricultural simulation models is a potentially powerful approach for climate applications. However, the two methods are difficult to connect and the most successful climate applications to-date still rely on statistical climate forecasting approaches, rather than on dynamic climate modelling. Generally, biological models require daily point scale weather data as input (see Hoogenboom, 2000, for a more detailed discussion on these issues). Often, GCMs suffer from an inability to provide skilful predictability at the type of resolution needed for input into biological models.

Chaos plays a large role in climate systems and the atmosphere frequently acts like a 'random number generator'. This means that deterministic statements cannot justifiably be made. Scientists have a responsibility to communicate their degree of ignorance, as well as their knowledge. Only if uncertainties are clearly quantified can improved risk management practices be developed. Murphy (1993) discussed the need for uncertainties inherent in judgements to be properly reflected in forecasts. He stated that the widespread practice of ignoring uncertainties when formulating and communicating forecasts represents an extreme form of inconsistency and generally results in the largest possible reductions in quality and value. Most public institutions, and an increasing number of private service

providers, now acknowledge the necessity to communicate the known level of uncertainty *via* probabilistic statements. In part, this trend has been accelerated by the increasing awareness of potential liability (corporate risk) that organisations expose themselves through the provision of inadequate or misleading advice, be it real or perceived (Meinke et al., 2003).

Probabilistic forecasts are more valuable than deterministic forecasts (Moss and Schneider, 2000). This holds true even for events that are, by definition, rare (e.g., extreme events, such as a one-in-60-year flood) and hence have considerable uncertainty associated with them. The likely future introduction of predictions based on output from GCMs may allow more versatility in climate prediction than is currently the case, including better opportunities to predict extremes. Palmer and Rätsänen (2002) have quantified the additional value of probabilistic forecasts over a single, deterministic projection in their study of greenhouse scenarios and found that the economic value of probabilistic forecasts was significantly greater and never less than for the deterministic case.

3.3.1. *Analogue Year Approach*

Historical climate records can be partitioned into ‘year- or season-types’ based on concurrently prevailing ocean and atmospheric conditions (i.e., SOI and/or SST anomalies), resulting in ‘SOI phases’ (Stone et al., 1996) or ENSO phases (Messina et al., 1999; Phillips et al., 1999). Such categorisation must be based on an understanding of ocean–atmosphere dynamics and good statistical procedures to partition the data successfully. Current conditions can then be assigned to a particular category and compared to other categories in order to assess the probabilistic performance of the biological system in question (e.g., Meinke and Hochman, 2000; Podestá et al., 2002). This is an easy and convenient way of connecting climate forecasts with biological models, because it only requires historical weather records. The method has been used extensively throughout the world and provided valuable information for many decision makers (Meinke and Stone, 1992; Messina et al., 1999; Hammer et al., 2000; Nelson et al., 2002; Podestá et al., 2002). The SOI phase system has become the dominant scheme used in Australia and neighbouring countries while ENSO phases are often used in the Americas. However, both schemes are globally applicable. Hill et al. (2000) compared the value of the SOI phases *versus* the broader ENSO phases for Canadian and US wheat producers and found that in this particular case the SOI phases generally provided more valuable information than ENSO phases. However, the authors stressed that in some regions neither method had any value for their specific application and that forecasts need to be targeted to industries and regions.

3.3.2. *GCMs and RCMs*

Statistical approaches have considerable limitations and it is expected that dynamic climate modelling will provide much improved forecast skill in the near future. This will require appropriate solutions to solve the ‘connectivity problem’ we addressed

earlier. Ways must be found to convert large, grid point GCM output into something akin to point scale daily weather station data. The use of higher resolution RCMs initialised from GCM data is considered an alternative option, but statistical properties of these data usually differ considerably from the observed historical climate records, requiring further manipulation. Another approach may be to apply a statistical clustering process to GCM forecast output (hindcasts) in order to derive analogue years or seasons suitable for input into agricultural simulation models, as described above (Stone et al., 2000b). Alternatively, GCM output can be used to establish climate trends, with these trends then used to modify historical climate records for use with biological models. This approach is often taken when the impact of CC on agricultural systems is to be assessed (e.g., Reyenga et al., 1999; Howden et al., 2001). Hoogenboom (2000) also draws attention to the different scales implicit in GCMs and biological models. There are a number of promising approaches to using other forms and formats of forecasts with crop models, but they have not yet been widely tested. This issue is a high priority for most agricultural scientists using crop simulation for forecast applications (Jim Hansen, personal communication).

3.4. 'QUALITY' VS. 'VALUE' OF A FORECAST

Murphy (1993) argued that a good forecast requires three different attributes, namely consistency (correspondence between forecasts and judgments), quality (correspondence between forecasts and observations, often also referred to as 'skill') and value (the incremental benefits of forecasts to users). He further stated that this quality/value relationship is fundamentally non-linear. Some fundamental 'skill' and 'performance testing' is required before any forecast or prediction scheme can be applied. Most of the performance testing procedures originated from testing weather forecasting skill and are relatively transparent when dealing with deterministic prediction schemes. However, matters get more complex when probabilistic approaches need to be tested in climate-forecasting systems. Murphy (1994) and Potgieter et al. (2003) clearly showed that in order to measure the performance of probabilistic forecasting scheme, any assessment scheme must at least measure the two basic components of the system, namely (a) the shift in the forecast mean and median from the reference distribution, as well as (b) the change in the dispersion of forecast *versus* the reference distribution. Based on case studies of forecasts of regional wheat and sugar yields, they concluded that no single scheme tested was able to measure both attributes well and consequently there is no single statistical procedure available that measures forecast performance adequately.

This must be taken into account when developing internationally acceptable verification schemes for climate forecasts. We stress that verification of climate forecast output remains a fundamental requirement for both users and climate scientists in order to gain an assessment of real 'forecast' skill as opposed to historical 'hindcast' skill (Murphy, 1993; Elsner and Schmertmann, 1994; Nicholls, 2000).

A further concern is the issue of ‘artificial skill’, which arises particularly when a multitude of possible, statistical forecasting schemes can be employed and a number of ‘best’ performing schemes are selected on the basis of some test statistics, rather than first principles. This issue is complex and goes beyond the realm of this paper. However, we feel that we must at least flag it as a problem that needs to be addressed as an increasing number of potential forecasting schemes are promoted around the world.

The users perspective of forecast quality often differs considerably from that of mathematicians or statisticians. One of the most common problems leading to considerable confusion is the failure to differentiate between the quality of a forecast and its value or impact (Murphy, 1993). Climate information only has value when there is a clearly defined benefit, once the content of the information is applied. In other words: the information must lead to a changed decision, which must ultimately result in an improved outcome (Hammer et al., 1996, 2000; Weiss et al., 2000). Hence, a forecast can be extremely skilful, but still have no value whatsoever. Conversely, even a rather moderate forecast skill can translate into high value and impact under the right circumstances and if applied appropriately.

Demonstrating the effect of CV is often confused with either the real or potential impact of a forecast. Effective applications of climate forecasts (*impact*, I) depend on the *quality* of the forecast (Q), timing and mode of forecast delivery (*communication*, C) and its *suitability* for influencing specific decisions (S).

$$I = \delta * f(\alpha Q, \beta C, \chi S)$$

Coefficients α , β , χ and δ will vary and depend on individual circumstances (range: 0–1). Hence, the impact of a forecast is maximised when all coefficients approach unity. This, however, is unlikely to be ever achieved, because each coefficient is the product of sub-components whereby α is, amongst others, a function of a shift in the distribution’s mean and the dispersion compared to the reference distribution (usually the ‘no-skill’ scenario; Potgieter et al., 2003), β depends on timing, mode of delivery of the forecast and background knowledge of the user, χ describes the relative relevance of the forecast for a specific decision that could be altered based on the information provided by the forecasting scheme and δ measures the importance of the forecast quality for the overall systems performance. This, of course, implies that even low values of α can result in high impact (or value), providing the other parameters have high values. Conversely, even a α -value of unity can result in little or no impact (or value) of the forecast.

3.5. TARGETED FORECASTING AND PARTICIPATORY APPROACHES

Unless a forecast has ‘relevance’, i.e., it addresses issues in a way that will positively influence decision-making, the forecast will remain without impact (Hammer,

2000; Hansen, 2002). Perception, rather than facts, often influence such relevance. Podestá et al. (2002), in their case study of farmers in Argentina, found an apparent reluctance to use forecasts because the temporal and spatial resolution of the forecasts was perceived as not relevant to local conditions, indicating that the desired resolution of forecasts is not necessarily consistent with the outlooks that are produced (Buizer et al., 2000). Such issues of perception, whether they are justified or not, must be taken into account in order to improve the relevance (and hence the adoption) of forecasts.

Management decisions based on knowledge of future climatic conditions will have positive outcomes in some years and negative outcomes in others. Ideally, this should not be regarded as either a 'win' or a 'failure' of the strategy employed, since each season only represents one sample from a not very well-defined distribution of possible outcomes. To assess the true value of such probabilistic information requires comparison of results in each season against outcomes that would have been achieved in the absence of such information.

Development of appropriate management systems that are able to withstand undesired outcomes associated with the low-probability event remains a considerable challenge.

Decision-making in agriculture happens at many levels and involves a wide range of possible users. To provide these clients with the most appropriate tools for decision-making requires a clear focus on their specific requirements and needs. This is an important component of an effective systems approach that ensures the on-going connections between decision makers, advisors and scientists (Hammer, 2000). The importance of such participatory research approaches is now widely acknowledged (e.g., Meinke et al., 2001; Gadgil et al., 2002; Jagtap et al., 2002). Although farmers are one obvious client group, they are not necessarily the ones most responsive to a forecast. This responsiveness depends very much on the socio-economic and political circumstances, local infrastructure and the agricultural system in question. To clearly identify clients and their decision points, it is helpful to classify them according to geographic scale and information needs. Such a conceptual framework assists in identifying the information needs of decision makers, it also assists in selecting the most appropriate and efficient tools to use (Hammer, 2000). Modelling approaches are frequently the tools of choice, but the type of model required will differ depending on geographic scale, required inputs and information needs.

Some specific Australian examples of the beneficial use of forecasting in decision-making across the temporal scales are:

1. cotton growers in Queensland, many of whom are now scheduling the timing of their cotton harvests based on the expected passing of the next MJO;
2. farmers in northeastern Australia who use ENSO-based information to tailor their rotations and crop management based on local conditions at the time and rainfall probabilities for the coming months (Meinke and Hochman, 2000);

3. sugar growers and millers in Northern Queensland who use targeted climate forecasts in management decisions involving harvest strategies, planting decisions, and mill throughput operations (Everingham et al., 2002);
4. bulk handling and marketing agencies, which require accurate regional commodity forecasts to assist them in storage, transport logistics and export sales well before harvest (Hammer et al., 2000; Potgieter et al., 2002);
5. government agencies, which require objective assessments of the effect and severity of CV on production (e.g., Keating and Meinke, 1998); and
6. policy makers, who require impact assessments of greenhouse scenarios for input into international treaty negotiations (e.g., Howden et al., 2001).

3.6. FARMER DECISIONS

Hammer (2000) demonstrated the basis for effective application and valuing of seasonal climate forecasting using a simple example of tactical management of row configuration in a cotton crop grown in Queensland, Australia. He asked: Is it possible to improve profitability by tactically manipulating row configuration in dryland cotton in response to a seasonal climate forecast? Using a simulation approach and 100 years of historical rainfall data, he determined the most profitable option for row configuration (solid, single skip or double skip) for either all years or those years associated with each SOI phase prior to sowing. The 'all-years' case relates to the situation where no notice is taken of the forecast each year. In this case (fixed management), the most profitable option over the 100-year period was to employ the solid row configuration every year. The other case takes account of the SOI-based forecast at the time of sowing. The analysis showed that with some forecast types it was on average more profitable to adopt either single or double skip row configurations (responsive management). To examine the value and risks over all years associated with adopting responsive management, he then calculated the gross margin difference for each year between the responsive (tactical) and non-responsive (fixed) management options.

On average, the tactical management approaches increased gross margins (profits) by 6% (11%). However, there were a number of specific years in which responsive management was inferior. Understanding this point about outcome risk is critical in effective applications of climate forecasting. While a significant advantage will often result over a period of years (as in this simple example), there can be no guarantees that this will occur in any particular year and in fact the decision maker will sometimes be worse off. This process is described as 'prototyping' decision rules that are relevant to the decision maker and generate collective learning (Hammer, 2000). Although the modelled predictions do not cover all aspects of the system involved, they behave essentially as 'discussion' support systems in

dealing with the complexities and risks associated with some decisions (Nelson et al., 2002).

This simple example demonstrates how the value associated with knowledge of shifts in rainfall probabilities can be determined for production management. The balance of probabilities dictates that users of this information will be better off in the long term. However, it does not eliminate production risks associated with a tactical response to a forecast nor does it eliminate the need for a farmer to make a decision. The analysis does not provide a rule for best row configuration management in cotton. Such rules can only be developed by taking account of the very specific physical and economic circumstances of a specific enterprise; they must also account for current production costs, commodity prices and soil condition.

Recent studies with selected farm managers in Queensland, Australia, indicate that by using climate information in conjunction with systems analyses producers can become less reliant on climate forecasts. By identifying decisions that positively influence the overall farm operation in either economic or environmental terms, these producers have gained a better understanding of the system's vulnerability and started to 'climate proof' their operations. Examples of actions taken when a forecast is for 'likely to be drier than normal' are: maximising no-till area (water conservation), applying nitrogen fertiliser early to allow planting on stored soil moisture at the most appropriate time; planting most wheat later than normal to reduce frost risk. In seasons that are likely to be wetter than normal, management options include: sowing wheat earlier; applying nitrogen to a wheat cover crop grown on a dry profile after cotton (normally not expected to produce a harvestable yield) and applying fungicides to wheat crops to minimise leaf diseases (Meinke and Hochman, 2000).

3.7. MARKETING DECISIONS

Based on SOI phases (Stone et al., 1996) and a regional (shire-based) wheat model (Stephens, 1998), Hammer et al. (2001) developed a regional commodity forecasting system. It allows the examination of the likelihood of exceeding the long-term median shire yield associated with different season types from the beginning of the cropping season. This system is now run operationally for Queensland, Australia, by updating the projection each month based on the actual rainfall to date and any change in the SOI phase from month to month. Although there appear to be commercial applications, this system was primarily designed to inform the Queensland Government of any areas that might be more likely to experience poor crops in any year. This information provides an alert for exceptional circumstances issues associated with potential drought in the same manner described for pasture systems in Queensland by Carter et al. (2000). Anecdotal information received from marketing agencies based on their experience with the 2000 regional wheat outlook showed that seasonal crop forecasting can be beneficial for their decision-making processes when it is used in addition to their current approaches. Possible decisions

to be taken when the outlook is for 'likely to be drier (wetter) than normal' are, for instance, forward buying (selling) of grain or shifting of resources from good yielding areas to poor yielding areas. Obvious links that exist between production volume and price need to be taken into account (Stone and Meinke, 1999; Jagtap et al., 2002).

Potgieter et al. (2002) used this regional model to investigate the relationship between spatial and temporal patterns of Australian wheat yields with ENSO. They found that the SOI phase system showed significant skill in discriminating among most wheat year types. 'Skill' in this instance refers to both hindcast and forecast skill using established numerical techniques. Together with the findings by Hill et al. (2000), this shows the global applicability of the SOI phase system for commodity forecasting. Results by Potgieter et al. (2002) are also consistent with findings at the field and farm scale (Hammer, 2000). However, they concluded that there is potential for considerable improvement in predictive ability and stated that *it may be possible to identify climate system or ocean-atmosphere features that may be causal and would be most useful in improved predictive schemas* [sic].

3.8. POLICY DECISIONS

For the seasonal to inter-seasonal time scale, Keating and Meinke (1998), Stephens (1998), and Hammer et al. (2000) have shown how point-source and regionally based production models can be used to quantify exceptional circumstances and drought impacts. Howden et al. (1999) gave an example of the value of model applications to guide policy decisions for global warming scenarios. They investigated key adaptation options for wheat such as choice of cultivars and sowing windows and found significant regional differences for 10 sites throughout the Australian wheat belt. Specifically, they found likely impacts not only on production but also on grain quality characteristics such as protein content. Their findings imply that nitrogen fertilisation rates need to be increased in future if current grain quality levels are to be maintained.

Using the same modelling approach, Reyenga et al. (2001) found that by 2100 changes in temperature, CO₂ levels and rainfall patterns could lead to a movement of the 'cropping frontier' in eastern Australia by about 100 km to the west. Such studies are likely to influence future land use policy decisions.

Phillips et al. (2002) found for Zimbabwe that seasonal climate forecasting tends to increase production volatility. They suggested that in future appropriate market or policy interventions may need to accompany information targeted at farmers in order to increase societal benefits from the forecast. Meinke et al. (2001) pointed out that while there are many case study examples of simulation approaches that could inform the policy process this is rarely achieved and the challenge remains to actually integrate such approaches into policy frameworks that result in improvements.

There are many examples how climate knowledge can influence policy setting. However, to ensure that actions by resource managers and policies are 'in tune' will

require a more coherent approach that allows to simultaneously influence policy and risk management decisions based on common data sources and tools.

4. The Bigger Picture: Applying Climate Forecasts Across the Value Chain

To be useful and valuable, climate forecasting must not only individually address relevant problems at farm or policy level, but be flexible enough to take a whole value chain perspective to ensure that benefits achieved at one level are not undone at the next (IRI, 2000).

An example of this approach is an assessment of the value of seasonal climate forecasting for the Australian sugar industry (Everingham et al., 2002). Australian sugarcane industries go across an integrated value chain comprising cane growing, harvesting, transport, milling, marketing and shipping. Sugarcane industries worldwide are exposed to uncertain variable climatic conditions, which have large impacts across all industry sectors. It is believed seasonal climate forecast systems offer the potential for improved risk management and decision-making across all these sectors, leading to enhanced profitability and international competitiveness.

Such a 'whole value chain approach' can:

- identify, in partnership with all relevant sectors of that industry, the key decisions influencing sustainability and profitability that are impacted by climate;
- identify the key vulnerabilities within the value chain related to CV and CC;
- develop the necessary and appropriate databases of climate and industry sector performance;
- establish the role of climate forecast systems for different geographical regions and key industry decisions;
- assess the benefits and costs of tactical decision-making based on climate forecasting across all the different components of the sugar industry value chain; and
- effectively facilitate the appropriate implementation and delivery of climate systems for enhanced risk management and decision-making (Everingham et al., 2002).

The application of the above approach is provided for those decisions relating to yield forecasting, harvest management, and the use of irrigation. There are key lessons to be learnt from this approach that can be considered generic in terms of preparedness for all agricultural industries. These include

- the absolute need for a participative R&D approach with stakeholders,
- the need to consider the whole industry value chain,
- the need for climate forecast systems with appropriate skill and underlying mechanistic foundation appropriate to different regions and different decisions (Stone et al., 2000b; Everingham et al., 2002).

In a recent example of an assessment of the economic value of seasonal climate forecasting, Antony et al. (2002) analysed the value of climate forecasting to management systems in just one sugar milling region in Australia. They determined that in one case study season (austral winter, 1998) the value of a probabilistic climate forecasting system amounted to in excess of AUD \$1.9 million for one relatively small cane growing region. The assessment was made incorporating decisions at both the farm and mill scale. However, they point out that if prior 'perfect knowledge' of rainfall patterns for that season had been possible, the value to industry would have amounted to AUD \$20 million, 10 times the value achieved through existing climate forecasting technology.

There is compelling evidence that during recent El Niño events media reports (often factually wrong or distorted) influenced factors such as bank lending policy and agribusiness advice in Australia. Better contextualised information appears to be required. Brennan et al. (2000) discussed how agribusiness might be able to use information about CV. The same issue exists to an even greater degree for CC issues. In 2001, a major Australian insurance company withdrew its insurance coverage for cyclone damage as a result of indications of more intense cyclones in a warmer world. Brennan et al. (2000) concluded that there is considerable potential to use simulation approaches to improve bank lending policies, crop insurance policies, product inventories and marketing advice. Specifically, they found that model predictions can reduce claimant disputes and cut legal costs. They also provide the option for individually tailored financial packages. They stated that *... while discussions with agribusiness indicate keen interest in such tools and information, they have yet to have impact on policy and operations. While clear outcomes have been seen in some areas of engagement (e.g., insurance/loss assessment), other collaborative efforts have only progressed some way to exploring the role for seasonal climate forecasts and simulation models in their business operations (e.g., banking, portfolio analysis) (sic).*

Chapman et al. (2000a) provided a further example of the powerful combination of simulation modelling and climate forecasting: Timing and severity of water limitation affect crop growth and yield differently. In order to screen germplasm for broad adaptation to drought, plant breeders conduct large-scale multi-environment trials for several seasons, where seasonal conditions vary spatially and temporally. These trials are conventionally analysed by assuming that each location is representative for an environment-type. However, it is unlikely that the few seasons encountered at these locations during a trial represent the true frequency of all possible season types at this location (particularly when considering some of the low-frequency variability discussed in Table I). Using a simulation model for sorghum, Chapman et al. (2000a) characterised the stress environments for each location and season (e.g., early, mid or late stress) and then analysed the results by environment type rather than location. This resulted in a considerable amount of additional information that was previously attributed to 'environmental noise'. Hence, this environment-type classification can lead to more rapid improvement in the

selection process, thus improving the efficiency of a breeding program leading to a more rapid development of better-adapted cultivars. Once such improved cultivars are available, seasonal climate forecasting can help farmers to select the appropriate cultivars for the most likely environment type at a location.

5. Pathways of Integration and Delivery

The global impact of climate variability has contributed to the establishment of pilot programmes around the world that brought together climate scientists, agronomists, crop modellers and farmer representatives. Examples are the initiatives by the Queensland Government in Australia or the International Research Institute for Climate Prediction (IRI) at Colombia University, NY. The number of groups is steadily increasing and interested readers are referred to publications in special issues of *Agriculture and Forest Meteorology*, vol. 103 and *Agricultural Systems*, vols., 70 and 74 for further details. Most of these groups are partly supported by state and national government sources, and also attract considerable amounts of industry funds and farmer support. Further, the issue has been recognized by international bodies such as the WMO, who through the International START Secretariat (Global Change System for Analysis, Research and Training, co-sponsored by IGBP, IHDP and WCRP) have initiated the CLIMAG projects (Sivakumar, 2000). CLIMAG aims to utilize the growing ability to predict forthcoming climate variations to improve cropping systems management and decision-making and increase production at local, national and international scales.

One of these CLIMAG projects used locations in southern India and northern Pakistan as case studies to demonstrate the utility and feasibility of combining seasonal climate forecasting with a structured, agricultural systems research approach in developing countries. With the help of the international agricultural modelling community, the project provided a means to assess the potential value of seasonal climate forecasting to agricultural producers in these regions. The project established links between research groups in Australia (APSRU; Keating et al., 2003), the International Research Institute for Climate Prediction (IRI, 2000) and partner institutions in India and Pakistan (e.g., Gadgil et al., 2002). The project team conducted agronomic and climatological systems analyses of cropping systems and provided recommendations on where additional research efforts are needed according to a general framework (Figure 2). This has led to the development of a loose network, known as RES AGRICOLA (Latin for Farmers' business), that draws on the collective expertise of the global research community to develop resilient farming systems. 'Resilient systems' allow farmers to draw on systems resources (e.g., water, nutrients, reserves) at times of need without causing permanent damage as long as these 'debts' are 'repaid' once conditions improve.

The multi-dimensionality of the problems requires effective cross-disciplinary research and communication. Interdisciplinarity and the human dimension are at the core of this approach whereby technically possible solutions will be evaluated

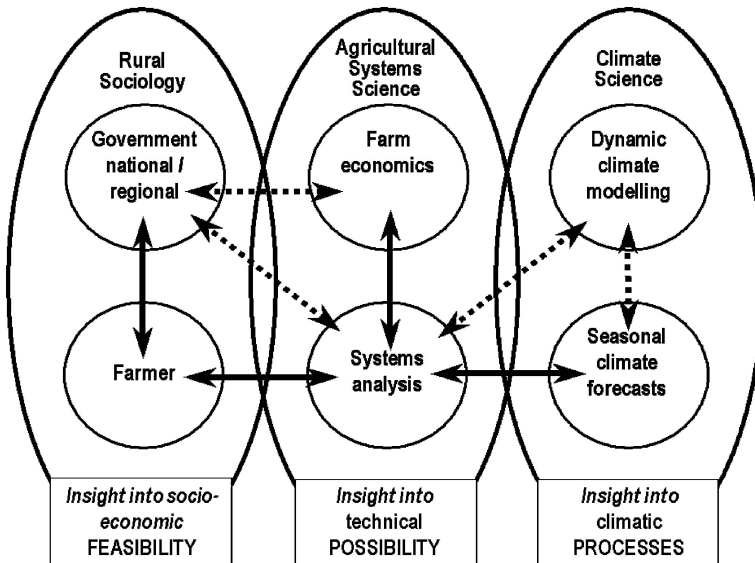


Figure 2. Outline of the concept behind the RES AGRICOLA network (adapted from Meinke et al., 2001). The diagram shows disciplines, relationships and linkages for effective delivery of climate information for decision-making in agriculture. Operational links are indicated by the solid arrows and show connections that have already proven useful; dashed arrows indicate areas where operational connections still need to be better developed. The basic principle of the concept (i.e., the requirement of cross-disciplinary research for effective delivery of climate forecasts) is generic and independent of the specific target discipline.

in terms of their socio-economic feasibility. RES AGRICOLA is a logical evolution of the 'end-to-end' concept proposed by Manton et al. (2000). To deliver benefits within agriculture, the concept distinguishes three discipline groups that need to interact closely, namely (i) climate sciences, (ii) agricultural systems sciences (including economics) and (iii) rural sociology (Figure 2). By operationally connecting research projects and through the establishment of international, cross-disciplinary teams, such a network will be able to convert insights gained into climatic processes *via* systems analysis and modelling into insights into the socio-economic feasibility of decision options.

Pay-offs are more likely when a truly integrated systems approach is employed that includes decision makers and scientists across the disciplines as equal partners and guarantees that they have ownership of this process. Such a truly participatory approach ensures that the issues that are addressed are relevant to the decision maker. This process will also ensure that there is sufficient scope for decision makers to alter their behaviour or management based on the information provided. This 'ability to move' might be constrained by external factors such as current policy settings or international market forces (Meinke et al., 2001). Hansen (2002) stressed that the sustained use of such a framework requires institutional commitment and favourable policies.

An example where the links shown in Figure 2 could be strengthened is in the area of connecting agricultural simulation approaches with whole farm economic analyses and policy decisions. Using a case study, Ruben et al. (2000) reviewed the available options for adapting land use systems and labour allocation for typical households in a region in Mali. They showed that consequences of climatic patterns and climate shocks could at least partially be offset by compensatory policy devices. Better-informed price policies would enable welfare-enhancing adjustments for better-endowed farm households, while poor farmers would benefit from reductions in transaction costs, particularly under dry conditions when dependency on market exchange tends to be intensified. *Contrary to most expectations, vulnerable households can benefit strongly from market reform policies and thus structural adjustment programmes might provide an adequate framework for containing adverse effects from climate shocks* [sic]. However, to influence policy requires operationalising the components outlined in Figure 2 *via* a participatory research approach, whereby economists and policy informants also become valued members of the research team.

This formal connection across disciplines must go hand-in-hand with an evolutionary strategy for climate applications, as proposed by Hansen (2002): (1) an exploratory phase (basic capacity building, gaining understanding of the system), (2) a pilot phase (co-learning through intensive interactions between researchers and decision makers) and, conditional on a successful pilot phase, (3) an operational phase that focuses on engaging, equipping and transferring ownership to those groups and institutions that will provide forecast information and support to a larger target audience on a sustained basis. The long-term aim is to achieve 'level 3' in all countries where CV impacts on agriculture. This requires a global and sustained commitment to the R&D process just outlined. We need to use the demonstrated successes where 'phase 3' is already operational (e.g., some places in Australia, US, and several demonstration projects in South Asia, South America and Africa) in order to initiate 'phase 1' activities at locations where such an infrastructure does not yet exist.

So far, we have outlined the global, scientific capacity to forecast future climate patterns probabilistically and shown how this capability can be translated into socio-economically feasible management options *via* a systems analytical approach and participatory action research. The question remains: how can these capabilities positively influence agricultural management practice? Nelson et al. (2002) addressed this issue by introducing the notion of 'discussion support' (rather than decision support). They provided an example of a simulation-based discussion support software that acts *as a key vehicle for facilitating infusion of forecasting capability into practice* (sic). This demand-driven analysis tool that allows decision makers to compare options either in terms of yield or economic returns is a consequence of years of simulation-aided discussions about crop management in northeastern Australia. This created the necessary demand for such a tool as well as the capacity to implement insights gained from this tool, hence improving outcomes. It is a clear example how we can progress beyond the intensive, case-study-based, participatory

research approach that by definition only reaches a small number of possible beneficiaries. However, its implementation was only possible because this region of Australia is one of the few places that has reached 'level 3' as proposed by Hansen (2002).

6. Conclusions

During the last decade substantial progress has been made in climate science and knowledge delivery. It is now time to consolidate the insights gained. Decision makers in developing and developed countries can benefit from climate knowledge through improved risk management practices or better-targeted policies. However, this can only be achieved if the broad disciplines of climate sciences, agricultural systems sciences and socio-economic sciences adopt a common, integrated framework for research and delivery.

We demonstrated how knowledge of CV and CC can lead to better decisions in agriculture, regardless of geographical location and socio-economic conditions. Amongst the most important tools are probabilistic climate forecasting capabilities and agricultural simulation models that facilitate objective evaluation of alternative decisions at the farm, marketing or policy level. An interdisciplinary systems approach to research and development will assist in capturing our ever-increasing understanding of the physical and biological systems components. This must be complemented by participatory communication methods that ensure the on-going connections between decision makers, advisors and scientists. Examples of decisions aided by simulation output ranges from tactical crop management options, to commodity marketing and to policy decisions about future land use. Any scientific breakthroughs in climate forecasting capabilities are much more likely to have an immediate and positive impact if they are conducted and delivered within such a framework.

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Note

¹In the Nordeste region of Brazil, the word 'inverno' (winter) is used to refer to the rainy season, February–June.

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USING TRADITIONAL METHODS AND INDIGENOUS TECHNOLOGIES FOR COPING WITH CLIMATE VARIABILITY

C.J. STIGTER¹, ZHENG DAWEI², L.O.Z. ONYEWOTU³ and MEI XURONG⁴

¹*TTMI/African Network & Asian PMP Liaison Office, Wageningen University, The Netherlands
E-mail: kees.stigter@wur.nl*

²*College of Resources and Environment, China Agricultural University, Beijing, P.R. China*

³*TTMI-Project, Kano out-station, Forestry Research Institute of Nigeria, Kano, Nigeria*

⁴*Center for Water Resources and Conservation Technologies, Chinese Academy of Agricultural Sciences, Beijing, P.R. China*

Abstract. In agrometeorology and management of meteorology related natural resources, many traditional methods and indigenous technologies are still in use or being revived for managing low external inputs sustainable agriculture (LEISA) under conditions of climate variability. This paper starts with the introduction of an “end-to-end” climate information build up and transfer system in agrometeorology, in which the use of such methods and technologies must be seen to operate. It then reviews the options that LEISA farmers have in risk management of agrometeorological and agro-climatological calamities. This is based on the role that the pertinent meteorological/climatological parameters and phenomena play as limiting factors in agricultural production and the expectations on their variability. Subsequently, local case studies are given as examples of preparedness strategies to cope with i). variable water/moisture flows, including mechanical impacts of rain and/or hail, ii). variable temperature and heat flows, including fires, and iii). fitting cropping periods to the varying seasons, everywhere including related phenomena as appropriate. The paper ends with a series of important additional considerations without which the indicated strategies cannot be successful on a larger scale and in the long run.

1. Introduction

In a recent review of agrometeorology in tropical Africa, Olufayo et al. (1998) stated that consequences of climate variability show themselves at any time as the effects of the accumulated weather in the current growing season compared to those of the same period in previous years. There are countless farming communities which managed to survive and, in some cases, even to thrive by exploiting natural resource bases, which their forebears have used for generations (Reijntjes et al., 1992). Through a process of innovation and adaptation, traditional farmers have developed numerous different indigenous farming systems finely tuned to many aspects of their environment (LEISA, 2000). Such risk management strategies were in response to, among others, the limiting conditions of varying climate. Over the microclimate they nevertheless exercised significant control, as numerous review publications have indicated (e.g. Smith, 1972; Wilken, 1972; Bunting, 1975; Stigter, 1988, 1994; Stigter et al., 1992). However, new operational services in agricultural meteorology are badly needed for decision making in risk management for

specific on-farm conditions. These agricultural environments of peasants in non-industrialized regions are now endangered by new and expanding hazards that rapidly change the living conditions in many places in the tropics and sub-tropics (e.g. Stigter and Baldy, 1993; Baldy and Stigter, 1997; Blench and Marriage, 1998).

Among much other literature, the IPCC reports, from many sources that they used, have convincingly reviewed the scenarios. Increasing climate variability, resulting in more frequent and more serious extreme meteorological and climatological events, will be a factor with which all farming systems will have to cope. Salinger (2004) has unmistakably concluded that we are heading for hard times in agriculture and forestry. From Africa (e.g. Mungai and Stigter, 1993; Stigter, 1995; Baldy and Stigter, 1997) to Latin America (e.g. Wilken, 1987) and different parts of Asia (e.g. Anonymous, 2001; Luo, 2001; Manton, 2001), those working in rural areas have become convinced of two essential issues. Firstly, traditional knowledge, indigenous practices and identified local innovations (e.g. LEISA, 2000, 2001) contain valuable information that should be used as a basis for improved farming systems practices to cope with the necessary changes in risk management. Secondly, contemporary science and new methodologies and technologies should, also in agrometeorology, be guided by appropriate policies, that themselves need a scientific basis and a humane socio-economic basis. They should be locally applied to develop agrometeorological services to assist in the risk management transformations needed (e.g. Smith, 1972; ILEIA, 1995; Stigter, 1999; Salinger et al., 2000; Stigter et al., 2000). Figure 1 reviews this systematically.

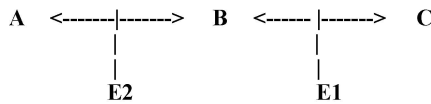
In their classic treatise, Brokensha et al. (1980) refuse to define indigenous knowledge and point to the case studies collected to describe it. Fifteen years later Warren et al. (1995) call it "the local knowledge that is unique to a given culture or society" and contrast it with the international knowledge system, which is generated through the global network of universities and research institutes, that we have called contemporary knowledge in Figure 1. Our context of LEISA farmers, this way defines traditional knowledge and indigenous technologies, also when, as may be expected, components of that knowledge have found their way into higher input and even high-tech growing systems. Local innovations are knowledge and technologies empirically generated by the, in this case LEISA, cultures and societies from within their present farming systems (LEISA, 2000). In line with the stewardship advocated by Houghton (1997) and the highest resilience emphasized by LEISA (2001), to the role of science applies the paradigm change worded by Norse and Tschirley (2000): technological change should no longer be driven by science but by environmental objectives and social concerns, like farmer innovations, operating through the market where appropriate. It is these policy environments that should guide the knowledge pools towards operational agrometeorological services for farm management decisions (Stigter 2002a, 2002b).

This paper exemplifies the valuable local knowledge of preparedness strategies. It wants to work with case studies in which indigenously developed technologies

A = Sustainable livelihood systems

**B = Local adaptive strategies (knowledge pools based on traditional knowledge and indigenous technologies)
+ Contemporary knowledge pools (based on science and technology)
+ Appropriate policy environments (based on social concerns and environmental considerations, scientifically supported and operating through the market where appropriate)**

**C = Support systems to agrometeorological services:
data + research + education/training/extension + policies**



**E1 = Agrometeorological Action Support Systems
on Mitigating Impacts of Disasters**

**E2 = Agrometeorological Services Supporting
Actions of Producers**

Figure 1. Relations between the three activity domains (A, B and C) defined, guided by agrometeorological action support systems on mitigating impacts of disasters (E1) and agrometeorological services supporting actions of producers (E2). This “end-to-end” system in agrometeorology, for transfer of climatological information, combines earlier ideas in Stigter et al. (2000), Norse and Tschirley (2000), Shumba (2001) and Stigter (2002a, b).

are used for agrometeorological services in risk management, illustrating this new paradigm in coping with climate variability. The context of this must be that particularly over the last two decades or so, developments in the field of meteorology, climatology and the environment as well as socio-economic changes occurred much faster than new adapted and innovative agrometeorological services could be established. This is due to difficulties in making interdisciplinary knowledge operational for sustainable agriculture in developing countries and to problems in having new information absorbed and applied in rural areas, against the background of a deteriorating infrastructure (Stigter, 2001). It is now widely accepted that only where households are fully incorporated in all phases and aspects of development processes, may future innovative services in agrometeorology make any difference for the income of LEISA farmers (e.g. Das, 2001; Norman, 2001).

We deal in an end-to-end system for build up and transfer of climate information in agrometeorology with the relations between sustainable livelihood systems (domain A in Figure 1), pools of knowledge allowing useful strategies towards

agrometeorological services (domain B in Figure 1), and basic support systems (domain C in Figure 1) (Stigter et al., 2000; Norse and Tschirley, 2000; Shumba, 2001; Stigter 2002a; 2002b). After all, the good intentions of the agrometeorological action support systems on mitigating impacts of disasters that we established so far (E1 in Figure 1) did not lead to sufficient operational agrometeorological services to support farm management decisions (E2 in Figure 1). In LEISA, traditional methods, indigenous technologies and local innovations still have an important role to play. This shows the context of the approach in this paper.

2. Options that LEISA Farmers have

We do no longer have to argue in favour of an increase of necessary inputs. It has been generally accepted that without such improvements of i. soil fertility and other soil conditions that are basic to sustainable farming systems, ii. soil moisture conditions, iii. varieties, crop combinations and rotations and iv. land husbandry as a whole, there is no future for successful LEISA farming (e.g. Reijntjes et al., 1992; Shaxson et al., 1997; Olufayo et al., 1998). However, such improvements must be seen within their socio-economic context. The options that farmers have, to cope with (increasing) climate variability, apply to their actual conditions, which vary greatly geographically and agronomically.

Of the basic atmospheric conditions that limit agricultural outputs, radiation, CO₂ and wind (flow of momentum) are changing. They will in the existing scenarios continue to change measurably over time, but their variability will not, peak winds during calamities excepted. To cope with this general variability, the LEISA farmer will generally not have to take precautions different from those that have been or could have been taken in the recent past and at present. The options defined by Stigter (e.g. 1988, 1994), for microclimate improvement by management and manipulation of radiation and impacts of (consequences of) wind, including gas exchanges other than water vapour, also remain virtually the same. This is not true for such options coping with moisture and vapour flows, temperature and heat flows, mechanical impacts of rain and/or hail and technologies to fit cropping periods to the seasons. It is, therefore, also not true for the phenomena due to (mitigations of) drought, flood, water erosion and other related matters, such as those regarding desertification, forest and bush fires, pests and diseases. This differentiation is largely due to the role of these phenomena as limiting factors in agricultural and forest production and the expectations on their future variability. There may always be local exceptions to the above distinctions, such as in a particular variation in wind direction reported to be used in traditional forecasting of the strength of the monsoon (Anonymous, 2001).

The time scale for (new) options for farmers to cope with (increasing) climate variability may vary from several seasons to the ongoing (part of a) season. An example of the first end of the scale was given by Bakheit et al. (2001) and Stigter

(2002a, b), using work of Abdalla et al. (2002a). The Sudanese government was advised on a forecasted climate change scenario in which longer sequences of dry years would be intermitted with longer periods of wet growing seasons. The government proposed research on improved underground storage of sorghum, for longer storage periods. On a large scale, as practised in strategic grain reserves by the government (up to 300 tonnes), as well as on the small scale of mainly subsistence and other small farmers (2–10 tonnes). It was found from a questionnaire that the latter farmers experimented with pit linings to insulate the grain from the soil (Abdalla et al., 2001) and with shallower pits (Abdalla et al., 2002b). These innovations with respect to traditional methods were quantified and optimised. Wide surface caps were added from research experience. This way improved traditional underground grain storage microclimate assisted to cope with consequences of forecasted changes in the distribution of bad and good rainy seasons.

The shorter time context is exemplified by Anonymous (2001) in the proposal to use traditional knowledge in determination of the start of the growing season in India. The flowering peak of blooming of the *Cassia fistula* tree appears to do an admirable job in Gujarat of predicting whether the monsoon will come early or late. As these examples are dealing with traditional farming systems or more recently derived innovative indigenous knowledge, they fit this paper. However, for example, Ati et al. (2002) proposed to determine the start of the growing season on-line from soil moisture observations. This could replace a traditional method, based on the occurrence of the Ramadan, that in retrospect appeared inferior to scientific methods and kept yields considerably lower at all levels of fertilizing (Onyewotu et al., 1998). Probabilistic forecasting, through the use of the Southern Oscillation Index, may well be able to compete with the above-mentioned traditional knowledge in India (CLIMAG, in WMO, 2002). This shows that no generalized statements may be used on the value of traditional methods and that local case studies have to illustrate the usefulness of options. Organizing timely availability of the information and services, in the right form, then becomes a decisive factor in being able to use them in risk management decisions.

The options remaining valid with respect to wind have recently been exemplified for smallholder agroforestry by Stigter et al. (2001, 2002), while those of radiation are particularly scattered throughout the intercropping literature (e.g. Stigter and Baldy, 1993; Stigter, 1994; Baldy and Stigter, 1997). A wind example is the use of trees to combat desertification and limit damage by dry air through mitigation of wind speeds and turbulence, contributing to resource and crop protection (Onyewotu et al., 1998; Stigter et al., 2002; Onyewotu et al., 2003). Another is the reduction of wind erosion by keeping stubble in winter from summer intercropping belts on sloping land in Inner Mongolia (Zheng, internal publications, 1999; An and Tuo, 2001). Radiation examples may be found in i. shade protection; ii. pruning of trees in all kinds of agroforestry systems and iii. other intercropping systems aiming at resource sharing (Stigter and Baldy, 1993). Note that these risk management examples deal more with mitigation of the parameter itself and not

with the climatological variability of that parameter. However, these short examples illustrate the importance of modifying a parameter, this way influencing the range of its variability. It should, in addition, also be stressed that these examples may play a key role in transfer of climate information for risk management strategies and agrometeorological services towards sustainability of LEISA farming systems with improving inputs, and therefore in their stability.

3. What LEISA Farmers do and may do

Climate variability and related disasters can be mitigated by temporary or permanent protective measures or by avoidance strategies that try to escape the peak values or their consequences. These are all aspects of preparedness strategies. We have indicated above that i. heavy moisture flows or the lack of water, ii. changing heat flows and related temperatures, iii. cropping seasons' climate distributions are the meteorological/climatological factors we should particularly deal with in this paper on traditional knowledge and indigenous technologies that mitigate consequences of climate variability in LEISA farming systems.

3.1. WATER

The IPCC reports clearly indicate rainfall variability and related disasters as the single most determining factor endangering agricultural production in developing countries. Drought being already a serious threat, indications for longer dry spells in rainy seasons and longer sequences or higher frequencies of abnormal rainfall seasons, with respect to total rainfall and rainfall distribution, make ways of coping with drought situations even more important.

As early as 1986 the FAO/UNEP/UNESCO/WMO Interagency Group on Agricultural Biometeorology had Orev publishing his "*Practical Handbook on Desert Range Improvement Techniques*", containing two long chapters devoted to the problems of mobilizing, managing and utilizing water resources for local technicians in local agro-pastoral populations in the drier parts of Africa, starting from local experience. Most recently, Das (2001) has reviewed examples in which prosperity of districts and villages in India were directly related to preservation of traditional water harvesting methods and technologies of the use of underground water. A related technology of which also IPCC advocates more intensive use is that of water impoundment, surface storage for later use. This is for example contemplated in Indonesia to make the country again self-sufficient in rice production (Syarifudin Karama, personal communication, 1997), which is at present becoming increasingly lower (Paltridge and Ma'shum, 2002), and in El Salvador after the most recent ENSO triggered drought (Zimmerman, 2001). In Sri Lanka the traditional so called "bethma" practice combines such reservoirs with temporary land

redistribution and sometimes field rotation, and attempts are made to revitalise this old practice (MOST/CIRAN, running database (1)).

In Niger, traditional planting pits were improved by making them into water collecting reservoirs imitating part of a soil improvement technology traditionally used in other parts of the country and in Burkina Faso (MOST/CIRAN, running database (2)). From Burkina Faso, it has most recently been reported that villages that adopted land reclamation techniques such as this pitting through crusted soils, filling the pits with manure and water, have seen crop yields rise by 60%, while villages that did not adopt these techniques realized much smaller gains in crop yields under very recent rainfall increases (Reij, cited in Katz, 2002). In north Nigeria small pits in sandy soil are filled with manure for keeping transplanted tree seedlings wet after the first rains. This is tried in China by stony structures in pits, diminishing soil evaporation. Permaculture, water harvesting and infiltration pits, together with the use of drought tolerant crops, have been more recently extended in Zimbabwe, particularly by women, with the help of NGOs, in reply to the recurrent droughts (Shumba, 2001). In semi-arid Nigeria water-harvesting constructions with gutters and bonds are traditionally used around Cassava plots. Again for West Africa, Slikkerveer (1999) mentions a project case study of the successful re-introduction of indigenous "demi-lunes" for better water harvesting. This method was also successfully used in Sudan by the TTMI-project for tree establishment in an arid area near the White Nile (Adil Ahmed Abdalla, personal communication). The earlier example in Niger and these latter two examples further demonstrate the significance of integration of indigenous knowledge and practices in development co-operation projects aiming at increasing resilience (e.g. LEISA, 2001; Stigter and Ng'ang'a, 2001).

Traditional methods and farmer innovations of using occult precipitation under very dry conditions have been dealt with by Acosta Baladon (1995). Further evidence that many of the current traditional adaptation strategies with agrometeorological components also hold for the situations of increasing climate variability is the following quotation from Lin Erda in Zheng et al. (2001) on future measures in China:

"the response strategies include changing the land topography to reduce run off, improve water uptake and reduce wind erosion, introducing artificial systems to improve water availability and to control soil erosion, changing farming practices to conserve soil moisture and nutrients, changing farm operations timing to fit new climatic conditions and using different crops or varieties to match variations in the water supply and temperature conditions. (...) In the course of time new technologies may have to be developed to cope with anticipated impacts and to reduce the costs of adaptation".

It is of course not always a(n) (increasing) variability of climate leading to innovative water use. Changes in cultivation due to population pressure, such as

being forced to use sloping land prone to water erosion (Ong et al., 1996; Zheng and Tuo, 2000), as well as income and market considerations have also led to extending or replacing old practices and using new practices that at the same time increase the resilience of the farming systems (Tchawa, 2000) and protection against consequences of drought (Nasr et al., 2000).

As to floods, the technological literature is less abundant and the solutions have most often little to do with agrometeorology as such. For example, traditional drainage ditches and tunnels have been reported from wheat fields in China (Cheng Yanian, personal communication, 2000). In some cases evaporation and occasionally soil conservation and shading by water absorbing trees play a role. Mitigation by reforestation is an often-mentioned aspect (e.g. MOST/CIRAN, running database (3)). However, preparedness and post-disaster measures are more often referred to because, large infrastructural measures apart, there are few ways to counteract serious floods (e.g. Berg et al., 2001).

As to mechanical impacts of rain and hail, although they are forecasted by IPCC to increase in several regions during peak rainfall, we have not found any examples in the literature dealing with increasing protection attempts. The usual protection of crops and soil by the cover from trees, bushes, crops, crop residues left standing, and grass cover and/or mulching will be increasingly necessary, where these problems of mechanical damage of crops and soil are most serious, depending on the specific crops and soils concerned (Stigter, 1994). Classic work from China reviews various traditional adaptations after serious hail damage, assisting plant recovering, through management and compensation measures, or planting follow-up crops in accordance with the length of the remaining growing season (SAAS, 1977). Rivero Vega (2002) reviews other evidence on traditional adaptation measures for hail protection. Such technologies are applicable elsewhere when such damages are increasing (like in India: V.R.K. Murthy, 2002).

3.2. HEAT

Even small changes in the frequency of extreme temperature events may have disproportionate effects. Salinger et al. (2000) mention the life cycle of perennial plants and the stability of forage supplies as well as the balance between temperature and sub-tropical species as examples. It appears that response farming, as we will deal with it in Section 3.3, should not only be considered with respect to fitting the cropping seasons to variable rainfall patterns, but also for fitting it to variable temperature patterns (Van Viet, 2001). This shows that heat is another important factor to be considered in strategies to cope with climate variability. In this case study (Van Viet, 2001), using seasonal temperature forecasting, recommendations could be given on planting date or a combination of planting date and variety, to make sure that rice was flowering in decades for which the

required optimal temperatures had been forecasted. Contemporary scientific knowledge has taken over from traditional knowledge here. For example, the detailed knowledge available, as reviewed, on the influence of temperature, temperature extremes and temperature distributions on growth, development and yield of rice (Salinger et al., 1997) makes this possible. Temperature may be involved in flowering peaks of plants used as a traditional forecast for monsoon arrival (Anonymous, 2001).

Farmers near Beijing adapted their sayings on the best seeding time since the 1980s, because of the warming of which they observe the agronomical consequences. So also traditional weather lore may change. Where temperature is a limiting factor to photosynthesis, traditional farmers may react to cooling/warming by changing their cropping system. This is exemplified by the North China Plain, where originally a change from double cropping to more traditional intercropping of early maize with late wheat took place. In southern parts intercropping, that gave higher degree-days for maize, was after a decade again replaced by double cropping, while in cooler mountainous areas and further North the intercropping was kept (Zheng et al., internal publications in the 1990s). However, in many other cases the protection will again very likely not change with any increase in variability of temperature. We are then back to the relevant examples of microclimate management and manipulation (Stigter, 1988, 1994), among which there is the classic example of too severe heat flow/temperature modification, by traditional grass mulching against water erosion, leading to subsequent death of young tea (Othieno et al., 1985). Another example of this kind is the traditional furrow sowing of winter wheat in northern China, giving stronger seedlings less suffering from winter damage, due to more soil moisture and higher temperatures in the furrows (Zheng et al., internal publications in the 1980s).

Protection of crops against hot air by shelterbelts was reported by Onyewotu et al. (1998) for reclaiming a desertified area under highly variable climate conditions (Onyewotu et al., 2003). However, it is indeed in traditional parkland agroforestry and other stabilising intensive management of scattered or clumped or alleyed trees that such risk management may be most efficiently found when risks increase (Arnold and Dewees, 1998; Boffa, 1999; Mungai et al., 2001; Onyewotu et al., 2003). It is generally accepted that the weather conditions that create the infamous drought and flammable forests under Indonesian conditions are quite natural, even when their frequency and intensity have increased. However, the factors that have turned this into a disaster, are man-made because most fires are deliberately lit for various reasons. They are due to deliberate policies of non-preparedness and inaction in the face of warnings of extreme fire dangers (Byron and Shepherd, 1998). That is why the appropriate policy environments occur in the B Domain in Figure 1. With the appropriate policies in place, preparedness using meteorological forecasts for grading fire danger has been shown to be a good solution under highly varying conditions (WMO, 1993).

3.3. FITTING CROPPING PERIODS TO THE VARYING SEASONS

The oldest way of coping with climate variability is trying to fit cropping to the ongoing season, using in risk management any possible indigenous forecasts on its behaviour or adapting to what is experienced in the ongoing season. Flexibility and resilience of farming systems with respect to rates of change is a recurrent factor in such attempts. There are ample examples of permanent, slow and fast traditional adaptations to seasonal variability for reasons of risk management and food security (e.g. Bunting, 1975; Stewart, 1988; Blench, 1999; Clemens and Nashrullah, 1999; Gadgil et al., 2000). In fact, these adaptations may be seen as the oldest examples of response farming in the most direct meaning of the words. However, there are no expectations of improvement of these traditional “fitting” methods per se under the presently fast changing conditions. Their blending with more scientific meteorological/climatological and agronomical/breeding approaches appears the only way forwards (Blench, 1999; Gadgil et al., 2000), as also implied by the end-to-end scheme of Figure 1.

Stewart (1988, 1991) defined response farming in a more limited way, with respect to adapting cropping to the ongoing rainy season by guidance of agronomical operations, using experiences of the past, preferably from interpretations of meteorological rainfall records with support from traditional expert knowledge where available. Given the indications for increasing variability and change of the climate in terms of rainfall, this will have to be adapted to those new conditions, limiting the period in the past over which the experience can be used (Ati et al., 2002). In agrometeorology, pilot projects with the use of on-line agrometeorological information for farmers to respond to, successfully exist already for two decades in West Africa (e.g. Traore et al., 1992; Diarra, 2001). When such changes in definitions of response farming are accepted, it is only a little step to include other parameters like temperature, a possibility earlier mentioned above in Section 3.2, due to better probabilistic seasonal forecasting techniques (Van Viet, 2001).

The situation described above also has another policies related face. Blench and Marriage (1998) have noted that in rain-fed farming areas of eastern and southern Africa, governments and development projects have encouraged high-input, high-risk strategies such as planting hybrid maize instead of sorghum and millet. This, although long experience of uncertainty about weather patterns had induced farmers to develop complex cultivar mixtures to ensure yields under all conditions. The effects of the prolonged drought of the early nineties could have been less, if the risks had been spread across a range of crops with greater tolerance of low-rainfall regimes, as that had been traditionally done. In another example, the dominance of a few seed companies combined with commercial pressure on farmers and an extremely negative attitude to “old” crops and open-pollinated varieties, as well as the replacement of many traditional livestock breeds with “modern” breeds, has massively increased small farmers’ vulnerability to climate shock events. Because the high risks under adverse conditions are more important for poor farmers than the

opportunities of better years, here the right policy environment is again surfacing as a necessary condition for services towards sustainable livelihood systems (Blench and Marriage, 1998).

In an even more recent paper, Blench (1999) has noted that multi-lateral agencies are urging that climate forecasts be made available to small-scale farmers. Disaster preparedness strategies, both of governments and NGOs, have begun to take account of such forecasts, and there is considerable interest in assigning them an economic value. However, field studies of the impact of recent forecasts in southern Africa suggest that there is a considerable gap between the information needed by small-scale farmers and that provided by the meteorological services (Blench, 1999). This was confirmed by investigating the role of intermediaries such as Agricultural Demonstrators in Botswana (Stigter, 2002b) and Provincial Agrometeorologists in Vietnam (Stigter, 2002a). Risk-aversion strategies in LEISA production systems do pose a problem for adapting forecast information. Low-income farmers are interested in a broader range of characteristics of precipitation, notably: total rainfall, patchiness of rainfall, intensity, starting date, distribution of rainfall, end of the rains and prospects for dry spells and their length (Blench, 1999; Ati et al., 2002). The use of this information then has to be adapted to local soils and topography.

It is exactly here, where scientific quantification/extensions and improvements of Stewart's response farming approach would bring highly needed solutions (Stewart, 1991; Gadgil et al., 2000). There are recent attempts to define conceptual strategies for demonstration projects of this kind, demanding strategic and tactical interactions between physical, agricultural, social and economic systems, with a long list of elements (Manton, 2001). Carefully organized, but less science driven pilot projects of that kind are highly needed, in which other experience referred to in this paper could be of much use as well (Gadgil, 2001; Stigter, 2002a, b).

4. Additional Considerations for Improving LEISA Farming

The literature on water related examples of combating climate variability and related phenomena of environmental hazards hold a series of lessons also applicable more generally. The above examples show that traditional management technologies and innovations of all kinds are and still become locally available. They belong to the best strategies to cope with climate variability. Dissemination through government and NGO efforts is, however, very necessary because successes are not widespread (Stigter, 2001). Upscaling of results from pilot projects has been reported to face particular barriers and needs wide additional attention (Turton and Bottrall, 1997).

Reports that population growth and agricultural intensification have been accompanied by improved rather than deteriorating soil and water resources (Tiffen et al., 1994) appear very conditional. Improvement of total land husbandry and wider livelihood as a whole are more important than controlling land degradation per se (Shaxson et al., 1997; Boyd and Slaymaker, 2000). The literature indicates that in places prone to frequent disaster or insecurity, simple solutions

are bound to be more successful for services to decision making in the prevailing farming systems (Marsh, 2001). An analysis of soil and water conservation projects in Africa concluded that indigenous techniques should be a starting point to obtain success (Reij, 1993). More recent experience confirms this (Stigter and Ng'ang'a, 2001). Examples from Sri Lanka illustrate the role women's indigenous knowledge can play in conserving sustainability aspects (Ulluwishewa, 1994).

Science can play an appreciable role in increasing understanding and choosing between options for agrometeorological services (Figure 1, also e.g. MacLeod, 1997; Gadgil et al., 2000), but differences in concepts and interests between farmers and scientists should be explicitly recognized (e.g. Cartier van Dissel and de Graaff, 1998). Finally, it should be observed that experiments with traditional aspects of sustainable agriculture as exemplified in this paper provide important information, evidence and morale boosting for building agrometeorological services for decision making on risk management in agricultural systems. However, knowing their inherent limitations in actual agricultural practice, using contemporary science and policy support systems for guidance, is absolutely necessary. We want to make objectives and action plans (and their support systems) more realistic and to the point for creating (improved agrometeorological services for) sustainable livelihood systems (Santhakumar, 1995).

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TOMORROW'S FORESTS: ADAPTING TO A CHANGING CLIMATE

DON C. MACIVER¹ and ELAINE WHEATON²

Meteorological Service of Canada, 4905 Dufferin Street, Downsview, Ontario, Canada, M3H 5T4

E-mail: Don.Maclver@ec.gc.ca

²Saskatchewan Research Council, 15 Innovation Blvd., Saskatoon, Saskatchewan, Canada, S7N 2X8

Abstract. Today's forests are largely viewed as a natural asset, growing in a climate envelope, which favors natural regeneration of species that have adapted and survived the variability's of past climates. However, human-induced climate change, variability and extremes are no longer a theoretical concept. It is a real issue affecting all biological systems. Atmospheric scientists, using global climate models, have developed scenarios of the future climate that far exceed the traditional climate envelope and their associated forest management practices. Not all forests are alike, nor do they share the same adaptive life cycles, feedbacks and threats. Much of tomorrow's forests will become farmed forests, managed in a pro-active, designed and adaptive envelope, to sustain multiple products, values and services. Given the life cycle of most forest species, forest management systems will need to radically adjust their limits of knowledge and adaptive strategies to initiate, enhance and plan forests in relative harmony with the future climate. Protected Areas (IUCN), Global Biosphere Reserves (UNESCO) and Smithsonian Institution sites provide an effective community-based platform to monitor changes in forest species, ecosystems and biodiversity under changing climatic conditions.

1. Introduction

It was perhaps Sigmund Freud who provided some further insight into the scale and importance of emerging issues. Freud observed, "humanity has in the course of time had to endure from the hands of science two great outrages upon its naïve self love. The first when it realized that our earth was not the center of the universe but only a speck in a world system of magnitude barely conceivable and the second was when biological research robbed man of his particular privilege of having been specially created and relegated him to a descent from the animal world" (Gould, 1977). In hindcast, the degree of uncertainty, at the time, associated with each of these outrages might possibly be equated to the uncertainty of the climate change debate, today. But more importantly, what would be the consequences if climate change were, in fact, the "third outrage" on humanity?

The Intergovernmental Panel on Climate Change (IPCC, 1996) concluded "the balance of evidence . . . suggests a discernible human influence on global climate." The most recent IPCC assessment (2001) suggests "there is new and stronger evidence that most of the warming observed over the past 50 yr is attributable to human activities." We know from past experiences that weather and climate have a powerful influence on biological and human environments and that today's forests are the culmination of a long evolution within a climate envelope containing many natural fluctuations and extremes. The conclusion by the IPCC is alarming with

the result that today's forests will be maladapted to future climate and its many variabilities and extremes. This projected magnitude of climate change, especially the anticipated rate of change because of human influences on the climate system, is beyond our current level of knowledge and adaptation mindset. This "outrage" imposed by humanity on the climate system will require a significant paradigm shift and new levels of knowledge for forest managers. However, knowing the anticipated future climate scenarios, continuing population demands, and emission increases, forest managers can begin an adaptation process to design the forests of the future to satisfy a multiplicity of needs, products and services.

The Earth's climate is not static. Shifts between climate states have occurred not only repeatedly but also often abruptly in the past (Charles, 1998). Gedalof and Smith (1998) highlight these step-like climate shifts using western North America tree-ring evidence, such as mountain hemlock (*Tsuga mertensiana*), where climate variability is largely a function of the winter size and position of the Aleutian low-pressure system. Interannual climate variability in this system is largely a response to El Nino/southern oscillation (ENSO) related teleconnections and interdecadal climate variability are driven by the Pacific Decadal Oscillation (PDO). The PDO is distinct in that it does not appear to be an oscillatory system, as the name implies, but rather switches between states abruptly, in step-like time periods. There is strong evidence suggesting that the North Pacific underwent a massive reorganisation following the winter of 1976 with significant repercussions in fisheries, water resources, forestry, agriculture and other areas of natural resources management in western Canada (Ebbesmeyer et al., 1990). The tree-ring studies by Gedalof and Smith (1999) show that annual radial growth of mountain hemlock is sensitive to the types of climate variability associated with the North Pacific-Ocean-Atmosphere system. The climate shift of 1976 may mark a return to greater interdecadal variability. Under climate change, is it expected that future changes will perform in a similar abrupt fashion, or gradual or both?

Forest biodiversity, at all taxa levels, has become increasingly important and other traditional forest issues, such as growth and yield have evolved, for example, into detailed modelling of global carbon sinks and sources under climate change. It is the human expectation of the roles performed by trees, woodlots and forests, managed or unmanaged, that makes it difficult to set global targets for biodiversity conservation, tourism, industrial, natural, environmental, social and spiritual services, to name a few. Values are diverse and the incremental costs of conservation and national benefits are sometimes difficult to articulate. Regardless, the changing climate affects all of these processes either directly or indirectly, nothing is stationary, and abrupt climate shifts are expected to occur in the future.

Why should adaptation to climate change and variability be considered? Responses to global warming are popularly considered to be mainly in terms of mitigation with the aim of reducing human generated greenhouse gas emissions. However, adaptation is also a main part of the response set. Pro-active adaptation actions, especially the many benefits, are needed for several reasons, principally because

human-induced climatic change appears unavoidable, regardless of the mitigation actions to slow the speed of global warming.

Characteristics of systems related to adaptation are identified in several literature streams, including disciplines in both the natural and socio-economic sciences. These include concepts, such as resilience, sensitivity, tolerance, thresholds, critical levels, susceptibility, vulnerability, adaptability, adaptive capacity, coping range, flexibility, size (individual or collective) and part of the forest ecosystem (e.g. human, plant, animal, water, soil, air). Several of these are described in Smithers and Smit (1997). Any new operative word will need to focus much more on enhancing the "resourcefulness" of the forest estate, specifically, the interlinkages between forest ecosystems, species and genetics and the changing atmosphere.

It is important to collectively understand, develop adaptation options, design and manage forests, enhance the benefits, and reduce the dangers of climate variability and climate change (Wheaton and MacIver, 1999). For example, the recent IPCC Special Report "The Regional Impacts of Climate Change: An Assessment of Vulnerability" (Watson et al., 1998) addresses the vital question: what is "the degree to which human conditions and the natural environment are vulnerable to the potential effects of climate change?" The degree of vulnerability indicates the amount of adaptation that is required within the context of our history, infrastructure, and changing technologies.

2. Challenges of Adaptation Science: Understanding the Process

A main challenge facing adaptation science is to improve our theoretical understanding and predictive capacity. The purpose of this is to guide adaptive forest management. Adaptive management serves to reduce vulnerabilities to and enhance opportunities of climate variability and change. The IPCC (Watson et al., 1996b) defines vulnerability as "the extent to which climate change may damage or harm a system. It depends not only on a system's sensitivity but also on its ability to adapt." If a system is sensitive to climate and a climatic stress (either positive or negative) occurs, then damages and/or benefits will result. However, even if a human or natural system is sensitive to climate, it may be so well adapted or able to adapt that few or no damages occur. Conversely, if a system is maladapted and is climate-sensitive, climatic events of a certain type may result in irreparable damages. Forests serve as an excellent example of this latter case, when the rates of change of the future climate far exceed the historical rates of forest migrations and disturbance losses from forest fires and other insects, diseases and where population and land-use changes are expected to significantly change, as well.

Responses can be non-linear and may not occur until a certain threshold has been reached as paleo-forest evidence suggests that changes have been step-wise and abrupt. For example, a 1 °C increase in mean global temperature will have significant

impacts on forest ecosystems and species, especially where forest climates have little or no buffering capacity (MacIver, 1998). The anticipated change in global climate of 3 to 5 °C or more degrees could be devastating, leading to significant maladaptations over the next rotation cycle of most tree species. Adaptation actions, based on sound science, are needed now, but many questions remain:

- What do we understand about the adaptation of human and natural systems to past, present and anticipated future climate variability and change?
- What is the ability of the scientific community to accurately represent adaptation processes in impacts models and assessments? What are the best ways of modelling adaptation?
- How are the risks of climate variability and change perceived (e.g. by decision-makers, by managers, by those responsible for adaptive management)?
- The use of adaptation options is part of a broader process of the adoption of innovation, which is a component of social change. What is our understanding of the process of social change and of the adoption of innovation and new technologies?
- How well adapted are activities or systems? What options exist or are needed for developing forest-monitoring systems to determine how well activities or systems are adapted?

(adapted from Wheaton and MacIver, 1999)

The process of adaptation to climate occurs in a wide variety of ways and under many circumstances. The process depends on many factors, including who or what adapts, what they adapt to, how they adapt, what resources are used and how, and the effects of adaptation within and across forest ecosystems, species and genetic levels. These related themes are part of a model of an adaptation cycle (Figure 1) that changes through time and space. This framework is designed to organize concepts

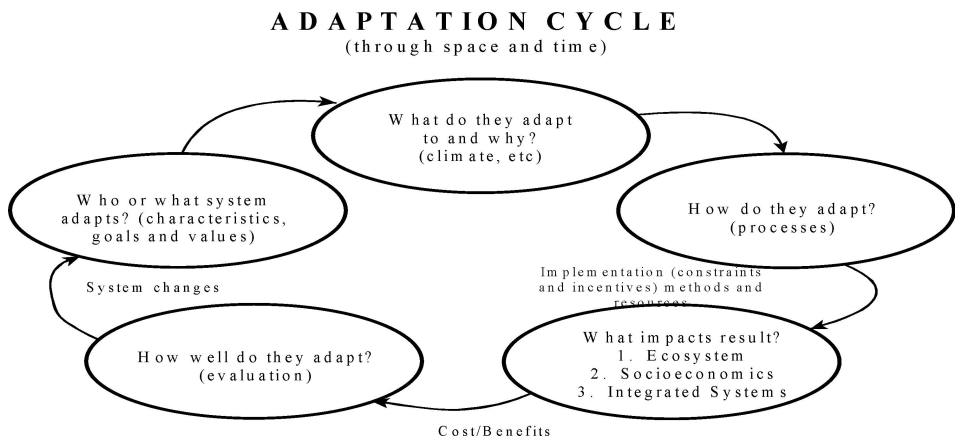


Figure 1. Adaptation cycle through space and time (Wheaton and MacIver, 1999).

regarding adaptation, to stimulate ideas, and to explore the linkages among parts of the adaptation cycle.

The adaptation cycle model is normally characterized as iterative, dynamic, interconnected, non-linear, and likely chaotic. This cycle reminds us that research can begin with examining the disturbance and impacts, as has been traditionally done, or it can begin directly with adaptation assessments. But more importantly, larger forest ecosystems have, on the one hand, a buffering capacity that will ameliorate the direct effects of climate change, especially the rates of change, whereas, in comparison, other forest ecosystems, such as individual trees and woodlots will likely be maladapted immediately (i.e. heat stress, insect outbreaks and so on). For example, the onset of a drought may be gradual and can be difficult to detect, but a forest fire or insect onset is sudden. Or, forests, including woodlots and trees, surrounded by highly impacted landscapes become more vulnerable, even if the species within the forest have the potential of adapting to the future climate. Under these circumstances, the erosion of the buffering capacity of the forest can be abrupt.

The science of adaptation (Figure 2) should address the questions, such as those posed earlier, with an overarching challenge to address: what is changing and why? Forest species have long rotation life cycles in the natural evolving world and species planted today are expected to thrive within the human-induced climates of tomorrow. Hence, adaptation is a key part of today's decision-making process, including the governance of the design and management of forests for the future. The design criteria will be influenced by many factors, including lessons from past experiences, traditional forest knowledge in adaptation, adaptation technologies, risks, uncertainties, costs, benefits, social vulnerability and resilience, buffering

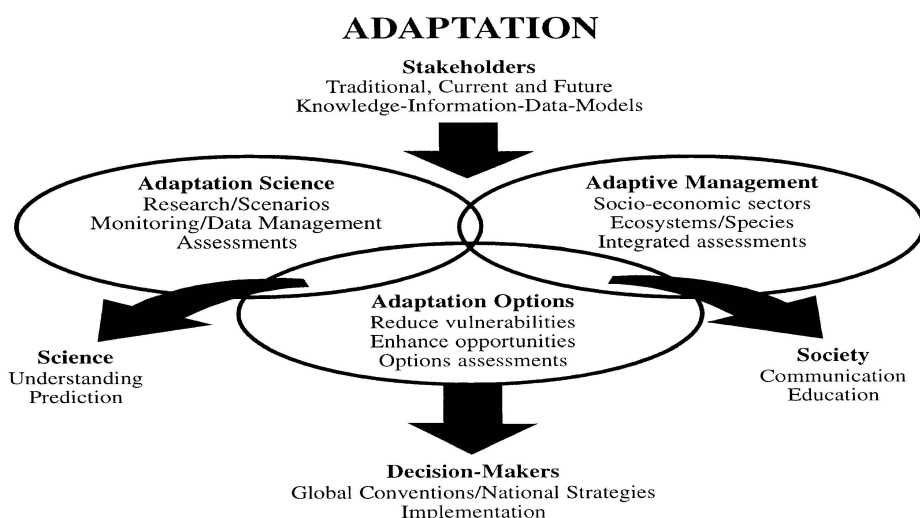


Figure 2. Adaptation framework (Wheaton and MacIver, 1999).

capacities, impact assessments, data and information needs and knowledge of the forest climate.

3. Challenges of Adaptive Management: Reducing Vulnerabilities through Application of Adaptation Science

Adaptive management is the practice of adaptation science. There are many ways that adaptation processes can be managed. Figure 2 depicts linkages of adaptation science with adaptive management and adaptation options, and the following key questions help identify some of the challenges:

- What aspects of our understanding of climate variability and change provide us with the best adaptive practices to reduce our vulnerability? What are the significant gaps in our understanding?
- What approaches are available to help resource managers or users identify “win-win” or “no regrets” adaptation options? Which activities or sectors have the greatest potential to achieve win-win outcomes?
- How do our existing institutional arrangements, training, and access to financial capital enhance or impede applications of known and appropriate adaptive management? What practices exist or should be developed to encourage these applications or to reduce these barriers?
- What sources of information and technology are available to individuals and groups in different sectors and regions that they could use to harmonize activities with climate and other forest environmental conditions?

(Adapted from Wheaton and MacIver, 1999)

When adaptive management first entered the vocabulary of forest management, it heralded a new way of thinking in which management policies were treated as experiments, learning from them and using them as a basis for changes and adjustments (Stankey, 2001). If we characterize current forest management policies within the overarching theme of natural capital, then Figure 3 provides some insight into the multiplicity of goals, values and life services managed by many groups worldwide. Trees and forests are more than wood. In many communities, they are the source of heat, food, shelter, and spiritual value. In others, they are the industrial forest, to others a habitat rich in biodiversity and to others a regulating influence on the atmosphere. The majority of forests worldwide continue to be natural and managed accordingly. But if we accept that humanity has created this third “outrage” on the world, then this graphical depiction quickly turns from a theme of viewing forests as natural capital to one of managed values for sustainability, by which all forests will be managed for a diversity of targets within the envelope of global climate change. Adaptive approaches offer hope for the successful management of natural-origin and planted forests for their multiplicity of values, but driven and defined at the local levels within a global climate change envelope.

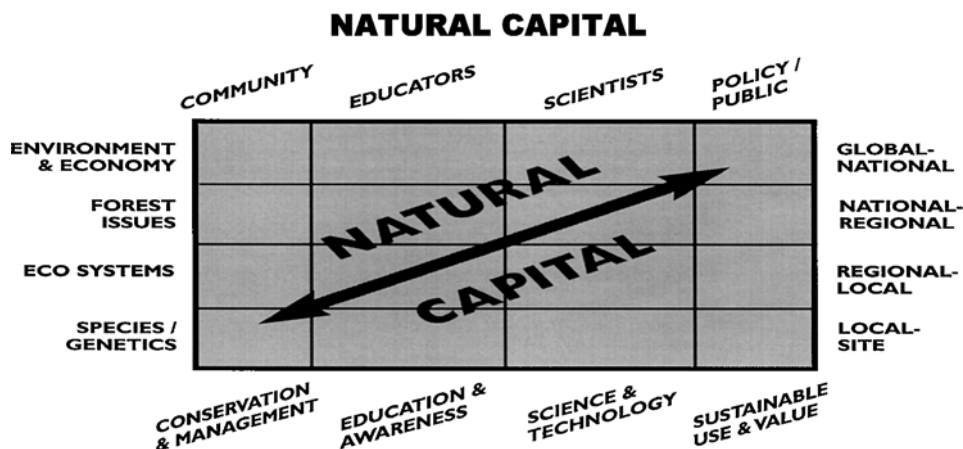


Figure 3. Natural capital framework.

4. Next Challenges: Adaptation Options

A preliminary framework to deal with adaptation options is presented in this paper and summarized in Figure 2. Adaptation options have been further subdivided into: reducing vulnerabilities; enhancing opportunities; and options assessments. Some key questions regarding the challenges of adaptation options are given below:

- What key adaptation messages are sufficiently well founded to establish policies for natural forest ecosystems, woodlots, individual trees, sustainability, resource, resource use, national security, socio-economic development, investment and so on?
- What types of options assessment processes or aids are available to assist selection and prioritization of particular forest technologies or practices from among several options?
- Are there priority needs and additional options that the international community should consider to improve the availability of information and to capitalize on adaptation options?
- What is the current role of the private sector in providing access to technologies and practices that facilitate adaptation? What options exist for improving the flow of technology and knowledge through the private sector?

(Adapted from Wheaton and MacIver, 1999)

Building adaptation work beyond initial steps is urgently needed now. Next steps include careful consideration of the implication of the Framework Convention on Climate Change and its Kyoto Protocol, the Convention on Biological Diversity (CBD) and many other international conventions and agreements. Several key adaptation-related articles and operative phrases in the Convention and Protocol have considerable strategic, analytical and information challenges for forest

SUSTAINABLE FORESTS



Figure 4. Sustainable forests framework.

management, including land-use and land-use changes, the Clean Development Mechanisms, carbon sequestration and many others.

Our collective challenge, given the climate change scenarios, population increases, land-use changes and emissions, is a clear definition of our values, projected into the future and figuring out where we go from today. There is a need to reach agreement on a broad and descriptive vision of sustainable forests, woodlots and trees, shared by all. For example, Figure 4 helps illustrate the many interconnecting values that would allow for global and local target setting, where heritage is added as the fourth pillar for sustainable forests. In other words, a pro-active adaptation approach is needed to design future forests to survive and thrive in the future climate. Sounds simple, but the real challenge is taking the first step, tolerant of other competing values and yet managing tomorrow's forests, now. For example, we know that forest migrations cannot keep pace with the expected rate of climate change. Forest ecosystems do not migrate *en masse*, but species are resourceful in their continuing search for new development opportunities when the hospitality of the local landscape and environment are conducive for seed, pollen and growth processes. Without human intervention, it is expected that many forest reserves will become islands of declining habitat. Interconnecting corridors may help some forest populations, but mass extinction of species is already underway. Humans have created this third great "outrage" and only humanity, not nature, can avoid expected maladaptations.

5. Global Adaptation Laboratories: Protected Areas, Biosphere Reserves and Smithsonian Biodiversity Sites

Knowing the future climate scenarios and increasing forest vulnerabilities, one of the key questions simply stated is how to we get from here to there? Convergence of major global efforts, such as Climate Change, Protected Areas (IUCN), World

Biosphere Reserves (UNESCO), Smithsonian Biodiversity Sites and others (e.g. ILTER sites and Model Forests) may provide some answers. The establishment of Smithsonian Forest Monitoring sites (SI/MAB), monitored by community groups using the same protocols and standards worldwide (Dallmeier, 1992), is particularly unique and noteworthy. For example, using these global protocols for forest biodiversity monitoring, there are now more than 80 SI/MAB sites in Canada located across climate, chemical and ecological gradients (MacIver, 1998). This also included the need for geo-spatial analysis based on Integrated Mapping Assessments (MacIver and Auld, 2000) and the establishment of Climate Change Forest Experimental Sites (e.g. in the City of Toronto).

With more than 400 Biosphere Reserves worldwide, each Biosphere Reserve has a conservation function, a development function and a logistic function. In this human-nature environment of conservation and development, the Biosphere Reserves consist of a core area, a buffer zone and a transition zone, in which development, human activities, agricultural and other uses are studied in relation to the core conservation area. This core area has been legally established, such as parks, and given long-term protection to the landscape, ecosystem and species it contains. In other words, this human-nature dimension of Biosphere Reserves is particularly noteworthy and unique since the management is local community driven along with society, as a whole (UNESCO, 2002).

Let us once more return to this third "outrage" on humanity, namely climate change, and recognize that this will be the greatest challenge facing the long-term sustainability of Protected Areas and Biosphere Reserves, and the conservation of forests contained within. In 1995, the International Conference on Biosphere Reserves, held in Seville (Spain), confirmed that Biosphere Reserves offer such experimental sites, worldwide. From an adaptation viewpoint, the Protected Areas, Biosphere Reserves and the Smithsonian Sites are well situated to become the Global Monitoring Network, linking together the human dimensions of development and natural conservation within an integrated abiotic, biotic and socio-economic framework.

6. Conclusions

Tomorrow's forests will need to be managed in a pro-active adaptive manner, given the anticipated threats of climate change. Lessons learned from past and current climate variabilities and extremes, future global climate scenarios and lessons derived from Protected Areas, Biospheres Reserves and Smithsonian Sites may help increase our collective understanding of forest adaptative capacities.

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MANAGEMENT STRATEGIES TO SEQUESTER CARBON IN AGRICULTURAL SOILS AND TO MITIGATE GREENHOUSE GAS EMISSIONS*

R. L. DESJARDINS, W. SMITH, B. GRANT, C. CAMPBELL and R. RIZNEK

Research Branch, Agriculture and Agri-Food Canada, 960 Carling Ave, Ottawa, Canada

E-mail: desjardins@arg.gc.ca

Abstract. Carbon sequestration in agricultural soils is frequently promoted as a practical solution for slowing down the rate of increase of CO₂ in the atmosphere. Consequently, there is a need to improve our understanding of how land management practices may affect the net removal of greenhouse gases (GHG) from the atmosphere. In this paper we examine the role of agriculture in influencing the GHG budget and briefly discuss the potential for carbon mitigation by agriculture. We also examine the opportunities that exist for increasing soil C sequestration using management practices such as reduced tillage, reduced frequency of summer fallowing, introduction of forage crops into crop rotations, conversion of cropland to grassland and nutrient addition via fertilization. In order to provide information on the impact of such management practices on the net GHG budget we ran simulations using CENTURY (a C model) and DNDC (a N model) for five locations across Canada, for a 30-yr time period. These simulations provide information on the potential trade-off between C sequestration and increased N₂O emissions. Our model output suggests that conversion of cropland to grassland will result in the largest reduction in net GHG emissions, while nutrient additions via fertilizers will result in a small increase in GHG emissions. Simulations with the CENTURY model also indicated that favorable growing conditions during the last 15 yr could account for an increase of 6% in the soil C at a site in Lethbridge, Alberta.

1. Introduction

Human activities are increasing greenhouse gas (GHG) concentrations in the atmosphere. In 2000, the global increase in atmospheric CO₂, the single most important anthropogenic GHG, originated mainly from the burning of fossil fuels, which contributed about 6.5 Pg C yr⁻¹, and from deforestation, which contributed about 1.6 Pg C yr⁻¹ (IPCC, 2001a). Globally, CO₂ accounted for about 60% of the global warming potential. Other GHG contributing to global warming were CFCs (15%), CH₄ (15%), and N₂O (6%). These changes in GHG concentrations are expected to lead to a general rise in global temperature and a modification in weather patterns (IPCC, 2001b). In order to minimize the impact of climate variability and climate change on the terrestrial biosphere, over 170 countries ratified the agreement of the Kyoto Protocol in 1997. This protocol aims at stabilizing GHG in the atmosphere at a level that will reduce the dangers from anthropogenic interference

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with the climate system. The protocol will become legally binding when ratified by countries accounting for at least 55% of the total 1990 GHG emissions. Countries have committed to reduce their GHG emissions to varying extent. Meeting their respective goal will undoubtedly be difficult for many countries. Canada will need to reduce its annual GHG emissions to 571 Tg CO₂ equivalent by 2008–2012, down from a projected level of 809 Tg under business-as-usual situation. Slowing the rate of increase of the concentration of these gases is expected to require efforts from many sectors of the economy. Agriculture is one of the sectors that could reduce the extent to which fossil fuel emissions need to be reduced by enhancing the C sink in agricultural soils. This paper focuses on the role of management practices in sequestering C in agricultural soils and, at the same time, mitigating GHG emissions. We present a global perspective, but examples are based on Canadian experience.

2. The Role of Agricultural Soil in Influencing the GHG Budget and Their Potential for C Mitigation

According to Houghton and Hackler (2001), the net flux of carbon between the terrestrial biosphere and the atmosphere between 1850 and 1990 was 124 Pg C from deliberate changes in land cover and land use. DeFries et al. (1999) estimated that total C loss from human-induced land cover changes were almost 200 Pg C for the same period. Lal et al. (1998) estimated that agricultural soils globally have lost 40 to 50 Pg C during the last two centuries, and about 80 to 117 Pg C have been released from biomass due to change in land use for agriculture. Until the 1970's more CO₂ had been released into the atmosphere from agricultural activities than from fossil fuel burning. The annual net release of C from agriculture has recently been estimated at 0.8 Pg C, that is, about 14% of current fossil fuel emissions (Schlesinger, 1995). Considering all these substantial losses in soil C, it is not surprising that land management strategies are considered to have considerable potential for carbon mitigation.

Cole et al. (1996) estimated that globally, between 0.4 and 0.8 Pg /yr of C could be sequestered in agricultural soils for 50–100 yr through good soil management. Paustian et al. (1997) calculated that the capacity for C sequestration in agricultural soils on a global scale is about 20–30 Pg C over the next 50–100 yr. Lal and Bruce (1999) estimated that the total soil C sequestration potential of the world cropland is about 0.75–1.0 Pg/yr or about 50% of the annual emissions by deforestation and other agricultural activities. This finite soil C sink could be filled over a 20 to 50-yr period. The International Panel for Climate Change (IPCC, 2000) recently reported that by 2010 the potential net C storage from additional activities under Article 3.4 of the Kyoto Protocol could be 0.29 Pg C/yr for developed countries and 0.72 Pg C/yr for developing countries. By 2040, the potential net C storage is expected to be 0.85 Pg C/yr for developed countries and 1.32 Pg C/yr for developing countries. These values represent the contribution from both agriculture and forest management.

There are still large uncertainties regarding the total amount of C that can be sequestered by agricultural soils. These uncertainties are primarily due to the difficulty of measuring a small change in soil carbon (e.g., 3 Mg C/ha) above a large background (e.g., 60 Mg C/ha) with high variability (e.g., ± 15 Mg C/ha). Garten and Wullschleger (1999) estimated that the smallest difference in SOC inventories that can be detected, and this only with exceedingly large sample size ($n > 100$), is approximately 2–3% or 1 Mg C/ha.

3. Opportunities for Increasing Soil C Sequestration

A number of agricultural land management practices have shown potential for increasing C content in agricultural soils (Desjardins et al., 2001b). Table I summarizes some of the results reported in the literature. These data are either based on measured or modeled values. As shown by Smith et al. (2001), a range of values are associated with most management practices. This range depends on soil texture, soil taxonomy, climatic conditions, and many other factors. The practices in Table I are shown independently, however, some practices are often adopted in unison and may or may not have an additive effect. For example, a reduction in bare fallow is usually accompanied by greater use of fertilizers and sometimes the adoption of conservation tillage. McConkey et al. (1999) discuss how several interacting effects can be calculated for cropping in various soil zones on the Canadian Prairies. There are probably several other practices that have the potential to sequester C in agricultural soils but their contribution to the net GHG budget still remains to be clarified. For example, improvements in manure and nutrient application could lead to increased C sequestration. Moldboard plowing in combination with the application of liquid dairy manure has been shown to increase soil C at a depth of 20–40 cm (Chantigny et al., 2001).

We will focus on some of the more promising agricultural practices that may be used to increase soil C sequestration.

3.1. CONVERTING CROPLAND TO GRASSLAND

Converting cropland into perennial forage production may result in a substantial increase in soil C sequestration. Conant et al. (2001), in a comprehensive literature review, reported rates of soil C sequestration of $1.01 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ for conversion from cultivation to grassland. This value is slightly larger than the value of $0.62 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ predicted by the CENTURY model for Canada (Smith et al., 2001). Conversion of cropland to forage production does not always lead to increased soil C. For example, Campbell et al. (2000) observed very little increase in soil C when cultivated land was cropped to crested wheat grass for 10 yr in Southwestern Saskatchewan. They ascribed this somewhat surprising result to poor weather conditions for growing grasses during the experimental period.

TABLE I
Amount of C sequestered in agricultural soils for various management practices

Practice	Amount C sequestered (Range) (Mg C/ha/yr)	Region	Investigators
Nutrient additions via fertilizer	0.30	42 data points	Conant et al., 2001
	0.05–0.15	U.S.A.	Lal et al., 1998
	0.14–0.18	U.S.A.	Halvorson et al., 1999
	0.16		Lee and Dodson, 1996
	0.04	Canada	Smith et al., 2001
Nutrient additions via manure	0.2–0.5	U.S.A.	Follett, 2001
Converting cultivated lands to grasslands	1.01	23 data points	Conant et al., 2001
	0.62	Canada	Smith et al., 2001
Including more forages (especially legumes) in rotations	0.75	6 data points	Conant et al., 2001
	0.44	Canada	Smith et al., 2001
Adopting conservation tillage	0.06	Canada	Smith et al., 2001
	0.3–0.6	U.S.A.	Follett and McConkey, 2000
	0.1–0.5	U.S.A.	Lal, 2001
Conversion from conventional till to no-till	0.13	Canada	Smith et al., 2001
	0.20–0.35	Canada	McConkey et al., 1999
	0.14–0.56	U.S.A.	Lal, 1997
	0.5–0.8	U.S.A.	Lal et al., 1998
	0.17–0.56	Dev. Countries	Lal, 1997
	0.12–0.29	Asia	Lal, 1997
	0.09–0.29	Africa	Lal, 1997
	0.12–0.29	L. America	Lal, 1997
Reduction of summer fallow	^a 0.123–0.185	Canada	Campbell et al., 2001a
	^b 0.07	Canada	Campbell et al., 2001a
	0.03–0.14	Canada	Smith et al., 2001
	0.02–0.04	Canada	McConkey et al., 1999
	0.05–0.4	U.S.A.	Lal, 2001
Improved grassland management	0.5–0.6	Australia	Gifford et al., 1992
	0.59	Canada/U.S.A.	Conant et al., 2001
	0.28	Australia	Conant et al., 2001
	0.05–0.3	U.S.A.	Lal, 2001

^aChange from 50% fallow to continuous cropping.

^bChange from fallow-wheat to fallow-wheat-wheat.

3.2. REDUCED TILLAGE

No-till management is considered to be one of the most efficient practices for sequestering C in cropland. Currently, the rate of $0.2 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ has been suggested for use across Canada (Bruce et al., 1998). However, the net effect of tillage on C sequestration is complex. The increase in soil moisture associated with no-till often results in higher crop yield, especially in arid or semiarid environments; but this may also lead to more rapid soil C decomposition. The lower temperatures and more limited soil aeration at higher soil moisture may lead to less soil decomposition. Hence, it is no surprise that there are conflicting observations with respect to the impact of this practice on soil C, depending on where the measurements are carried out. No-till also has benefits such as minimizing C loss associated with soil erosion. In addition, there is a reduction in fossil fuel emissions because of reduced machinery and tractor use. Greater conservation of soil moisture by the surface residue layer under conservation tillage may also facilitate continuous cropping in semi-arid environments thereby resulting in less summer fallowing in certain regions and increased crop production and C inputs to soil.

Conversion of conventional tillage to no-till will increase SOC if it: (a) reduces the rate of SOC decomposition; or (b) increases yield and thus C inputs. The latter is often observed in some areas of the prairies but less often in the more humid regions of the country. Under arid or semiarid conditions, the yield increase from no-till is more a function of greater water conservation and the latter benefit may either not be significant in more humid regions or may even be a detriment on heavy textured soils. No-till may also increase SOC at a given site by preventing erosion, though this does not represent a net removal of C from the atmosphere. The results of Campbell et al. (2001a) indicate that without adequate fertilization the adoption of no-tillage will not necessarily increase soil C.

Conservation tillage appears to be more prevalent in North America than in Europe (Smith et al., 2000). In European countries, where no-tillage would yield great benefits in terms of water conservation (eg. in Spain), reduced tillage accounts for less than 5% of total land cultivated in 1995 (Costa, 1997).

3.3. REDUCTION OF BARE FALLOW

Greater cropping intensity by reducing the frequency of bare fallow in crop rotations will increase crop production and thus increase C inputs to soil and increase SOC (Campbell et al., 2001b). This will also increase water use, keeping soils dryer longer and thus reduce soil decomposition. On the Canadian Prairies, the area under summer fallow has decreased from 12 to 5 million ha in recent years and is expected to decrease to 3 million ha in 10–20 yr (Dumanski et al., 1998). It has been estimated that reduction of summer fallow by 1.8 million ha in the Canadian prairies would remove about $1.5 \text{ Tg CO}_2/\text{yr}$ by 2010 from the atmosphere (Desjardins et al., 2001a). This reduction in summer fallow has many implications on the GHG budget.

In Canada, conversion from summer fallow to cropped land takes place primarily on the Canadian Prairies. This conversion will result in increased soil C if it: (a) reduces the rate of SOC decomposition; (b) increases crop production and thus C inputs; (c) reduces erosion (though this is not truly C sequestration). The rate of increase in SOC due to this change is a function of climatic conditions. That is, if weather is consistently favorable, production (C inputs) will be greater than if weather is consistently unfavorable and hence, SOC gains will be greater in favorable weather situations.

3.4. INTRODUCING FORAGE IN CROP ROTATION

Most studies have shown a consistent positive contribution of grasses to soil carbon sequestration. Perennial grasses or legumes in rotation, high yielding varieties and soil management practices that permit the return of large amounts of crop residues to the soil can potentially increase SOC, thus increasing the likelihood for sequestering atmospheric CO₂. Use of legumes in crop rotations can also appreciably reduce the requirements for N fertilizers for various cropping systems, thereby reducing net fossil fuel requirements and the C cost of manufacturing N fertilizers. Forage crops are, however, largely relied upon for food for animals. Hence, some of the benefits of C sequestration may be offset by increased CH₄ emissions from livestock (Desjardins et al., 2001a). Further, forage crops grown in rotation with cereals and oilseeds in the semiarid prairies of Canada often negatively influence yields of the cereals thus resulting in a reduction in C inputs (Campbell et al., 1990). Thus such systems are most advantageous in subhumid regions such as the Black Chernozems and Gray and Dark Gray Luvisolic soils of western Canada.

3.5. NUTRIENT ADDITIONS VIA FERTILIZERS

Many agricultural ecosystems are nitrogen-limited. Adding N fertilizer usually results in increased crop production (i.e., C inputs) and may therefore increase C sequestration in soils. As expected, the addition of nutrients has been shown to increase carbon content in soil (Table I). In considering the net effect on the GHG budget we must take into account the fact that nutrient additions via fertilizer can lead to higher N₂O emissions and may also tend to reduce the CH₄ uptake by soils (Mosier et al., 1997). Further, there is about 1 kg C emitted in the manufacture and transportation of 1 kg N fertilizer that must also be accounted for in any C balance (Janzen et al., 1999). Still, in a long-term experiment conducted in a Black Chernozem in Saskatchewan, Campbell et al. (2001a) recorded significant increases in C sequestration even after allowing for the latter expenditures in C from fertilizer N manufacture and transportation.

When assessing the impact of management on GHG, there is often a tendency to ignore the impact of the various mitigating practices on the emissions of the other

GHG. For example, trace gas fluxes of CH_4 and N_2O may change the mitigation potentials of a land management option and hence, all GHGs should be considered when estimating the net C sequestration potential of a management practice. This is especially important when one considers the relative impact of these 3 gases in terms of their global warming potential.

4. Impact of Soil Management Practices on the Net GHG Fluxes

As we have discussed, several agricultural practices have great potential to increase carbon sequestration, and in some cases, decrease the net emissions of GHG. However, to date, very few field studies have been made that simultaneously examine C sequestration together with the other GHG emissions. Hence, we often have to rely on model estimates. The following analysis relies extensively on the application of the soil carbon model CENTURY (Parton et al., 1993), and on the estimation of N_2O emissions based on analysis with DNDC (Li et al., 1992 a, b). Simulations were carried out using soil and climate data from 5 locations in Canada (Table II) to estimate the influence that selected changes in agricultural management practices are likely to have on N_2O and CO_2 fluxes.

To calculate changes in soil C stock (0–20 cm depth) and stabilization of the soil organic C pools, the CENTURY model was run from 1910 to 2029. Crop production yields were calibrated for each run. Management practices, including tillage, fertilizer addition, etc., were taken from the work by Smith et al. (1997). The DNDC model was run for the period between 1970 and 2029. Weather data for the 1970–1999 period were obtained from weather stations close to each site. The same weather data were used to simulate the weather for the next 30-yr period (i.e., 2000 to 2029).

A description of the soils, fertilizer application and climate at the 5 sites (Table II) is as follows:

1. The Dark Brown Chernozem soil at the Lethbridge, Alberta site has a sandy clay loam texture changing to a clay loam below 30 cm depth. A rotation of wheat-wheat-fallow was simulated with a fertilizer application of 15 and 40 kg ha^{-1} N applied in the 1st and 2nd year of the rotation, respectively. Long-term annual precipitation averages just over 400 mm, moisture deficits (evapotranspiration minus precipitation) average 268 mm and the annual air temperature averages 5.5 °C (Campbell et al., 1990). Snow packs are discontinuous and wintertime soil surface (5 cm depth) temperatures can range between –20 °C and 10 °C, undergoing numerous freeze-thaw events during Chinook wind occurrences that are common to this region.
2. The Brown Chernozemic soil at the Swift Current, Saskatchewan site is primarily of loam texture. A wheat-wheat-fallow rotation was also run at this location with fertilizer application of 15 and 40 kg ha^{-1} N applied in the 1st and 2nd year of the rotation, respectively. Long-term precipitation

TABLE II

Modeled cumulative change, over the next 30 years, of the combined N₂O and CO₂ emissions due to a change in management practice from conventional tillage

	150% Fertilizer application	50% Fertilizer application	No-tillage	Permanent grassland	Reduced summer fallow	Forage in rotation
Mg CO ₂ equivalent ha ⁻¹						
(A) N ₂ O						
Three hills	-1.6	2.6	13.1	10.3		
Lethbridge	-7.1	2.1	5.1	5.0	-0.8	
Swift current	-9.4	2.1	6.5	6.5	0.9	
Harrow	-24.0	17.4	15.9	15.5		6.5
St. Foye	-16.1	26.9	24.6	29.3		19.5
(B) CO ₂						
Three hills	-0.1	0.0	34.9	111		
Lethbridge	5.6	-5.0	11.6	101	13.1	
Swift current	5.7	-1.7	11.5	93	11.9	
Harrow	1.7	-15.0	23.9	201		20.1
St. Foye	2.1	-16.4	22.1	202		19.2
(C) Combined N ₂ O & CO ₂						
Three hills	-1.7	2.6	48.0	121		
Lethbridge	-1.5	-2.9	16.7	106	12.3	
Swift current	-3.7	0.4	18.0	100	12.8	
Harrow	-22.3	2.4	39.8	217		26.6
St. Foye	-14.0	10.5	46.7	231		38.7

Note. Plus denotes a reduction in net GHG emissions and minus denotes an increase.

averages 334 mm, moisture deficits average 395 mm and the annual air temperature averages 3.3 °C (Campbell et al., 1990). Winter snow packs are often discontinuous, thus surface soil (5 cm) temperatures can reach -20 °C.

3. The Three Hills, Alberta site is located in the Dark Brown-Black soil transitional area, having a soil with clay-loam over clay texture. A continuous wheat system was simulated with fertilizer applied at 70 kg N ha⁻¹. Long-term precipitation averages 408 mm, moisture deficits average 250 mm, and the annual air temperature averages 3.4 °C.
4. The soil at the Harrow, Ontario site has a poorly drained clay-loam soil (Ortho-Humic Gleysol) on which we simulated a corn-corn-barley-barley rotation with 180 kg ha⁻¹ fertilizer N applied to the corn and 70 kg ha⁻¹ to the barley. Long-term precipitation in this region averages 827 mm, moisture deficits average 86 mm and the annual temperature averages 8.7 °C.
5. The research station near Ste Foye, Quebec is approximately 30 km south of Québec city. The soil is a clay loam belonging to the Gleysolic soil group. We simulated a corn-corn-barley-barley rotation with 180 and 70 kg ha⁻¹ fertilizer N applied to corn and barley, respectively. Growing season precipitation averages 640 mm, moisture deficits are less than 100 mm, and the

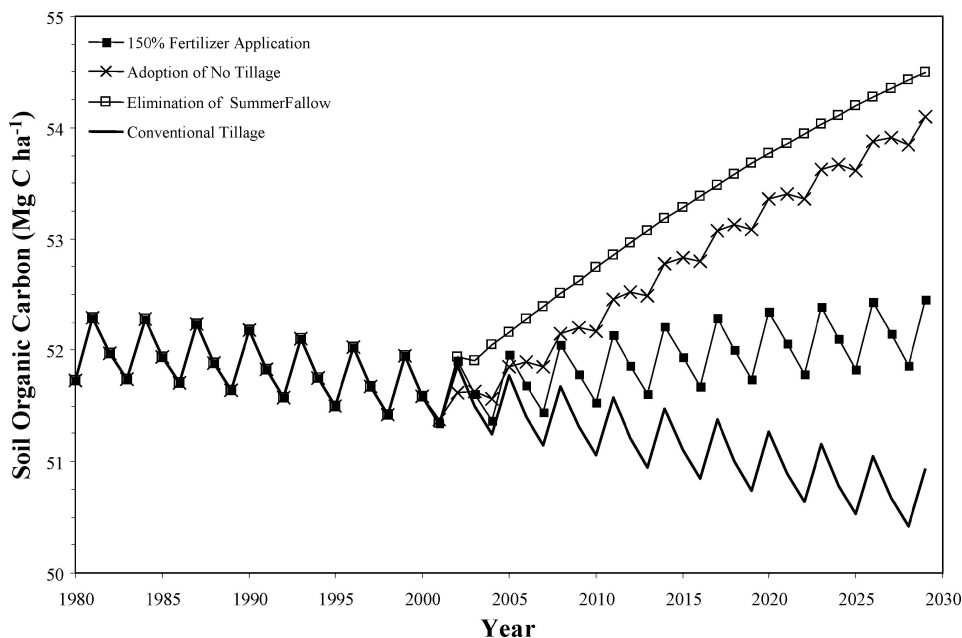


Figure 1. Annual changes in soil C for various management changes for a wheat-wheat-fallow rotation in Lethbridge, Alberta (1980–2029).

mean annual air temperature averages 4.1°C . While soils are only frost-free for about 150 days, they remain only slightly below 0°C for most of the winter as snow packs can reach depths of 1 m.

The following changes in management were simulated: conversion from conventional tillage to no-tillage, conversion from cultivated land to permanent grassland, elimination of summer fallow, introduction of forage in a rotation, and a decrease by 50% and an increase by 150% of N fertilizer addition. Figure 1 presents an example of the soil C change predicted using the CENTURY model. It shows the cumulative soil C change over 30 yr for some of these management practices for a wheat-wheat-fallow rotation located near the Lethbridge research station in Alberta. The largest changes in soil C were due to the elimination of summer fallow and a change from conventional tillage to no-tillage (Figure 1).

CENTURY and DNDC models were also used to calculate the cumulative changes over 30 yr in CO_2 and N_2O emissions, in CO_2 equivalents (Table II). The global warming potentials as given by IPCC (1996) were used for these calculations. The introduction of permanent grassland to previous cropland resulted in the largest net reduction in GHG. The largest changes were at the Ontario and Quebec sites where rainfall is less limiting to crop production than at the prairie sites. It was estimated that conversion of cropland to grassland reduced the combined emissions of CO_2 and N_2O by over $200 \text{ Mg CO}_2 \text{ equivalent ha}^{-1}$. Conversion from conventional to no-tillage, reduction of summer fallow and introduction of

forage into rotations all reduced net CO_2 and N_2O emissions. The increase in C sequestration was predominant over increased N_2O emissions. The DNDC model generally indicated less N_2O emissions due to the introduction of no-tillage, reduction of summer fallow and introduction of forage in the crop rotation. Reduction of fertilizer-N application reduced N_2O emissions but also resulted in less C sequestration, while increasing N application increased C sequestration but also N_2O emissions. In general, the models suggest that changes in the amount of N fertilizer applied will not have much effect on the net CO_2 equivalent flux at most locations. The wide range of numbers in Table II clearly show that large errors can result if one merely multiplies the percent of arable land use by a carbon change coefficient when estimating the carbon mitigation potential of various land management practices.

The combined cumulative fluxes of N_2O and CO_2 from year 2000 to 2029 clearly indicate that several practices have the potential to reduce GHG emissions by shifting from conventional tillage to other management practices (Figure 2). This figure shows the relative net changes in CO_2 equivalents due to CO_2 and N_2O emissions as compared to the control run which was business as usual using conventional tillage for a normally fertilized fallow-wheat-wheat rotation. Note that, at this site in Lethbridge, Alberta, the introduction of no-till, elimination of summer fallowing, and increased fertilization continued to reduce GHG emissions right up to the year 2029. Though the SOC pools have stabilized to some extent,

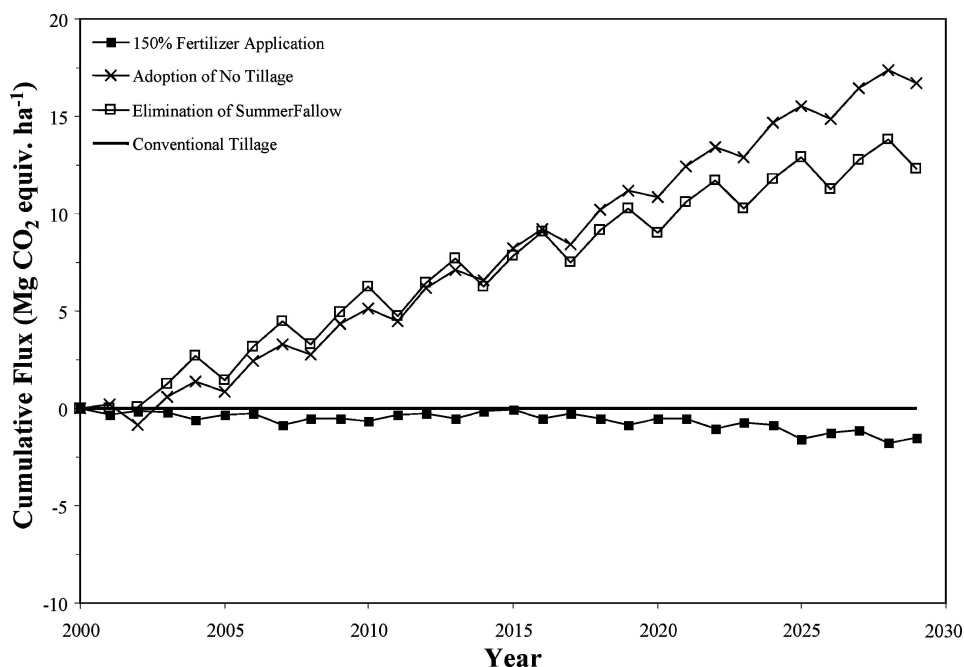


Figure 2. Predicted cumulative flux ($\text{Mg CO}_2 \text{ equiv. ha}^{-1}$) over the period between 2000–2029 due to a change from conventional tillage to various management practices in Lethbridge, Alberta.

less N_2O emissions are predicted to occur, particularly from permanent grassland. The other sites also showed similar trends (Table II).

5. Impact of Climatic Variations

Research results aimed at determining the influence of various management practices on C change in agricultural soils may be affected by climatic variations. It is well known that drought and excess precipitation can have a negative effect on crop production and thus C sequestration. In many semi-arid regions, a moderate increase in temperature accompanied by increased precipitation would likely lead to an increase in crop production. It is then possible that favorable weather over a number of years may enhance crop growth and inflate C sequestration rates for a particular management practice, whereas the practice may produce less C storage under normal weather conditions. The CENTURY model was run for a wheat-fallow rotation under conventional tillage (CT) using soil and weather data from a site near the Lethbridge Research station in Alberta in order to discern the impact of climate variations on SOC storage. Two simulations were carried out. First, the model was run for the period 1910–1999 using 30-yr climate normals, and then from 1910 to 1969 with 30-yr climate normals followed by monthly weather data from 1970 to 1999. For this case, the model predicts substantially more C sequestration (3 Mg C/ha or about 6%) for the period between 1983 and 1999 using monthly weather data (Figure 3). The increased C sequestration is not necessarily due to greater

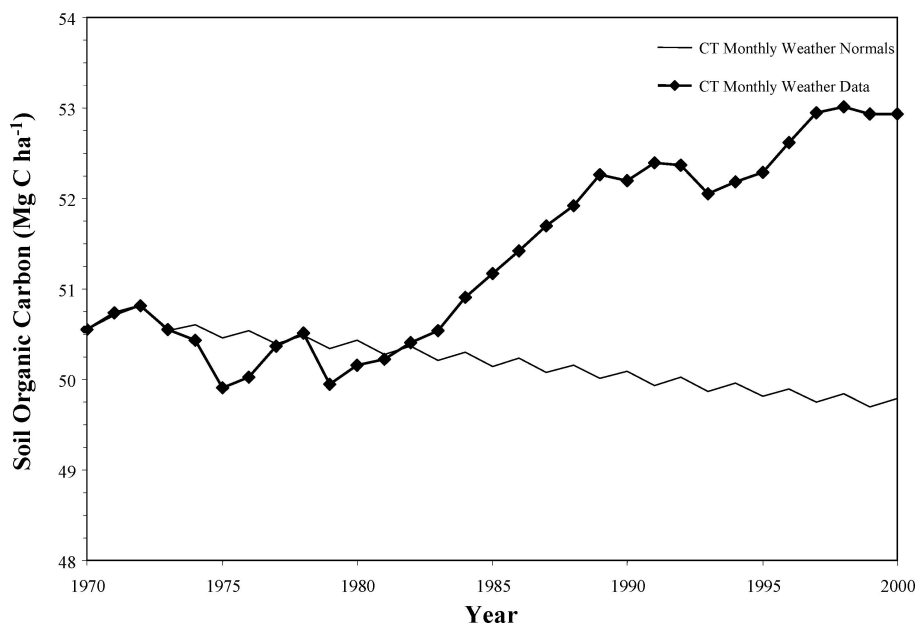


Figure 3. Climatic effects on predicted soil C change at Lethbridge, Alberta for a wheat-fallow rotation under conventional tillage (CT) for the period between 1970–1999.

yearly rainfall, but more to differences in rainfall distribution during the growing season and a slight increase in temperature. Several other simulations were carried out for the same period using actual weather data and in many cases no change in soil organic matter were predicted. These results confirm that climatic variations from year to year can influence carbon change coefficients as determined from field data. It demonstrates that over a short period, climatic variations can have almost as large an impact as management practices. We emphasize that these are model projections and that they must be interpreted with care, however, supportive field observations have been reported by Campbell et al. (2001b).

6. Summary

We reviewed the potential of agricultural soils to sequester C and presented several examples of how management practices can increase C sequestration in agricultural soils. Our results suggest that a conversion of cropland to grassland will result in the largest reduction in net GHG emissions. Many of the practices that promote carbon accumulation, such as reduced tillage, and reduced summer fallow, will also reduce erosion thereby improving soil productivity and profitability of farming systems. Increasing organic matter in soil makes soil more productive, which is likely to lead to increased crop production and C sequestration. Soil carbon accumulation will however reach a saturation point because soils eventually become less responsive to increased carbon inputs. Hence, promotion of carbon sequestration in agricultural soils will be most relevant over the next few decades. Later on, GHG mitigation efforts will need to concentrate on maintaining the sequestered carbon in the soil and on reducing N₂O emissions. Permanence of the sequestered C is, therefore, an important criterion to consider when we examine the net impact of management practices on C sequestration. Soil C in the surface layer can be quickly lost to the atmosphere by discontinuing some practices like conservation tillage or by increasing practices such as summer fallowing. This means that it is difficult to guarantee that sequestered carbon will never return to the atmosphere. Further, because C increases in soil are directly related to the amount of C inputs to the soil, and the latter is dependent on weather conditions, then the amount of C sequestered over time is very much a function of climatic conditions. We resisted the temptation of multiplying the amount of C sequestered for various management practices by the percent of arable land where this practice is employed to come up with the world carbon mitigation potential, because of the wide range of response of management practices to soil and climatic conditions. We also demonstrated that reducing N₂O emissions is also extremely important because the global warming potential of N₂O is about 300 times greater than that of CO₂ and it provides an indefinite mitigation potential as compared to the C sequestration option where the mitigation potential is finite. In this paper we have not accounted for the absorption of methane, which is also an important GHG.

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CLIMATE, COMMUNICATIONS, AND INNOVATIVE TECHNOLOGIES: POTENTIAL IMPACTS AND SUSTAINABILITY OF NEW RADIO AND INTERNET LINKAGES IN RURAL AFRICAN COMMUNITIES*

MOHAMMED BOULAHYA¹, MACOL STEWART CERDA², MARION PRATT³ and
KELLY SPONBERG⁴

¹*African Center for Meteorological Applications for Development, Niamey, Niger*

²*Institute of International Education, Funding Provided by the U.S. Agency for International
Development (USAID)*

³*University of Wisconsin-Madison, and Social Science Advisor, USAID*

⁴*Climate Information Project, U.S. National Oceanic and Atmospheric Administration (NOAA)
Office of Global Programs
E-mail: kelly.sponberg@noaa.gov*

*Just tell me where it has rained.
I will know where to take my flocks.*

–Nomad near Hirir, Algeria, February 1988

1. Introduction

Communicating drought information to remote rural populations is a major challenge for drought monitoring and prediction in Africa. Seasonal rainfall forecasts, precipitation and stream flow monitoring products, key environmental information, and even life-saving early warnings are commonly trapped in the information bottle-neck of Africa's capital cities. Without access to reliable communication networks, the majority of Africa's farmers and herders are cut off from the scientific and technological advances that support agricultural decision-making in other parts of the world.

Inspired by the potential that drought monitoring and prediction technologies hold for improving the quality of life in rural Africa, the African Centre of Meteorological Applications for Development (ACMAD) worked with herders and farmers to design the RANET system. RANET is an information and communications support network based on the needs of remote communities and the realities of rural

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living in Africa. The RANET system, named for its innovative linkage of radio and Internet, brings new communications and information technologies together with the oral traditions of Africa to deliver scientific drought information over a distributed network owned and managed by local communities.

RANET combines data from global climate data banks in the U.S., seasonal rainfall predictions from the international scientific community, data and forecasts generated in Africa, along with food security and agricultural information, to disseminate a comprehensive information package via a network of digital satellite, receiving stations, computers, radio, and oral intermediaries. Prior to RANET, this information was rarely available outside of capital cities, and much of it never traveled far beyond the research centers where it originated.

RANET was met with enthusiasm when it was initiated in Niger in 2000 and in Uganda in 2001. Hailed as a technology that has finally caught up with the needs of rural populations, RANET is already demonstrating positive impacts on agricultural production and vulnerability reduction. RANET, however, has come to be more than a drought monitoring and early warning system. Involvement of rural populations in local RANET implementation has motivated community members to become part of the communication system, unleashing their creativity and capacity to address a variety of local needs. Early indications show that the program's positive effects on sectors such as rural health and civil society have caught the attention of the international development community.

As the RANET system is replicated in other African countries and as potential expansion to Asia and the Pacific is considered, it is important to explore the advantages and limitations of RANET as a technology and as a communications framework. Experiences with RANET in Niger and Uganda reveal the system's successes and challenges in two very different African contexts, highlighting key issues for communicating drought monitoring and prediction information within the RANET context and beyond.

2. A Communications Network is Born in the Desert

The need for a drought communications system tailored to the realities of rural Africa was initially articulated to the RANET implementing partners by a nomad in the desert of southeastern Algeria as he declined the gift of a radio offered by a young meteorologist researching desert locusts near Djanet. The nomad maintained that information was vital to his survival. "Just tell me where it has rained. I will know where to take my flocks." He explained that he knew every rise and fall of the terrain, and would lead his flocks to the lowest point to meet the water as it moved through the landscape in seasonal streams. After drinking, they would make their way uphill to meet the new grass where it grew. But as much as the nomad needed information, a radio in the Sahara becomes little more than a burden once its batteries lose power.

It was not until 10 years later, as the Director of the African Centre of Meteorological Applications for Development (ACMAD), that the meteorologist discovered the Freeplay wind-up radio. Subsequently modified to incorporate a solar panel and other improvements suggested by rural listeners, the Freeplay radio was to become the front line of the RANET communications interface for remote communities.

Continuing the trend of community-driven innovation, the women of the dusty village of Bankilare in western Niger, delighted with the concept of wind-up radios, further challenged ACMAD to modify the technology so that they could create information as well as receive it. ACMAD came back with the Wantok solar-powered FM radio transmitter. So compact that it ships in a 28-kg suitcase, this low-cost and fully portable FM radio equipment proved strikingly durable in the harsh, dry conditions of the pilot site in Bankilare. Residents described the community radio station as having transformed Bankilare into an information oasis. Once the town had been like a well that compelled them to come to its center to draw the information they required. But the radio brought information to them where they needed it in their homes, in neighboring hamlets, and in the pastures with their flocks.

The addition of WorldSpace digital satellite radio provided a vital link with the outside world, permitting access not only to drought information, but also to a host of other information relevant to development. Unlike familiar satellite dishes, the WorldSpace digital satellite radio receiver is comparable in size to a standard radio and its small antenna can be easily held in one hand. The WorldSpace satellite broadcasts over 100 channels of clear digital radio signals across the whole of Africa. Voice transmissions can be rebroadcast directly over community-owned FM radio or interpreted by community radio animators and incorporated into locally produced programming. Because the WorldSpace system is digital, it can broadcast data files as well as voice transmissions. When attached to the WorldSpace receiver with a special “modem,” known as an adapter card, a common 486 PC saves the transmissions for display in a format that looks like a web page – a format ideal for transmitting drought and environmental information, so much of which is graphical.

3. The RANET System

RANET depends on four critical steps to move information from capital cities to rural communities: information gathering and integration, satellite transmission, reception and interpretation, and dissemination (see Figure 1). First, scientists at the U.S. National Oceanic and Atmospheric Administration (NOAA), the African Center of Meteorological Applications for Development (ACMAD), National Meteorological Services (NMSs) in Africa, and RANET partners gather vital climate, weather, and food security information and integrate it into a satellite compatible presentation. Control of drought monitoring and prediction information broadcast over the RANET system is distributed among the network of scientific organizations

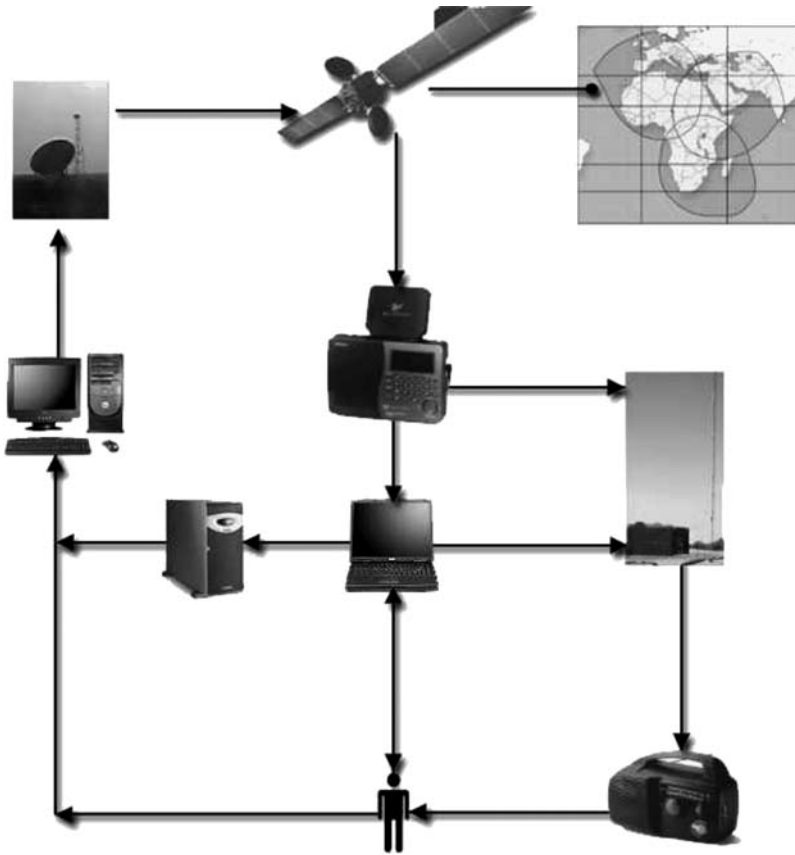


Figure 1. The four critical steps of RANET: information gathering and integration, satellite transmission, reception and interpretation, and dissemination.

contributing content. Input of multimedia climate and weather information originating from the U.S., Europe, and Africa is managed and maintained by the Climate Information Project at NOAA's Office of Global Programs, in cooperation with the World Space Foundation.

Management of national-level content is the responsibility of each country's NMS, which may, in turn, be working with other government offices or non-governmental organizations (NGOs) to develop national RANET content. The program as a whole is managed by ACMAD staff and faculty at the University of Oklahoma. The distributed nature of input to the RANET system supports a strong sense of ownership and responsibility among partnering institutions. The success of this distributed network, however, was founded on extensive training, ongoing technical support, and close communication among participants.

In the second step on RANET's communication pathway, information processed by this network of scientists is loaded to the WorldSpace digital radio satellite over the Internet. NOAA's Climate Information Project has automated satellite

uploading of RANET information to streamline participation by NMSs and other RANET partners. A partner with even the most basic computing and communications capabilities can e-mail its RANET contribution in text format to an external loading site where updates will be automatically collected and posted to the satellite. Partners with more sophisticated computing capabilities post a variety of advanced RANET products to ftp sites on their own servers which are automatically queried for updates on an hourly basis. RANET information compiled from all partners is delivered over the Internet to the WorldSpace uplink station in South Africa. At the top of every hour the uplink station sends updated RANET information to the WorldSpace digital radio satellite for broadcast over all of Africa.

Next, field sites download RANET information using a WorldSpace digital radio receiver, adapter card and PC, frequently powered by solar energy. Staff at RANET field sites, often extension agents, development practitioners, or trained members of the community, interpret RANET information according to the local context and translate it into the languages of the surrounding area. Like the network of scientists supplying RANET content, the local RANET interface requires training, technical support, and coordination. Without adequate training in interpreting and communicating climate and drought information, much of what RANET has to offer on the local level might be wasted, and could, under some circumstances, be counterproductive. ACMAD, for example, has provided training for sites receiving multimedia information in Niger, and the Department of Meteorology trained field personnel in Uganda. Ongoing technical support and follow-up training will continue to be important as these programs mature.

In the final step on RANET's information bridge from capital cities to rural areas, localized information is disseminated to communities by word of mouth and FM radio broadcasts (solar-powered in the case of remote sites) that are received by traditional radio receivers and Freeplay wind-up/solar-powered radios. According to local priorities, communities across Niger and Uganda have devised different methods of distributing Freeplay wind-up/solar-powered radios provided by the project – donating radios to the most vulnerable families (in particular female-headed households), providing radios to those most able to further disseminate information, awarding radios as prizes in a neighborhood hygiene competition, or selling radios to support activities of the local RANET project. Depending on local needs and capabilities, some communities have expanded this basic information system to include other technologies. Communities in Niger, for example, are developing RANET sites into Community Centers of Integrated Information for Development, or CIDs, that include technologies such as satellite television and two-way radio.

To complete the communication loop and to ensure that system evolution continues to be driven by the needs of rural communities, RANET partners are pursuing a number of strategies for collecting feedback. Some project sites have organized formal feedback systems such as weekly discussion groups or regularly scheduled

feedback visits to nearby communities, while other sites rely on input from radio councils or visiting community members who frequent radio stations in Niger and project sites in Uganda to communicate their opinions, support, and requests for clarification or modifications. Most feedback is generated through training workshops, site visits, and other person-to-person contact, and subsequently communicated among RANET partners via e-mail and web discussion groups. Two-way technologies such as VITA satellite-enabled e-mail and other portable ground stations are being explored as possible avenues for facilitating communication between rural RANET sites, their NMSs, and the broader RANET system.

Local ownership of the RANET interfaces puts control and responsibility in the hands of participating communities, mobilizing them to become part of the information system rather than passive recipients of information. One community in Niger, for example, requested 25 rain gauges to monitor local precipitation. On the national level, RANET triggered new broadcasting legislation in Niger as well as the creation of a national commission for radio broadcasting. As a further step in decentralization, local ownership strengthens the system as a whole, but ties success or failure at any site to the will and capacity of the community to vigilantly maintain and equitably manage the system for the benefit of local stakeholders. The experience at Bankilare's pilot site, for example, illustrates the importance of local training and support for developing the human infrastructure to manage and maintain a local RANET interface.

Before the first radio was installed in Bankilare, the community, with the help of ACMAD, formed a local radio association to guide community input, lead program development, and ensure that the radio station would serve the needs of different interests within the local population. Early attention to the balance of gender and ethnic groups and the involvement of youth in Bankilare shaped the evolution of the local station and set a standard that would influence development of the communication system as it spread across Niger. ACMAD built a coalition of partners to train Bankilare's residents as radio technicians and animators and to aid the radio association in obtaining licensing agreements, broadcast permits, duty waivers, and funding.

Thanks to funding from the U.S. Agency for International Development's Office of Foreign Disaster Assistance (OFDA), Bankilare's dream of becoming an information oasis in the desert was developed and shared with other communities that lack telephones, electricity, and paved roads. Such programs support OFDA's mandate of saving lives and relieving suffering by helping vulnerable populations in both rural and urban settings anticipate, plan for, and mitigate the negative impacts of natural disasters. As news of RANET's success spread across Niger, more communities sought participation in the communications system, attracting a heterogeneous constellation of donors and NGOs with mandates reaching beyond humanitarian assistance. These new partnerships have unleashed a powerful force for integrated, community-driven development, however, they increasingly demand more attention to coordination.

This complex and innovative human network supports the management, maintenance, and implementation of RANET at each step in the system. Though RANET would not be possible without technology, the system for transporting and transforming information from computer, to satellite, to receiver, to radio, to knowledge employed to improve dryland management, it is as much a human as a technological system. Together, the human and technical elements of RANET have created a new set of possibilities for improving drought preparedness and the quality of life in rural communities.

4. RANET Information in Action

Rural communities in Niger and Uganda have begun to use the RANET system to improve dryland management, increase agricultural production, enhanced food security, and reduce vulnerability to natural disasters. The greatest benefits are realized in field sites where both the community FM radio and satellite multimedia link are functioning smoothly together, the multimedia link supplying timely drought monitoring and prediction information and FM radio supporting broad dissemination to food-insecure and disaster-prone communities. Together, RANET multimedia and FM community radio permit rural populations to blend local knowledge and new information according to their needs. However, even in sites where only community radio or multimedia services were established, the communication system has still resulted in vulnerability reductions for rural populations. Some of these benefits were the direct result of access to drought monitoring and prediction information, while others are the fruit of unanticipated positive effects in related areas such as public health, women's empowerment, and democratization.

The RANET system in Uganda, for example, depends primarily on digital multimedia transmissions of drought monitoring and prediction products, without the advantage of a community radio component. Encouraged by the first season of largely accurate forecasts delivered over the multimedia system, farmers in two of three Ugandan field sites visited by a USAID assessment team in February of 2002 expect to reduce seed losses through timely planting and to improve production and food security through use of optimal crops and crop varieties. In seasons when insufficient rainfall is forecast, they expect to conserve seeds and fertilizer. The positive reception of climate and weather information disseminated over the multimedia system in Uganda is part of a wider orientation away from the riskier traditional forecasting methods of "rainmakers," towards a more scientific approach to agricultural production, especially among model entrepreneurial smallholders. The availability of both traditional and scientific information allows farmers to make more informed choices in their efforts to increase production.

Together the Uganda Department of Meteorology and the NGO World Vision have worked with farmers at RANET field sites to explain the information disseminated over the RANET system and develop local applications. Asserting that

"nature is not definite," farmers generally seemed to understand the concept of risk and probability in predicting the weather, as well as the possibility that forecasts are sometimes wrong. They expressed the sentiment that because "the world is becoming scientific," as are their seeds and fertilizers, they would also like scientific information about the rain. However, some farmers admitted that despite the enthusiastic reception that the RANET multimedia system has received, they could become discouraged if future forecasts are not accurate. The close working relationship between the Uganda Department of Meteorology, World Vision, and rural communities is a promising foundation for ongoing applications of RANET information; however, without the addition of community FM radio, RANET's impacts in these project sites remains limited to the number of people that can be reached by word of mouth.

Radio is one of the most pervasive technologies in Africa. Its inclusion in the RANET system helps to maximize the number of people exposed to drought monitoring and predictions while building upon existing communications capabilities. Community-initiated FM broadcasts also promote a range of unanticipated vulnerability reduction measures. In recent pilot projects in Niger, for example, the improvements in local communication made possible by community radio stations improved dryland management and reduced resource pressures. Herders, for example, commonly confined their flocks to an area within two to three days walk from their home village due to security concerns in outlying rural areas. With the advent of community radio, herders picked up news from home on the first two to three days of their walk and could comfortably continue for another two to three days, knowing that they were still within only a few days walk of a report on local security. Community FM radio effectively doubled their range, significantly decreasing pressure on the fragile dryland ecosystem.

Evidence of reductions in disaster vulnerability made possible by community radio abound in Niger. For example, community broadcasters have helped fellow villagers to protect their families by disseminating warnings of brush fires during the dry season and instructions on how to prevent houses from collapsing during the rainy season. Radio advertisement of missing livestock has supported local food security by significantly reducing livestock theft in many villages. Broadcasts of market price information have helped families to economize household expenditures and maximize profits from goods sold. The opportunity to transmit announcements of births, deaths, weddings, and illnesses over the radio has led to significant savings in family travel costs, boosting disposable family income.

Public health applications range from identifying cases of serious illnesses for local health authorities to disseminating announcements concerning HIV/AIDS, nutrition, hygiene, the dangers of early marriage, the value of prenatal care, and the timing of vaccination campaigns. The village of Zinder near Niger's southern boarder arrested the spread of measles by encouraging residents to forego traditional courtesy visits to the sick during the epidemic in favor of wishing them well over the

radio. Zinder has also employed its FM station to diffuse tensions between farmers and herders when drought heightens competition over resources.

RANET community FM radio has also had a visible impact on the empowerment of women and youth. Women, the young, and the elderly are critical to disaster prevention, both as vulnerable populations and as sources of knowledge and capacity for preparedness and recovery. Ardent listeners of community radio, women have expressed enthusiasm for the technology and influenced the production of a wide range of programming addressing their needs and interests. Thanks to the inclusion of women's involvement among the initial goals of RANET in Niger, 50% or more of the animators at community FM stations are women, and women are strongly represented among technicians, animators, station administration, and local radio councils. Youth are heavily involved in the operation of stations in Niger as animators, journalists, volunteers and listeners. Youth radio clubs have sprung up in many villages and the stations have become popular places for young people to gather to share ideas and socialize.

The active role of women and youth in developing Niger's local radio stations has shaped the system to reflect their concerns, goals, and aspirations, raising their status in the eyes of their communities and shifting preconceptions about what is possible. On a community level, rural radio stations have enabled people in isolated areas to better communicate with one another, bringing villagers together and giving them a sense of connectedness and a voice that they did not have before. Communication has changed the way that communities understand themselves and their neighbors. Becoming a part of the communication system has unleashed the creativity and capacity of local communities across Niger and Uganda to address a variety of local development needs. In Niger and Uganda, RANET has proved to be much more than a drought early warning system.

5. Challenges and Sustainability

Challenge is as much a part of the RANET story as success. Broadly disseminating drought monitoring and prediction information to remote project sites with minimal access to support continues to present challenges in both Niger and Uganda. The main issues are maintaining equipment in working order and distributing information to a wider audience through already existing national or regional broadcasts or, where those cannot reach, via additional community radio stations or relay antennas. RANET's powerful radio-internet communication system risks breaking down at two critical junctures: the computer-enabled multimedia link with the outside world (the main challenge for Niger) and the dissemination of climate information by word of mouth and radio (the main challenge for Uganda).

In Niger, RANET's efficiency is hindered by the difficulty of installing and maintaining computer systems in hot, dusty conditions that lie beyond the reach of regular technical support. Technical problems frequently reported include insufficient

knowledge to hook up parts of the solar power systems, inadequate battery storage, power surges that burned up computers, and sudden losses of power that unexpectedly shut down the computers, necessitating reinstallation of the WorldSpace software. Conditions in remote field sites are so damaging to equipment that even the most durable items require regularly scheduled maintenance. Minor malfunctions in FM station equipment such as tape recorders, microphones and lights, frustrate station personnel and hamper efficiency. More serious breakdowns such as loss of batteries or transmitter blowouts can severely limit transmission range or shut a station down altogether. Curtailed transmission range not only limits RANET's efficiency, it also jeopardizes the viability of stations that depend on memberships and paid advertisements.

Although RANET field sites in Uganda have had much more success installing rural computer systems and maintaining multimedia capabilities, technical hurdles are not unique to Niger. Solar power proved to be the weakest link in the multimedia system in Uganda. At times, 20 to 30% of the multimedia field sites in Uganda were not operational due to complications resulting from power fluctuations. Transmission at some sites was temporarily suspended because field personnel lacked the knowledge to reinstall the WorldSpace software after a power shock. Other sights suffered from serious malfunction or damage due to improper installation of the solar and computer equipment such as hooking up batteries in series rather than in parallel.

Reaching a broad user base remains RANET Uganda's biggest challenge. Dissemination relies primarily on printouts of multimedia downloads (limited by a lack of funding for stationery supplies and by the large draws on solar power sources) and word of mouth through dissemination workshops and supporting community networks. In a country where community radio stations are not common, private FM stations and the government radio station represent a potential resource for addressing what has become a rural information bottleneck at the village level. Existing radio infrastructure however, has its own drawbacks. Few people listen to the government station when private FM stations are available, and private stations have such a strong commercial orientation that they expect to be paid to air public service announcements. RANET Uganda is seeking to build relationships with commercial and government producers, and will explore the possibility of establishing community radio stations at sites that cannot be effectively served by national or private FM radio.

Technical solutions, such as new software that will not require reinstallation after power outages, are being developed to address specific technical problems. Other areas of technical improvement include reconfiguration of solar power systems, installation of relay antennas for augmenting the reach radio programming, and strengthening the vital digital information link with the outside world by introducing voice transmission of drought information over the WorldSpace satellite system. The most pressing technical issue, however, continues to be the need for ongoing training and technical support.

Consistent technical assistance to field site personnel is essential during the first 2 years of operation. In remote sites, visits by technical staff and implementing partners are normally the only opportunity for community members to ask technical questions or hand over broken equipment for repair. Ideally, technical support should be provided in conjunction with opportunities for additional training on subjects such as WorldSpace and FM radio technology, station repairs, solar power, journalism, and station management. Follow-up training opportunities allow participants to learn from each other's experiences, build upon the basic knowledge gained in initial training sessions, and solve problems that arise during program implementation, including revenue generation and long-term financial viability. Unfortunately, budgetary constraints often curtail technical support and follow-up training.

Co-locating RANET sites in conjunction with pre-existing development projects has helped to provide crucial training, technical support, and institutional support. Regularly scheduled field visits by NGO staff, for example, provided opportunities to transport technical experts, broken equipment, and field sight requests between remote areas and the capital city. Integrated development projects have played important intermediary roles, interpreting information delivered via the radio-internet system and applying it within the local development context. As implementing partners, development projects can often provide the use of computers and other equipment which are maintained as a part on ongoing project activities. The institutional support of an integrated development project can also be invaluable for establishing baseline survey data and tracking results, and the development orientation of such a partner can lead the project to support the local community in new and innovative ways.

However, as the web of supporting partners becomes more complex, so too does the problem of coordination. Overextension can also undermine sustainability. In the rush to expand the benefits of RANET to communities that are hungry for communication, it is easily forgotten that a few well-supported field sites are far preferable many that languish without assistance for months at a time, often in extremely remote locations with malfunctioning equipment and few resources.

6. Conclusion

New radio and internet technologies are bringing drought and development information to rural Africa through the RANET communication network. The key to RANET's early successes lies in its dual nature as both a technological and a human communications system. Its human and technical elements depend one upon the other for their combined strength, but at the same time they expose the system to potential pitfalls. RANET is, at base a network of people supplying, interpreting, and utilizing drought and development information. Technology exponentially increases the ability of this human network to work together to achieve results that

were previously inconceivable. The Internet, digital satellite technology, wind-up mechanics, solar energy, and computing power have created new possibilities for rural communication. Yet the tremendous power of RANET's technology is completely dependent on the human system that manages and maintains the RANET's infrastructure and supplies, interprets, and utilizes RANET information.

RANET's main strengths and weaknesses are wrapped up in this way. Distributed control of the system at both national and local levels creates an empowering sense of ownership and responsibility. Decentralization permits the system to be readily adapted according to each country's and community's needs and capabilities, but it also leads to uneven results. The multiplicity of RANET partners bring a wealth of expertise and depth of support to the system, but the increasing coordination burden may result in diminishing returns, and spreading responsibility among too many organizations blurs accountability. The rapid spread of the system across and among countries is a testament to RANET's ability to serve rural populations; however, rapid and uncontrolled replication can lead to dangerous overextension.

In the end, the strength of RANET's model for communication of drought monitoring and prediction information lies in its diversity and flexibility. As an open system that invites rural populations to participate, it offers tremendous returns to those who are willing to invest their energy and imagination, and, who, like the desert nomad and the women of Bankilare, challenge the limits of technology and dare to dream.

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ROLE OF EDUCATION AND TRAINING IN AGRICULTURAL METEOROLOGY TO REDUCE VULNERABILITY TO CLIMATE VARIABILITY

SUE WALKER

*Department of Soil, Crop and Climate Sciences, University of the Free State,
P.O. Box 339, Bloemfontein 9300, South Africa
E-mail: walkers.sci@mail.uovs.ac.za*

Abstract. Agricultural meteorologists are concerned with many operational aspects of the effects of climate on crop production, livestock, and natural resource management. For them to continue to make a contribution to the economy of a country they must continually sharpen their skills and remain updated on the latest available information. Training should include a variety of skills, including transferable skills (e.g. communication, numeracy), professional skills (including cognitive skills) and information technology skills. Problem-based learning can be used to promote critical thinking, decision making and analytical skills. More use should be made of computer-aided learning for agricultural meteorologists' in-service training. In particular, the Internet or CDs could be used to disseminate specific recently developed techniques and applications to improve the understanding of the variability in climate and its effect on agricultural production and natural resource management. Examples that can address the vulnerability of farmers include crop–climate matching, the use of indices, crop modelling and risk assessment together with seasonal outlooks. A strategy needs to be formulated to address these needs and implement changes in the education and training of agricultural meteorologists. These training needs must be constantly updated to meet the changing demands of new technology to cope with climate change and climate variability.

1. Introduction

Agricultural meteorology is an applied science that brings together the effects of the climate and weather on the production of crops, livestock and forests. Our lives are closely affected by daily and annual variability in climate. The agricultural community is no exception. Farmers are affected by the extremes in climate and its variability that often lead to wide interannual fluctuations in yields and productivity. In many parts of the world climatic variability is large, creating potentially severe problems for farm managers to solve. If the agricultural meteorologists are to help the farmer, they need to remain up-to-date on advancing knowledge of forecasting, climatic change, and the tools being developed to address these issues. But, most importantly, they must find ways to adapt local farming systems in a practical manner to predicted near-term forecastable events and to long-term climatic change.

For this to happen agricultural meteorologists must receive in-service training and be able to attend short courses to sharpen their skills and learn new techniques. A common basis for success is competence in numeracy, communication and general

computer skills and these skills should be strengthened where necessary. However, agricultural meteorologists also need many specific scientific skills in highly specialised areas of meteorology, climate analysis, and the agricultural sciences and these too must be provided.

2. Basic Education

Advances in the fields of weather analysis and prediction, and climate change and climate variability have been rapid. Thus, it is necessary that agricultural meteorologists have full understanding of the scientific background relating to these areas in order to effectively service the agricultural community. This means that agricultural meteorologists themselves need to attend frequent update sessions where they are continually challenged to refresh their understanding and skills based on the latest knowledge.

As long as agricultural meteorologists have a firm science background, they will be able to maintain a current state of awareness in developments related to impacts, adaptation, vulnerability, and mitigation resulting from trends in climate change and climate variability. The undergraduate education of agricultural meteorologists needs to be diverse and broad so as to ensure that they have a firm scientific and technical base on which to build for the future. In their undergraduate studies, students need to prepare for professional careers that focus on advances in operational agrometeorological services and developing new, innovative techniques for improving services to their local communities. Furthermore, students must be equipped to keep abreast of possible future developments in the science of agricultural meteorology, including rapid changes in climate that may alter land-use planning or force significant changes in agricultural practices.

Training requirements should not only focus on those who have received formal degrees in agricultural meteorology but also on those now working in the field who were trained in related disciplines. Meteorology is based on sound physical, mathematical, biological and statistical principles (Lomas et al., 2000). If any of this background is lacking, then those from other disciplines may be in need of special training to catch-up and understand the science at a more advanced level. Training tools should be developed for use at the secondary school, technical, undergraduate, and graduate levels.

Another matter that should receive attention is the best ways to convey agrometeorological information to the lay groups that have a vested interest in the interpretation of climate science and its application to their specific needs. In order to promote the use of climatic data in agricultural applications, agricultural meteorologists should have a wide range of knowledge and experience of the kind that makes them respected in their users communities. This will enable them to interpret complicated scientific issues for their clients, few of whom will have a science background. In many countries successful efforts of this kind can bring much goodwill

among communities of farmers/pastoralists/foresters and strengthen support for the continuation of local and national weather services.

The aim of this paper is to address some of the options available to educators in preparing agricultural meteorologists to address climate variability and change and their possible impacts on agricultural production systems. The first part of the paper will focus on the basic professional skills essential for agricultural meteorology training. The second part will address how these skills relate to the application of agriculture as a sensitive indicator to climate change and climate variability.

3. Skills Training

The ultimate goal of the agricultural meteorologist is to make a positive impact, in the face of the variability of weather and climate, on the livelihood of the agricultural community. To accomplish this they need basic skills and more refined professional skills to deliver the correct message in a timely and appropriate manner. There are several different types of skills that should be included in continuing education programmes for agricultural meteorologists. These include the basic skills of communication and numeracy, professional skills (including cognitive skills) and information technology skills (e.g. retrieval and analysis of weather datasets). If agricultural meteorologists are to succeed in their jobs and remain abreast of current developments, then all of these skills are necessary.

The training of agricultural meteorologists must address information gathering skills, as this will enable them to retrieve the latest information from various sources and include evaluating the sources and interpretation of the data (Gibbs, undated). These skills should include traditional library as well as networking skills and the ability to use contemporary technology. However, it is essential, with the availability of modern electronic technology, that agricultural meteorologists have computer skills at a level sufficient to allow them to search the Internet and download relevant information and data. At a minimum, basic computer literacy, spreadsheet and word processing skills are essential. In addition, they should also develop the necessary ability to “surf the web” and be able to discern the difference between information that is scientifically sound and correct and that which is poorly grounded. At least some agricultural meteorologist should acquire skills in Geographic Information Systems (GIS), statistical packages and international databases. Finally, but very importantly, once the agricultural meteorologist has acquired the appropriate information or data, they must know how to transform it into forms or products useful to the end user.

4. Agriculture as a Sensitive Indicator to Climate Change and Climate Variability

The agricultural sector is probably the most sensitive indicator of changes in general climatic conditions and in climatic variability. Agriculture can be particularly

sensitive to climate anomalies. For example, crops typically grown under certain agroclimatic conditions may face large increases in yield variability due to weather extremes during the growing season. Persistent extremes, such as drought, excessively hot summers, and excessively cold winters may alter the growing season, cause soil erosion, and land degradation. Other factors such as crop diseases and crop pests may be influenced by variable climatic conditions in a specific growing area.

The two primary portions of the training program for an agricultural meteorologist focus on operational services and developing new techniques to support these services for farmers, extension service personnel, and the agricultural community, in general. However, an essential training component must also be devoted to the current awareness of agriculture's keen sensitivity to climate change and climate vulnerability. Further, given the vulnerability to agricultural losses that occur in many local communities caused by weather extremes, it is essential that agricultural meteorologists take a proactive role in understanding local adaptation and mitigation measures that farmers may apply to reduce the negative impact of weather and climate extremes on their farm productivity.

The type of professional skills needed to assess the vulnerability of a community to climate variability will be those of integration and simulation where different scenarios will be evaluated and contrasted in a logical manner and then explanations or causes can be related to a meaningful impact on agriculture. So, care must be taken to expose students to appropriate information and tools so they can extrapolate it to their own situations. They need to be taught to reflect on and apply theories to specific problems. If they can take the theoretical information and argue its relevance to the problem, then they may be able to deduce a logical solution or a number of options available to address the problem. One would also need to learn how to evaluate the various options available and to follow through to predict the consequences of the various options.

These skills are not usually acquired under the normal teaching approach that often focuses on memorisation, identification and description of the situations or superficial conditions (Biggs, 1999). This type of superficial learning needs to be supplemented with in-depth learning that will stimulate the adoption of the required skills. One of the methods of stimulating this learning is problem-based learning (Boud and Feletti, 1999). In a typical problem-based learning situation the student will be faced with a typical problem and then guided through the necessary steps to acquire the skills needed to solve the problem (Walker, 2002). The students need to begin to pull together isolated knowledge, skills and experience into a holistic in-depth understanding of the conditions and situation. This will enable them to develop a strategy for a structured approach to problem solving. This problem-based learning makes active use of the students' existing knowledge (Boud and Feletti, 1999) that in turn encourages the student to gain confidence and therefore be able to succeed sooner.

Although specific technical meteorological skills are needed, sometimes the general professional, information and transferable skills are in need of further

development as well. If these skills can be improved and applied to the variability of the climate in a certain area so as to address the specific needs and requirements of the clients, then agricultural meteorologists will be able to consider the problems and provide some solutions for their clients. These skills and techniques are invaluable to students in training in agricultural meteorology. The subject of climate change and climate variability is complex in itself. The impacts on agriculture are enormous. How farmers and the agricultural community respond to potential adaptation and mitigation measures to cope with variable climatic conditions will likely depend upon the ability of agricultural meteorologists to successfully communicate with their clients.

5. Computer Aided Learning (CALMet)

There is considerable expertise available throughout the world on the study of climate change and climate variability and its impact on regional agriculture communities. However, the results of scenario analyses and scientific evaluations are often not effectively communicated widely to the appropriate user community. As electronic communication technology improves, it is possible to share information, experiences, and data more efficiently with many other people around the world. Computer-aided learning provides an opportunity to use CDs or the Internet to develop self-paced modules on any topic of interest. The use of computer-aided learning in meteorology has mainly been confined to the synoptic weather patterns and daily weather predictions (Floor, 2001). As the various systems become more widely used, modules will be developed and this method of learning will be expanded into other areas including agricultural meteorology (Spangler and Fulker, 2001). This could become a highly efficient method of teaching the agricultural meteorologists many of the skills and techniques necessary to assess the impact of climate change and climate variability on agriculture. Using such computer-aided learning tools, agricultural meteorologists could study various scenarios based on unique climate and agronomic features within their regions. Using these scenario analyses, the agricultural meteorologists could then become more aware of potential future conditions. These scientific results can form the basis of advisories issued to farmers and decision-makers on adaptation and mitigation measures to reduce the vulnerability to climate variability.

6. Examples of Professional Expertise Training

To show the application of the above logic some specific examples will be given of the types of applications that could be taught to agricultural meteorologists to empower them to make a contribution to decreasing the vulnerability of the community.

6.1. CROP – CLIMATE MATCHING

Crop–climate matching can be used to select the most suitable crop for specific climatic conditions. All the aspects of the situation need to be considered including the socio-economic acceptability of the alternatives to the community (FAO, 1990). An approach that can be taken is to characterise the specific crop requirements from the perspective of the climate (Doorenbos and Kasaam, 1979; Doorenbos and Pruitt, 1992). The ecotope must also be described and defined in similar terms (Sys et al., 1991) so as to determine the potential of the environment for crop production. It is important at this stage to identify the limitations of both the cropping systems and the environmental conditions and also to clarify the predicted changes. The logic is then followed whereby the most limiting factor must be satisfied first and then the others can be considered. For example, in many climates the length of the growing season is a limiting factor for crop selection. A suitable crop or cultivar can be selected using the length of the frost-free season. With changes in the growing season due to climate variability, or trends over decades, it may be necessary to alter cropping patterns, crop types, and crop cycles to adjust to the climate extremes.

6.2. USE OF INDICES AND CROP MODELS

In operational agricultural meteorology much use has been made of climate based indices to assess and integrate the effect of the environment. Many indices have been developed from an empirical perspective and do not really represent the cause and effect relationships. Under these circumstances they will inevitably fail under some conditions so that the boundary conditions should be carefully defined (Rosenberg et al., 1983). Among the most common is the use of thermal time calculations for prediction of flowering and maturity dates of crops (McMaster and Wilhelm, 1997). Such an index can be used with the long-term climate data to make recommendations for cultivar choice and select planting dates. However, it is difficult to include climate variability into such calculations and still make it easily understood at the farmers' level. This can be addressed by the use of deterministic crop models together with the long-term data to provide improved cropping recommendations (Singels and de Jager, 1991).

6.3. RISK ASSESSMENT AND SEASONAL OUTLOOKS

Risk can be defined in various ways and should be considered from the communities' perspective using the available long-term weather data. Communities face different circumstances and have different historical experiences so they can be classified as risk averse or risk susceptible (Anderson and Dillon, 1992). The climate data can be used together with modelling techniques to develop cumulative

distribution curves of probabilities for obtaining a certain yield under certain conditions (Muchow et al., 1991). These curves have been used to advise farmers on selection of cropping systems or choice of crops or tillage practices or the management of natural resources. As seasonal outlooks improve (Mason et al., 1996), and become more readily available, they can make a contribution to reducing the vulnerability of the communities to extreme weather events (Walker et al., 2001). If these probabilities can be used in conjunction with seasonal outlooks (Hammer and Nichols, 1996), then it is possible to take into consideration some degree of climate variability in a specific place and to make a recommendation to the producers in that area.

7. Conclusions

There should be no question that education and training must be used to empower and equip the agricultural meteorologist to address the issue of climate change and climate variability and their effects on agricultural communities around the world. At the present time there is a large gap between the state of the art in the world as a whole and the information and knowledge that is available and used at an operational level, particularly in developing countries. Strategies need to be developed to formulate plans of action to rectify this serious lack of adequate proactive planning. One of the most promising methods to address this need would be to introduce a problem-based curriculum into the formal education system for both undergraduate and graduate studies. The use of computer-aided learning modules made available on CD or the Internet would be a good approach to distribute the information, thereby allowing agricultural meteorologists in the work place to access the latest technologies and information. There are various methods available that can be used to classify the variability in the climate and its effect on vulnerable communities and they need to be made available to all national meteorological services. The agricultural meteorologists can then adapt the methods and utilise their own local datasets to develop recommendations for the areas that they serve.

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AGROMETEOROLOGICAL RESEARCH AND APPLICATIONS NEEDED TO PREPARE AGRICULTURE AND FORESTRY TO 21ST CENTURY CLIMATE CHANGE

VICTORINE PERARNAUD¹, BERNARD SEGUIN², ERIC MALEZIEUX³,
MICHEL DEQUE⁴ and DENIS LOUSTAU⁵

¹*Météo-France-Direction de la Production, 42 avenue Coriolis, 31057 Toulouse, Cedex, France*
E-mail: victorine.perarnaud@meteo.fr

²*Institut National de Recherche Agronomique, Unité Agroclim Site Agroparc, domaine St-Paul,
84914 Avignon, Cedex 9, France*
E-mail: seguin@avignon.inra.fr

³*Centre de Coopération Internationale en Recherche Agronomique pour le Développement,
Cirad-DS, TA 179/01, avenue Agropolis,
34398 Montpellier, Cedex 5, France*
E-mail: malezieux@cirad.fr

⁴*Météo-France- Centre National de Recherches Météorologiques, 42 avenue Coriolis,
31057 Toulouse, Cedex, France*
E-mail: michel.deque@meteo.fr

⁵*Institut National de Recherche Agronomique, Recherches Forestières,
BP 45, 33611 Gazinet, France*
E-mail: Denis.Loustau@pierreton.inra.fr

Abstract. The adaptation of agriculture and forestry to the climate of the twenty-first century supposes that research projects will be conducted cooperatively between meteorologists, agronomists, soil scientists, hydrologists, and modellers. To prepare for it, it is appropriate first of all to study the variations in the climate of the past using extensive, homogenised series of meteorological or phenological data. General circulation models constitute the basic tool in order to predict future changes in climate. They will be improved, and the regionalisation techniques used for downscaling climate predictions will also be made more efficient. Crop simulation models using input data from the general circulation models applied at the regional level ought to be the favoured tools to allow the extrapolation of the major trends on yield, consumption of water, fertilisers, pesticides, the environment and rural development. For this, they have to be validated according to the available agronomical data, particularly the available phenological series on cultivated crops. In addition, climate change would have impact on crop diseases and parasites, as well as on weeds. Very few studies have been carried out in this field. It is also necessary to quantify in a more accurate way the stocks and fluxes of carbon in large forest ecosystems, simulate their future, and assess the vulnerability of the various forest species to a change in climate. This is all the more important in that some propagate species choices must be made in the course of the next ten years in plantations which will experience changed climate. More broadly speaking, we shall have not only to try hard to research new agricultural and forestry practices which will reduce greenhouse gas emissions or promote the storage of carbon, but it will also be indispensable to prepare the adaptation of numerous rural communities for the climate change (with special reference to least developed countries in tropical areas, where malnutrition is a common threat). This can be accomplished with a series of new environmental management practices suited to the new climatic order.

1. Introduction

To prepare agriculture and forestry for the climatic change forecast for the twenty-first century, particular efforts must be made in research, based on the knowledge on climate data currently available, for the development of the most up to date applied management techniques. This development must be accompanied by efforts in agronomic research which take climatic change into account for research in plant genetic improvement and development of sustainable cropping systems to attain operational applications for adaptation strategies. It then becomes indispensable to single out two ways of adaptation depending on the final user: those which can be implemented by the farmer (for example modification of sowing dates, varietal choice or use of seasonal forecasts) and those of decision-makers (e.g. land and natural resource managers) which necessitate investment in infrastructures (particularly water resource projects). Thus, in operational terms, the results of research will have to contribute to the implementation of durable construction and management options which enable the adaptation of agrosystems and forest ecosystems to climate change. This will include identification of sensitive areas, choice of new crops, understanding mechanism of species replacement, calculation of future water needs and collection, visualisation of geographical species area and potential changes in impact of pests and diseases.

To the scientific and technical problems raised by adapting agriculture and forestry to climatic variability and change must also be added socio-economic considerations which will not be covered in this article but which will have to be borne in mind. Hence, any significant modification in local production will necessarily affect the global organisation of markets and economic and social systems. Conversely, agriculture and forestry are likely to make a significant contribution to climatic change dynamics through the emission of greenhouse gases (GHG) or, on the contrary, the storage of CO₂. The combination of these elements will be analysed in the text below, supported equally by climatic research in relation to agricultural and forestry production issues.

Our arguments will rely principally upon examples relating to France, a temperate region, but we have tried to extend their scope by broadening our considerations to semi-arid and tropical zones. In these areas, the precariousness of ecological and social systems combined with the impact of climate change is likely to have a major effect on the productivity and balance of cultivated ecosystems (reduction of biodiversity due to an increased drought, irreversible erosion of land linked to flooding). This may lead in some cases to the migration of human populations if food safety is affected. Indeed, even though the simulations show a higher elevation of temperature in polar and temperate latitudes, in relation to the tropical latitudes, tropical crops are today much closer to their thermal optimum and hence more likely to suffer from thermal excesses in the future. Insects and diseases, already very active in tropical zones, could proliferate and widen their area of influence. The combination of these factors, to which must be added the dependence of less developed

countries on agriculture and its risks stress, the fragility of economic and social conditions. This makes a number of tropical regions risk areas likely to suffer the implicit negative effects linked to climatic change (Rosenzweig and Hillel, 1978).

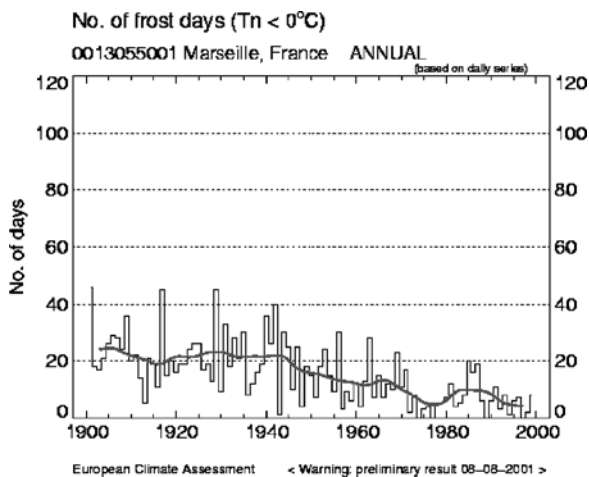
2. Improve Understanding of the Variation of the Current Climate and its Impact on Agriculture

2.1. COLLECT AND ANALYSE INFORMATION ON ECOSYSTEMS

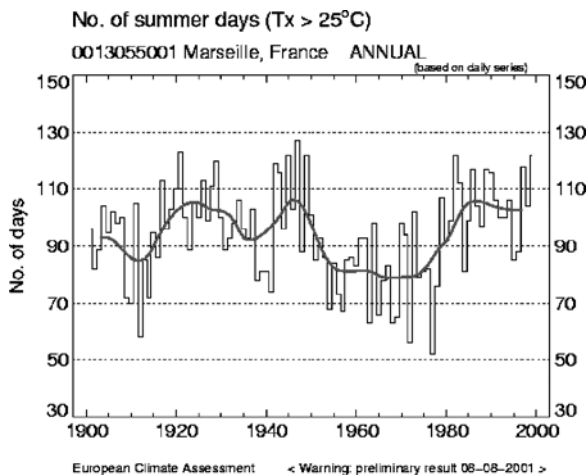
To study the impact of climate change on agriculture and forestry and improve our understanding of certain climate mechanisms, it is important to gather numerous data on ecosystems (inventories of land use per species, phenological observations or production statistics) to evaluate ecosystem trends in recent decades at the landscape scales. The remote sensing is now a valuable tool in obtaining spatialised information on areas of the planet where ground measurements are difficult. Moreover, additional spatial information is essential in establishing sensitivity to water excess or deficit, water and wind erosion, and the risks of salinization.

2.2. STUDY THE LONG CHRONOLOGICAL SERIES OF CLIMATIC AND PHENOLOGICAL DATA

The national meteorological services (NMS) must adopt an ongoing policy of research and documentation of existing historical data which enrich national climate heritage. Indeed, it is important to study the behaviour of extended series of meteorological measurements on national territories over a period which extends from the end of the nineteenth century to the present day. To detect long term trends, the raw data must be processed using statistical methods designed to constitute homogeneous chronological series, which mean isolating the climatic signal from the other signals linked to modifications of observation techniques, relocations of measurement areas, or modifications of their environment (Moisselin et al., 2001). The analysis of these so-called “homogenised” series on a particular territory would then allow us to determine the significant variations of each parameter which may be relevant for the type of crop studied on the annual, seasonal or monthly scale and highlight spatial particularities. This kind of analysis generally shows that there is no single trend observed on the national scale (Moisselin et al., 2002). This type of study is essential when, for example, one considers the behaviour of crops in response to temperature, to its cumulative or limiting effects (frost or high temperature). Figure 1 shows the annual number of days with frost and heat waves observed in the period 1901–2000 at the meteorological station in Marseille (France). The regular decline of the number of days of frost between the beginning and end of the twentieth century is quite spectacular. The increase of the number of days of heat wave is more marked over the last two decades, which



(a)



(b)

Figure 1. (a) and (b) Annual number of days with daily minimal temperature (T_n) below 0°C and daily maximal temperature (T_x) above 25°C over the period 1901–2000 at the weather station in Marseille (France).

is consistent with the results in the report made in 2001 by the Intergovernmental Panel of experts on Climate Change (IPCC) as regarding to average temperature (Houghton et al., 2001). The processing of extended series of climatic data should also allow a validation of the regional climate simulation models.

These extended data series should also to be complemented by phenological series coming either from observations of the natural vegetation or forest species, or from cultivated species and particularly for perennial ones (fruit trees or vines). The analysis of the latter is, of course, of great importance in supporting the phenological models which constitute the basic modules for crop simulation models (as we

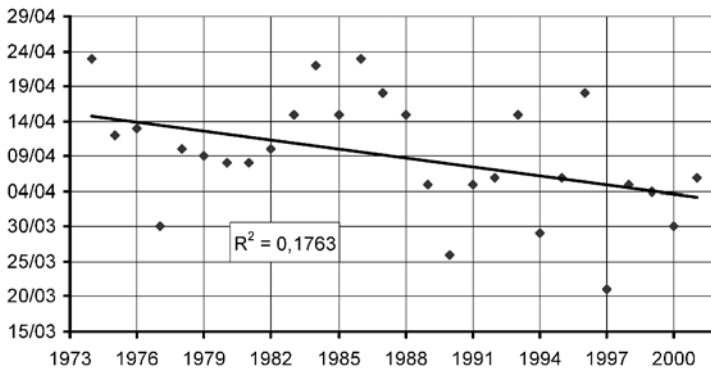


Figure 2. Flowering dates (stage F1) of the apple tree in south-east France (Balandran) over the period 1974–2001 (according to Domergue, 2001).

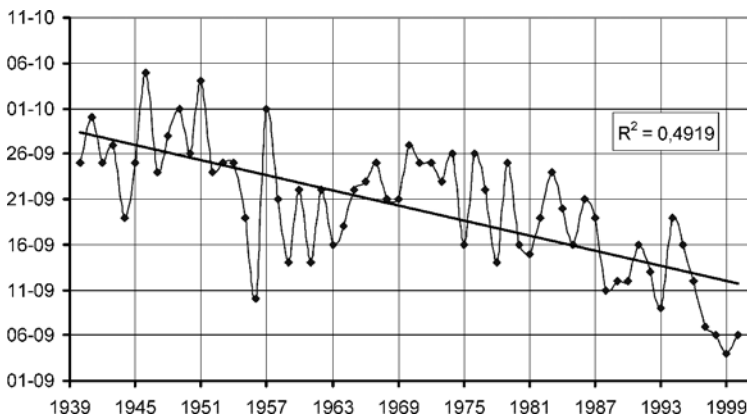


Figure 3. Dates of the beginning of the grape harvest in Chateaufeuf du Pape (South of France) (according to Ganichot, 2002).

shall discuss later). Thus, by way of an example, Figure 2 shows the evolution of the flowering dates of the apple tree in south east France (Balandran) over the period 1974–2001 (Domergue, 2001) and Figure 3 that of the grape harvest dates in Chateaufeuf du Pape in the south of France from 1940 to 2000 (Ganichot, 2002). These two examples show an evolution in the phenological precocity of the various crop stages but also large interannual variability. It is therefore appropriate to be careful in analysing these results as to the partitioning of causes between growing techniques and climate interannual variability.

3. How Well Can the Climate of the Future be Simulated?

The climate is the result of the combination of processes of natural and anthropogenic processes that interact together. The climate of the future will continue to be conditioned by global atmospheric circulation which will result from the

evolution of the radiative forcing imposed by the future atmospheric contents of greenhouse gases and aerosols. The simple extrapolation of the current trend would suppose a perpetuation of the socio-economics global trends currently observed. We now know that this is not realistic and we cannot predict the direction that these developments will take in the medium and long term. There is a large number of provisional scenarios in which respective plausibilities and probabilities are far from being confirmed, particularly because of uncertainties on the policies of some countries in terms of the reduction of emissions.

3.1. IMPROVE THE GENERAL CIRCULATION MODELS

Climate models constitute the basic tool for making projections about the future. The most advanced models describe atmospheric and oceanic circulation, surface processes, the evolution of icebergs and the cryosphere, the carbon cycle and the influence of the physico-chemical composition of the atmosphere (greenhouse gases, aerosols). They take account of the interactions between the various components in the climatic system, for example between oceans and atmosphere, and between the land, vegetation and atmosphere. The general circulation models (GCM) coupled with the ocean and ice bank can still be improved. Moreover, even though the predictions on global temperature are generally consensual, disparities exist in the behaviour of the hydrological cycle as to regional responses to the increase in atmospheric greenhouse gas content. Finally, questions remain on the response of our natural environment to global warming. For example, land use changes (particularly the natural or cultivated vegetation), the storage of carbon (particularly in the ocean and in the continental biosphere), or possible modifications in oceanic circulation would all change the response of the natural environment.

3.2. NECESSITY TO IMPROVE DOWNSCALING CLIMATE SIMULATIONS

When we consider the impact of a climatic change on agriculture and forestry, in a particular country or a continent, it is clear that we must work at a suitable spatial scale. Such a scale would generally be more detailed than the current horizontal resolution of the general circulation models (having a grid in the order of 200 km). Research on the regionalisation of climatic changes (Wilby et al., 2000) ought to be carried out, which focus on improving the techniques themselves but also on the evaluation of their impact on agriculture and the environment. Two techniques, based on the modelling, are now used to study the regionalisation of climatic impact (Gibelin and Déqué, 2001). The first consists in using nested models. We take an atmospheric model, the scope of which covers only the region being studied (Europe, for example): this model is called the regional model. Hour by hour, we impose on its boundaries the meteorological conditions calculated by a global model with a coarser resolution. This method has already been used by numerous countries (e.g.

the U.S.A., Great Britain and Germany). The methodological disadvantage comes from what happens at the boundaries of the area. There is no feedback between the global Circulation Models and the parameters (winds, temperatures, etc.) calculated by the regional model. We may therefore be led to link a depression calculated by the regional model to an anticyclone calculated by the global model. To correct this error, we can extend the boundaries far outside the area under consideration.

The second method consists of using a model with a variable grid, which allows us to zoom in on the area of interest or, to use a restricted area to curb the complementary model. The implementation of such models is now possible thanks to the power of supercomputers. This latter method seems the most promising and is used by Météo-France with the Arpège-Climate model in its stretched grid version aimed at the region under consideration (Déqué and Piedelievre, 1995). This numerical model, which arises from the operational meteorological forecasting model, covers the planet with a more detailed horizontal resolution (60 km) in France than in the South Pacific (450 km) as shown in Figure 4.

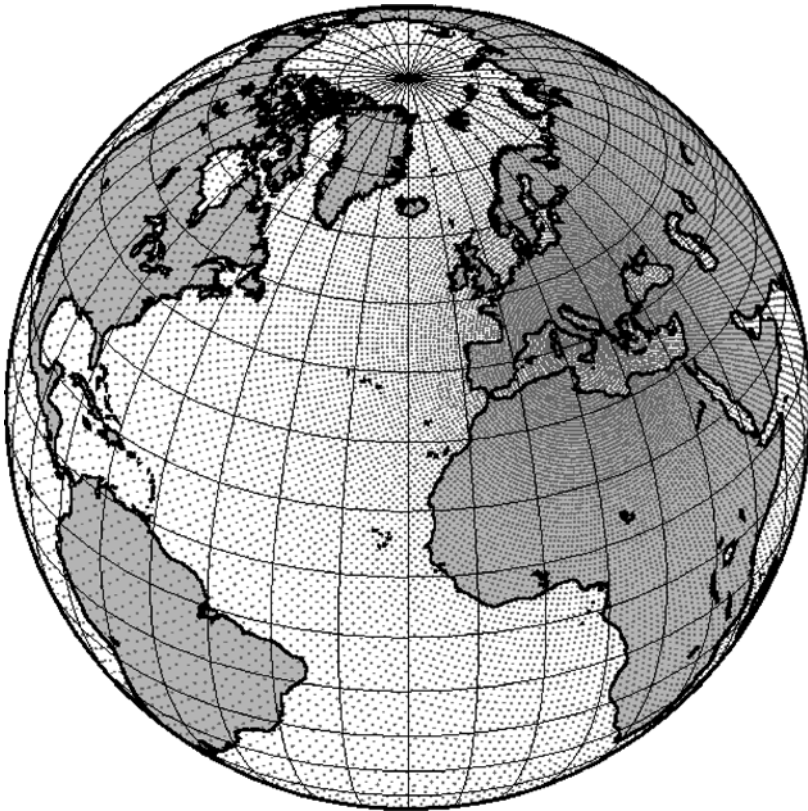


Figure 4. Horizontal grid of the Arpège-Climate model in which the focal point is placed in the Mediterranean (between Italy and Sardinia).

3.3. WHAT DO MODELS SAY ABOUT REGIONAL CLIMATE CHANGE?

There is no doubt about a warming impact, in global mean, in response to the expected anthropogenic change. The uncertainty is about the amplitude of the warming and its geographical distribution. IPCC (2001) provides an interval between 1K and 5K for the end of the 21st century. The primary source of uncertainty is the anthropogenic input. Several scenarios have been proposed by IPCC, from the most optimistic to the most pessimistic. The scenario studied here is labeled B2 by IPCC. It corresponds to a modest reduction policy in the emissions, leading to a double CO₂ concentration with respect to preindustrial values by the end of the 21st century: we are much below the 1% per year concentration increase used in the previous scenarios (Giorgi et al., 1992). The global temperature response to this forcing is about 2K amongst the GCMs (it is 1.8 K with Meteo-France model).

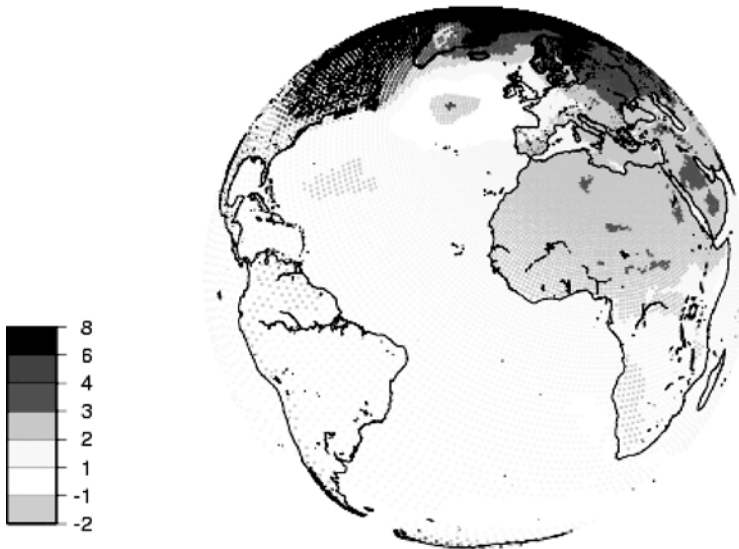
This warming is not uniform and some models like ARPEGE predict a cooling in the mid-Atlantic in winter due to the change in the thermo-haline ocean circulation. A warmer atmosphere should contain more water, so that the precipitation-evaporation cycle is expected to be enhanced. However, the GCMs do not predict a rainfall increase over all regions, but positive and negative precipitation anomalies spread over the globe. There is a consensus, however, about an increase over most tropical regions. In Europe, the consensus in the global as well as regional models is an increase in winter in the northern part and a decrease in summer in the southern part (Mediterranean basin).

Figure 5 shows the impact of the B2 scenario in winter (December, January, February) for temperature and precipitation over the western hemisphere (Figure 5a and b) and a zoom over Europe (Figure 5c and d). The precipitation decrease over the Mediterranean basin is also found by Timbal et al. (1995), but other models (e.g. Giorgi et al., 1992) predict a precipitation increase over the whole Europe. Over northern Europe, most regional (limited area) models predict warmer and moister conditions (Christensen et al., 2001).

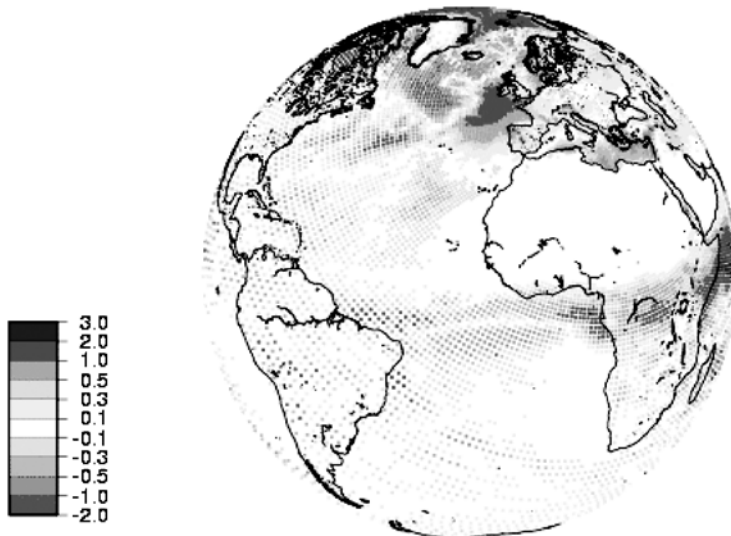
3.4. IMPROVE THE SIGNIFICANCE OF THE PREDICTED VARIABLES

In relation to the forecasts currently available, progress is expected by users on the following points:

- Increasing the number of considered variables. (Even though temperature is obviously given priority treatment, and rainfall is already the subject of studies (which should, however, be intensified), it would appear necessary also to consider global solar radiation, as well as air humidity and wind speed, variables which affect agricultural and forestry production.)
- For the various meteorological variables, it is necessary to obtain information not only on the average values, but also on the extreme values (for example,

T2m DC2-DA9 medias DJF

(a)

Precip DC2-DA9 medias DJF

(b)

Figure 5. (a) and (b): Impact of the B2 scenario by Arpège-Climat in winter for temperature (a) and precipitation (b) over the western hemisphere. (c) and (d): Anomalies in average temperature (on the left in °C) and precipitation (on the right in mm/days) forecasts for the end of the twenty-first century using the IPCC B2 scenario and the Arpège-Climat model in the stretched/ aimed version.

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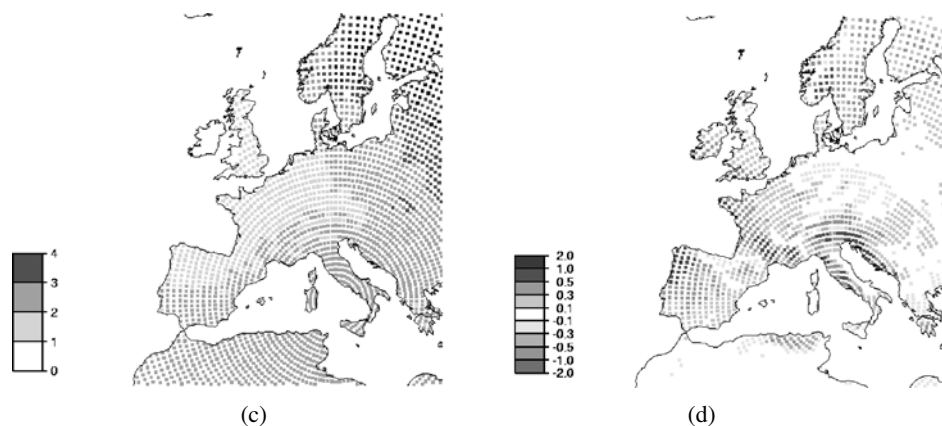


Figure 5. (Continued).

for rainfall or wind speed) and exceeded threshold values (the case of frost or shrivelling).

- The duration of the period simulated using a climatic model subject to a defined scenario. If we consider the average zonal atmospheric response to the doubling of the concentration of CO_2 , a simulation over a single year is sufficient.

3.5. IMPROVE THE MODELLING OF INTERANNUAL VARIABILITY

If we wish to consider the interannual variability of a parameter in the course of a season in a given region, a simulation over ten years is necessary. If we wish to study the variability of the precipitation regime, at least 30 years are necessary (Déqué, 2000). To provide a concrete illustration of this thesis, consider that an average reduction in precipitation of 10% in the course of a single summer will not be too damaging to vegetation if it is regularly reproduced each year. But, if this average value of 10% corresponds to a decrease by 50% which may occur once every five years, the damage to the biosphere could be higher, or even irreversible. In studying the impact of climatic change on agriculture and forestry, it is therefore essential to have an extended series of simulated meteorological data. Thus, for example, Météo-France has put together a simulation of 140 years on the ARPEGE-Climate model using the IPCC B2 scenario.

4. Improve the Production Forecast

Climatic change may engender several kinds of impact on agriculture (Delecolle et al., 2000):

- On production, in terms of quantity, and also of quality, by direct effect of the climate on crop productivity and also indirect effect on diseases, insects, and weeds.

- On various upstream modifications of the consumption of irrigation water, fertilisers, herbicides, and pesticides, and downstream in the quality of the products available and/or sold.
- On the environment, particularly if the frequency and intensity of rainfall, combined with an increased use of nitrogen, mineral elements and pesticides leads to a leaching or a run-off of these substances.
- On the rural environment, if climatic change forces the abandonment of certain species or the introduction of new ones, the modification of land-use, and the development of water management projects.

The integration of these various components represents the main challenge needing to be addressed and coordinated in the near future.

4.1. IMPROVE THE AGRONOMICAL MODELS

Various projects have already been carried out to evaluate the impact of climate change on agriculture. They generally incorporate the effect of the increase in CO₂ on photosynthetic production, in addition to the direct effect of modification of climatic factors (particularly temperature, radiation, rainfall). The expected effects are highly variable depending on the cultivated species or forest ones studied, and the regions under consideration. They also depend on the climatic scenarios being used. A global increase in CO₂ generally leads to an elevation in crop productivity. This latter increase depends on carbon metabolism : it is more marked for C3 plants (like wheat) which are more frequent in temperate latitudes, than for C4 plants (like maize), which are more current in tropical agriculture.

Thus, if we forecast an increase in rice productivity in Northern countries in relation to the broadening of the period favourable to the crop, we forecast a fall in the productivity of this cereal in numerous countries in South-East Asia, particularly linked with the negative effect of high temperature induced spikelet sterility (Matthews et al., 1997). The current assessment of this work has been carried out in the context of the work of the IPCC but it remains incomplete.

The empirical models based on statistics available in agrometeorology have been established with implicit combinations between climatic variables which will have to be discussed again because of climate change. Thus, we want to emphasize the fact that predictions must increasingly rely on crop simulation models that are likely to effectively combine the differentiated effects of CO₂ and the various variables of the climate on the physiological processes. To address this issue, we propose sophisticated dynamic models which simulate and integrate specific mechanisms:

- Ecophysiology of the aerial parts of plants (development, aerial growth, elaboration of yield),
- Soil functions in interaction with the underground parts of plants (root growth, water uptake, nitrogen uptake, transfers),

- Management of interactions between cultivation techniques and the soil-crop system, whether they concern the contribution of water, fertiliser or climate.

Integrating the accumulated knowledge in terms of the influence of climate, the soil, and culture practices on production, these agronomical models can be provided with climatic data from the general circulation models. They should thus provide a production forecast per type of crop, the quantities of water or fertilisers consumed, and allow to test strategies for adapting to modifications in the environment. The results from this will need to be validated using numerous experimental results. Taking into account the indirect effects of disease or insects, as well as weeds, however, still remains to be achieved in numerous cases.

Numerous of these models exist around the world (Hoogenboom, 2000). Without wishing to be exhaustive, we can cite CERES models (for maize, wheat, millet, sorghum or rice) and the CROPGRO models (for soya, peanuts, etc.). The CERES model has been used to quantify the consequences of climatic change in France on the production of wheat and maize (Delecolle et al., 1995).

STICS software (Brisson N. et al., 1998 – Brisson N. et al., 2002), perfected in France by a multidisciplinary team at the INRA (National Institute for Agronomic Research) with the collaboration of other research organisations and the agricultural profession is a multi-crop model. Coupling it with parameters from the soil database and spatialised meteorological parameters (Pérarnaud et al., 1997, Ruget et al., 2001), enables the estimation of grass production in France.

The international community should be able to take advantage of the results of the research carried out in the context of crop modelling. However, the use of these models must be approached with caution, ensuring that certain input parameters (types of soil, meteorological data, etc.) are adapted to the local or regional conditions of use. Therefore, retrospective evaluation of the models with series of observed data, together with their sensitivity and uncertainty analyses, are essential steps to build up confidence in model predictions.

4.2. SPATIAL APPLICATIONS OF CROP MODELS

Originally crop simulation models were designed to operate on a homogenous plot of land. The use of these models to evaluate the impact of climatic change on a regional scale (on production, water consumption or nutrient use) necessitates the use of specific techniques for spatial representation. It is essential to apply the model to a spatial unit defined according to use (simulation unit) and then aggregate the results (yield or quantity of water consumed by the crop) at the regional scale. This type of application necessitates a considerable volume of input data to understand the spatial and temporal variability of the studied parameter. Databases and geographical information systems (GIS) are essential tools in implementing such applications. However, it is appropriate to analyse the level of precision and

therefore the possible level of simplification in terms of each layer of GIS information (soil, management practices or meteorological parameters). One of the greatest difficulties lies in taking account the spatial heterogeneity of the soil, which is not always available in digital form and might suffer from a lack of precision in terms of georeferencing. Moreover, the calculation of the different parameters of the soil water balance (like the available water), although estimated from the rules of pedotransfer, need improvement.

In the Sudano-Sahelian region, agricultural productivity is closely linked to the variations of the climate and, more precisely, to the intensity and duration of periods of drought. Thus, to forecast the yield of millet in the Sahelian area, the precision applied to water stress is essential regarding the forecast of the volume and the spatial and temporal rainfall distribution, and regarding the plant's use of water. However, other determinants of the crop production such as the cultivar, sowing date, and plant density make forecasting more complex. The development of models which account these factors enables the evaluation of risks and technological scenarios in real time or for the future (Samba et al., 2001). We can then for example visualise delayed sowing in certain areas or identify areas which may suffer a production deficit by using remote sensing and modelling outputs. Figure 6a presents the divergence between the beginning of the 1998 season and the average for the years 1961 to 1990 in countries in the Sahelian area, allowing us to visualise early or late sowings in certain areas in relation to a reference year. This model may be used to forecast the yields of the current year by adjusting the historical date and the provisional climatic data in real time. To counter the lack of rainfall data, rainfall estimation methods using satellite imaging (Meteosat) are used. Figure 6b illustrates the differences in yield estimated (at the end of the growing season) between the current year and the average of the last thirty years. This device, illustrated here for short term forecasting, will also allow us to evaluate the adaptation of Sahelian agriculture to climatic change by using GCM outputs.

The use of crop simulation models (Hansen and Jones, 2000) fed with spatialised information from diverse origins with varying degrees of uncertainty, leads to the propagation of errors which may distort the final results. It is therefore appropriate to carry out theoretical research to quantify these errors and try to minimise them.

5. Improve Pests and Disease Models

In natural ecosystems, and also in cultivated or forest ecosystems, climatic change is capable of disturbing the balance between the species, whether they are plant and/or animal, both in terms of the individual and the population (Loreau et al., 2001). These changes will also modify the development of weeds, diseases and parasites among crops, as well as their area of distribution. The effect of climatic changes on the development of pests and diseases could manifest itself in two main processes:

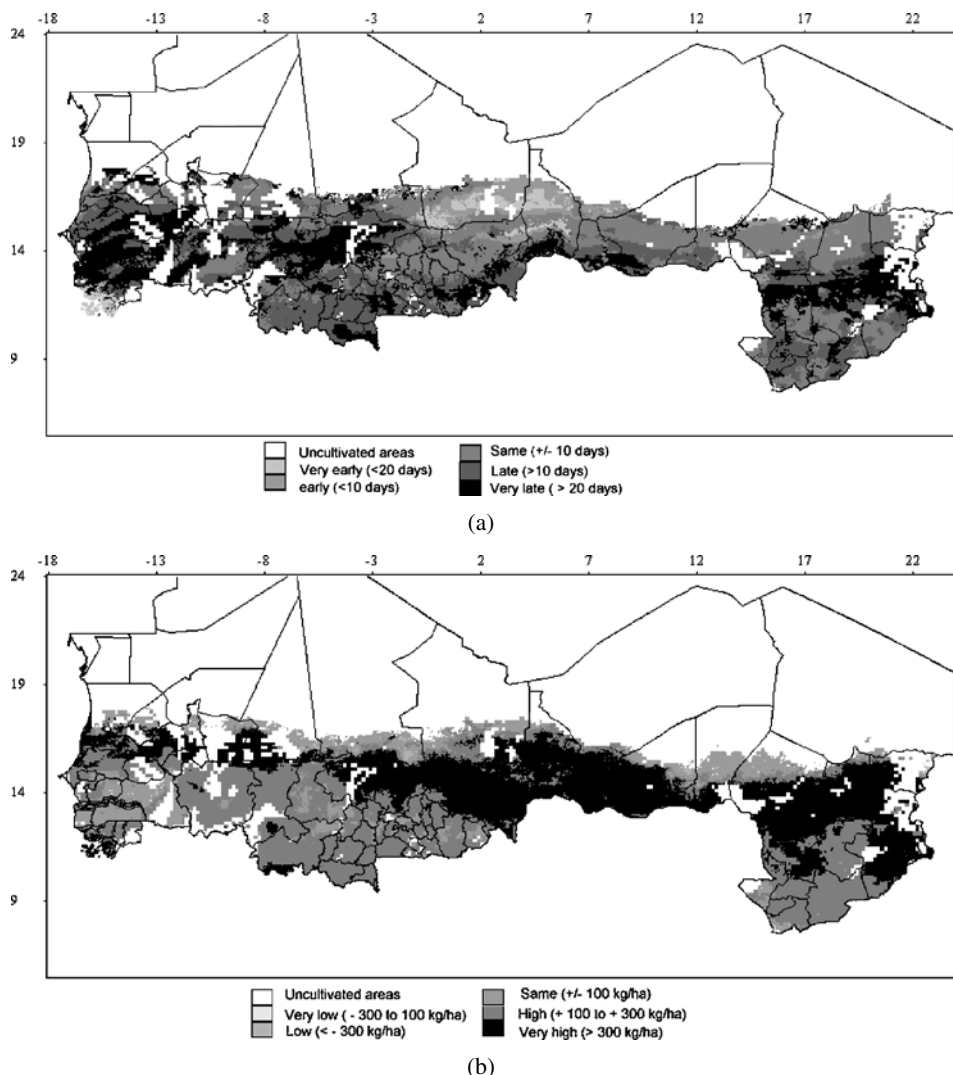


Figure 6. (a) A map of millet successful sowing dates differences between 1998 and an average 1961–1990 (from Samba et al., 2001). (b) A map of millet yields differences between 1998 and an average 1961–1990 (from Samba et al., 2001).

- A direct effect on the biological cycle of the parasites. In the event of climatic warming, certain thermophilic parasites would find even more favourable conditions in their current area of distribution and could extend this to as yet little affected areas where their hosts are present.
- An effect on host-parasite interaction and, more globally, on the complex interactions which exist in the trophic networks and which may modify the effectiveness of control using biological agents. Climatic changes will modify the development of crops, and hence might affect the phenology or resistance of

plants. The synchronisation between host and parasite could thus be markedly disrupted.

Several approaches are possible in trying to estimate the impact of climatic changes on plant diseases. Using climatic concordance models, similarities between the future climate in a given area and the current climate in another area can be used to forecast sanitary risks by analogy. We can also establish predictions based on previously established empirical relations between the impact of parasites and climatic variables (Coakley and Scherm, 1996). But, faced with the complexity of the problem, it is much more efficient to use epidemiological models: epidemiological development is described in the form of a functional model where each biological process and its integration are linked to climatic parameters (Goudriaan and Zadoks, 1995). The objective is then to couple these models to crop simulation models. However, creating these models necessitates the acquisition of various observed data and knowledge acquired by experimenting on the disease. At the present time, very few of these models are available and it is absolutely essential that progress is made in this area.

6. Simulate Potential Effects of Climatic Changes on the Soil

Future changes in the climate and the composition of the atmosphere will be shown in the evolution of thermal and rainfall regimes, vegetation and land uses, all factors which have an effect on the soil and its dynamics. The soil is at the interface between the lithosphere, the atmosphere, the hydrosphere and the life which it supports. In addition, because of its organic matter, it contains a major part of the biosphere's carbon (Robert, 2000). Any modification in soil agricultural practices or ground cover vegetation may therefore have consequences for the global carbon cycle via their impact on the dynamics of soil organic matter. Conversely, changes in the composition of the atmosphere may bring about changes in certain soil characteristics, particularly the organic reserve (C, N), nutritive elements and acidity, conditions of oxidoreduction, soil water and physical characteristics.

Numerous questions remain unanswered and would benefit from research campaigns. How will the organic reserves in the soil develop and at which rate? Will the soil behave like a sink or an additional source of CO₂ (particularly under the effect of the increase in respiration) and what, in return, will be the effect on the composition of the atmosphere? Changes in soil use will also be important. They themselves put a question mark over ecosystems in a transitory state. Will there be synergic or antagonistic effects between changes of usage (which are determined largely by economic factors) and climatic changes, will there be any effects in return? In this respect, the example of rice is very illuminating: if, as we have seen, climatic change has effects on world rice production and its distribution (Horie et al., 2000), the production of rice on the planet may itself have a significant effect

on climatic change, particularly through the emission of methane from flooded paddy fields (Reicosky et al., 2000). The hydrologic cycle, the properties of the soil, and the way crops are grown could significantly alter the fluxes of methane produced, mechanisms of which it is important to be aware.

To answer all of these questions, an understanding of the functioning of the current ecosystems is necessary. But facing the transitory nature of the expected impact, only modelling will be able to provide information on the simultaneous consequences of changing agrosystem and ecosystem management practices.

7. Improve Forests Planning

The carbon balance of a forest ecosystem may be a net storage, as is the case in young forests in the growth cycle, or it may also represent a net carbon loss for certain, ageing or declining forests, or for those suffering the consequences of disruption (storms, fires) (Valentini et al., 2000). This balance is subject to major spatial and temporal variations. In addition to current forestry operations (soil preparation, drainage, fertilisation or clearings), it is sensitive to the stand age and climate (Chen et al., 1999). The respective role of these different factors, which all interact, is particularly difficult to elucidate. The short and long term impact of forestry is unfortunately often ignored, in spite of its obvious importance.

Differing approaches and methods of measurement are available to study the processes concerned and their respective role in the carbon content of an ecosystem on varying spatial scales: measurements of turbulent fluxes, measurements of stocks, calculations based on data from repeated inventories.

Even though the recent progress in measuring the flows of carbon exchanged on the scale of ground cover allow us to correctly evaluate the methods of change of scale from leaf to ground cover, we have, on the other hand, a poor understanding of the link between the functioning of an ecosystem at the stand scale and the calculation of a stock of carbon and its variations at the regional or national level. Calculations based on woodland inventories and remote sensing are currently the only possible and verifiable way of detecting and measuring variations in national stocks. Despite the fact that these numbers are required in international protocols, we are only able to make a crude estimation of the changes in national stocks, and to quantify the respective impacts of land use changes, forestry and agronomical activities, indirect effects of human activities and non anthropogenic causes (e.g natural disturbances).

One of the main impacts of climatic changes will be to profoundly alter the potential ecological niche of species whose distribution is wholly or partly limited by climate. Such movements have already been observed for remarkable rare species which are clearly limited by climate. An awareness of these changes is particularly

important in the field of forestry, where the species planted or naturally regenerated are for temporal horizons in the order of a century. The forestry choices made today are therefore crucial for the longevity of the forest in a changing climatic context.

Providing a long-term assessment of the future of the functioning of forest ecosystems raises various questions on their vulnerability to biotic and abiotic stresses. This prediction supposes the use of meteorological data from a climatic model with high spatial resolution, together with data associated to the ecosystems under consideration (species, fertility).

Amongst numerous studies devoted to the impact of climate change, very few concern the diseases of forest trees (Coakley et al., 1999; Chakraborty et al., 1998). However, parasites are a major limiting factor for forestry production, in quantity and quality, and may affect the survival of a species, or even an entire ecosystem (Weste and Marks, 1987). It is even more essential to predict the impact of global change on the parasitic risk to the forest when the management of woodland parasites is essentially based on a preventive approach, as recourse to curative methods of combating the problem is often unrealistic and not actually desirable. Forecasting parasitic risks is one of the elements of forest planning.

In terms of research needs, it is therefore important to:

- quantify the stocks and fluxes of carbon in the large forest ecosystems.
- simulate the future of carbon sequestration in these major forest types based on a climatic scenario with high spatial resolution.
- inventory the various forestry practices which have a significant impact on the carbon stocks and fluxes and estimate the impact of various forestry managements on the sequestration of carbon in these ecosystems and their harvested products.
- assess the vulnerability of woodland species to allow alternative proposals to be made: replacement of species, fire prevention methods.

8. Towards New Cropping Systems

Agriculture in the twenty-first century will have to make its contribution to the reduction of GHG emissions (principally CO₂, CH₄, N₂O) but also and above all to adapt to climate change to continue to satisfy the vital needs of populations in food, energy, fibers, and other products. The end results and priorities will depend on the regions of the Earth concerned. It is clear that the global reduction of agriculture contribution in the production of GHG will be a priority for the developed countries. Most of the less developed countries in the tropical areas will still have the problem – and for some with increased intensity – of the absolute necessity of producing various food products for local and remote consumption. This context, of course, relates to world economic and legal situations, but also necessitates specific

research efforts in the development of sustainable systems, mobilising agronomists and agrometeorologists alike. Regarding the reduction of GHG emission and the storage of carbon in the agro-ecosystems, the necessity for research on the measurement of GHG emissions and storage has already been mentioned. It must be carried out for the existing ecosystems but also evaluate any new systems proposed. For several years, reduced tillage techniques combined with the use of mulches and ground cover plants (no tillage techniques, conservation agriculture) have undergone major development in various parts of the world (for example Brazil, United States, Canada) and may enable an increase in soil carbon storage and a reduction of erosion. However, the global assessment towards GHG still remains to be made, as well as the sustainability capacity of these systems. In the same way, the development of agroforestry systems may contribute to an increase of the quantity of carbon fixed in the soils and biomass, a reduction of the quantity of fossil fuel used for soil tillage operations, a reduction in the use of pesticides and also a stabilisation of the ecosystem in the face of climatic variability. It is, however, often difficult to persuade farmers to adopt these often promising solutions for various economic or social reasons. It is therefore important to use integrated approaches, which take into account the farmers' decision-making process, to design operational systems (Boiffin et al., 2001). Moreover the development of innovative systems necessarily combines experimentation on the ground and complex models with varied but coupled processes. For example the construction of models simulating the response of flooded rice-production systems to climatic change would involve to take into account the modification of CO₂ content and temperature on all physiological processes (photosynthesis, transpiration, phenology or ripening) and the effect of changes in practices (sowing date, density, varietal choice, fertilisation, management of groundwater) on the elaboration of yield and the emission of GHG (here CH₄).

9. Conclusions and Recommendations

The adaptation of agriculture and forestry to the climate of the twenty-first century requires that major research efforts will be made. The complexity of the problem necessitates cooperation between research scientists in various disciplines: meteorologists, agronomists, pedologists, hydrologists, modellers. This cooperation, which has to be international, must produce immediately useable results to respond to the questions of the developing countries. Indeed, though all regions of the world are different because of their climates, their soils, their water resources, the methods of using and managing the land, they are also different because of their vulnerability to climatic change. In this respect, an increased sensitivity appears in the less developed countries in the tropics. It is therefore becoming important that we rapidly identify the gaps in our knowledge and initiate research aimed at increasing the adaptability of agriculture in the face of climate change. This research

will aim both to increase our forecasting capacity and to anticipate the design of new cropping and forestry systems. It is also essential to deepen our expertise to orient and evaluate international negotiations in a critical manner, both in terms of quantifying stocks and forecasting impact. We must come up with calculations of sequestration potential of the various sources of carbon (soil, biomass), forest ecosystems and their behaviour in response to various management options and climate change.

The interactions between climate change, on the one hand, and agriculture and forestry, on the other, are numerous. Whatever technical progress is implemented, agricultural and forestry activities remain primarily dependent on fluctuations in the climate; they contribute, for their part, to the modification of the gaseous balance of the biosphere, whether directly or indirectly, through, for example, the emission of greenhouse gases through damage to the soil or deforestation.

In the first issue, it is appropriate to achieve a better understanding of the variability of the current climate and its impact on agriculture. This involves the study of extended series of homogenised meteorological data, and the analysis of ecosystems and their evolution. The most advanced models, which allow to simulate the climate of the future, are based on general circulation models. Even though considerable progress has been made in this field in the course of the last decade, it is essential today to specify the behaviour of the hydrological cycle, taking account of alterations by the continental land masses and the interactions of ocean and atmosphere. Climatic change may generate several types of impact on agriculture, on production, the consumption of irrigation water, fertilisers, herbicides, and pesticides, on the environment and on rural areas generally. This impact is of varied complexity, and the systematic recourse to crop simulation models (which integrate the effects of pests and weeds) appears to be the only way possible, on condition that major efforts are devoted to validating them. These models must also evolve in order to produce environmental output, enabling the simultaneous simulation of the effect of production on the environment associated with production forecasts, taking account of both the GHG levels and the impact on surface radiative and energetic balances.

The use of spatial sensors must become more systematic, both for long-term monitoring and through their capacity for measuring and mapping certain variables (global radiation, photosynthetically active radiation, surface temperature, soil moisture). The contribution of satellite remote sensing information appears to be an essential complement to the development of crop models and the research underway.

It is also essential to make progress in spatialisation and aggregation techniques to quantify the propagation of errors arising from the uncertainties linked to the coupling of information and to minimise them.

Finally, the prognosis for storage of carbon in ecosystems in a changing climate also constitutes a scientific challenge in understanding of the cycle of this element as relating to the behaviour of the ecosystems concerned.

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REDUCING VULNERABILITY OF AGRICULTURE AND FORESTRY TO CLIMATE VARIABILITY AND CHANGE: WORKSHOP SUMMARY AND RECOMMENDATIONS

M. J. SALINGER¹, M. V. K. SIVAKUMAR² and R. MOTHA³

¹*National Institute of Water and Atmospheric Research, P.O. Box 109-695, Newmarket, Auckland, New Zealand*

E-mail: j.salinger@niwa.co.nz

²*World Meteorological Organization, 7bis Avenue de la Paix, 1211 Geneva 2, Switzerland*

³*United States Department of Agriculture, 1400 Independence Ave, SW Room 5143, Washington DC 20250, U.S.A.*

Abstract. The International Workshop on Reducing Vulnerability of Agriculture and Forestry to Climate Variability and Climate Change held in Ljubljana, Solvenia, from 7 to 9 October 2002 addressed a range of important issues relating to climate variability, climate change, agriculture, and forestry including the state of agriculture and forestry and agrometeorological information, and potential adaptation strategies for agriculture and forestry to changing climate conditions and other pressures. There is evidence that global warming over the last millennium has already resulted in increased global average annual temperature and changes in rainfall, with the 1990s being likely the warmest decade in the Northern Hemisphere at least. During the past century, changes in temperature patterns have, for example, had a direct impact on the number of frost days and the length of growing seasons with significant implications for agriculture and forestry. Land cover changes, changes in global ocean circulation and sea surface temperature patterns, and changes in the composition of the global atmosphere are leading to changes in rainfall. These changes may be more pronounced in the tropics. For example, crop varieties grown in the Sahel may not be able to withstand the projected warming trends and will certainly be at risk due to projected lower amounts of rainfall as well. Seasonal to interannual climate forecasts will definitely improve in the future with a better understanding of dynamic relationships. However, the main issue at present is how to make better use of the existing information and dispersion of knowledge to the farm level. Direct participation by the farming communities in pilot projects on agrometeorological services will be essential to determine the actual value of forecasts and to better identify the specific user needs. Old (visits, extension radio) and new (internet) communication techniques, when adapted to local applications, may assist in the dissemination of useful information to the farmers and decision makers. Some farming systems with an inherent resilience may adapt more readily to climate pressures, making long-term adjustments to varying and changing conditions. Other systems will need interventions for adaptation that should be more strongly supported by agrometeorological services for agricultural producers. This applies, among others, to systems where pests and diseases play an important role. Scientists have to guide policy makers in fostering an environment in which adaptation strategies can be effected. There is a clear need for integrating preparedness for climate variability and climate change. In developed countries, a trend of higher yields, but with greater annual fluctuations and changes in cropping patterns and crop calendars can be expected with changing climate scenarios. Shifts in projected cropping patterns can be disruptive to rural societies in general. However, developed countries have the technology to adapt more readily to the projected climate changes. In many developing countries, the present conditions of agriculture and forestry are already marginal, due to degradation of natural

resources, the use of inappropriate technologies and other stresses. For these reasons, the ability to adapt will be more difficult in the tropics and subtropics and in countries in transition. Food security will remain a problem in many developing countries. Nevertheless, there are many examples of traditional knowledge, indigenous technologies and local innovations that can be used effectively as a foundation for improved farming systems. Before developing adaptation strategies, it is essential to learn from the actual difficulties faced by farmers to cope with risk management at the farm level. Agrometeorologists must play an important role in assisting farmers with the development of feasible strategies to adapt to climate variability and climate change. Agrometeorologists should also advise national policy makers on the urgent need to cope with the vulnerabilities of agriculture and forestry to climate variability and climate change. The workshop recommendations were largely limited to adaptation. Adaptation to the adverse effects of climate variability and climate change is of high priority for nearly all countries, but developing countries are particularly vulnerable. Effective measures to cope with vulnerability and adaptation need to be developed at all levels. Capacity building must be integrated into adaptation measures for sustainable agricultural development strategies. Consequently, nations must develop strategies that effectively focus on specific regional issues to promote sustainable development.

1. Introduction

Climate change and variability, drought and other climate-related extremes have a direct influence on the quantity and quality of agricultural production and in many cases, adversely affect it; especially in developing countries, where technology generation, innovation and adoption are too slow to counteract the adverse effects of varying and changing environmental conditions. The interdisciplinary nature of these issues requires a long lasting and where possible more substantial role for agrometeorology in the efforts to promote sustainable agricultural development during the 21st century. There is a need to develop locally new and better agrometeorological adaptation strategies to increasing climate variability and climate change, especially in vulnerable regions where food and fibre production is most sensitive to climatic fluctuations.

Because of uncertainties associated with regional projections of climate change, the Intergovernmental Panel on Climate Change has attempted to assess the vulnerability of natural and social systems to changes in climate, rather than attempt to provide quantitative predictions of the impacts of climate change at the regional level. The range of adaptation options for managed systems such as agriculture and forestry is generally increasing because of technological advances, thus opening the way for reducing the vulnerability of these systems to climate change. Some regions of the world, particularly developing countries, have limited access to and absorption capacity for these technologies. They lack local appropriate information on how to implement them under their conditions. However, innovations from within are of more than equal importance (Salinger et al., 2000). Incorporation of climate change concerns into resource use and development decisions and plans for regularly scheduled investments in infrastructure will facilitate adaptation.

The issues of climate variability and climate change need to be integrated into resource use and development decisions. Climate variability affects all economic sectors, but agricultural and forestry activities are perhaps two of the most vulnerable and sensitive sectors to such climate fluctuations. Agrometeorological services derived from a more informed choice of policies, practices and technologies will, in many cases, reduce the long-term vulnerability of these systems to climate change. For example, the introduction of farmer-oriented seasonal climate forecasts (Lemos *et al.*, 2002) into management decisions may reduce the vulnerability of agriculture to floods and droughts caused by the El Niño-Southern Oscillation (ENSO) phenomena.

The International Workshop on Reducing Vulnerability of Agriculture and Forestry to Climate Variability and Climate Change, held in October 2002 in Ljubljana, Slovenia, where the papers in this volume were presented assessed the varying global climates and their likely changing impacts, and examined adaptation options. Resources and strategies, including education and training, in reducing the vulnerability of agriculture and forestry, were also discussed.

2. The Varying Climate

The Intergovernmental Panel on Climate Change (IPCC, 2001a) has shown that prior to the 20th century Northern Hemisphere average surface air temperatures have varied in the order of 0.5 °C back to AD 1000. Various climate reconstructions indicate that slow cooling took place until the beginning of the 20th century. Subsequently, global-average surface air temperature increased by about 0.6 °C, with the 1990s being the warmest decade on record. The pattern of warming has been greatest over mid-latitude northern continents in the latter part of the century. At the same time the frequency of air frosts has decreased over many land areas, and there has been a drying in the tropics and subtropics. The late 20th century changes have been attributed to global warming because of increases in atmospheric greenhouse gas concentrations due to human activities.

Salinger (2005) has shown that beneath the longer-term trends there is decadal scale variability in the Pacific basin at least induced by the Interdecadal Pacific Oscillation (IPO). On interannual timescales ENSO causes much variability throughout many tropical and subtropical regions and some mid-latitude areas. The North Atlantic Oscillation (NAO) provides climate perturbations over Europe and northern Africa.

Projections from the IPCC (2001a, 2001b) indicate that in the course of the 21st century global-average surface temperatures are very likely to increase by 2 to 4.5 °C as greenhouse gas concentrations in the atmosphere increase. At the same time there will be changes in precipitation, and climate extremes such as hot days, heavy rainfall (causing floods) and drought are expected to increase in many areas.

The combinations of global warming, with decadal climate variability (IPO) and interannual fluctuations (ENSO, NAO) are expected to lead to a century of increasing climate variability and change. This could bring with it unknown climate surprises and their impacts, such as flooding from unmanageable catchments and inundation of land areas due to storm surges and sea level rise. In the perspective of human settlement and agriculture and forestry activities over the last 10,000 yr at least climate changes have been quite small, and certainly in the documented record for the last 1,000 yr small variations in global temperature have occurred compared with the glacial/interglacial changes. Although the changes of the past and present have stressed food and fibre production at times, the 21st century changes will be extremely challenging to agriculture and forestry. As the century progresses, the interannual and decadal phenomena will be superimposed on an unprecedented global warming trend. Together these will produce rapid climate change, increasing climate variability and more climate extremes. Thus agriculture and forestry will face unprecedented stresses in the 21st century. Some of these concerns were addressed in an earlier international agrometeorological workshop (Stigeter et al., 2000).

3. Impacts

3.1. TROPICAL REGIONS

Roughly 40% of the world population lives in the tropics, and agriculture is a very important sector for the economies of most countries in the tropics. For example, in tropical Asia, more than half of the labour force is employed in agriculture, accounting for 10–63% of the GDP in most countries of the region (IPCC, 1998). Given the current scenarios of enhanced temperatures and increased frequency of extreme events, climate change is likely to have significant impact in the tropics.

Sivakumar et al. (2005) pointed out that the arid and semiarid regions account for approximately 30% of the world total area and are inhabited by 1.1 billion people or approximately 20% of the total world population. The arid and semiarid regions are home to about 24% of the total population in Africa, 17% in the Americas and the Caribbean, 23% in Asia, 6% in Australia and Oceania, and 11% in Europe (UNSO, 1997). According to Zhao et al. (2005), humid and subhumid tropical conditions are found over nearly 50% of the tropical land mass and 20% of the earth's total land surface. Tropical Central and South America contain about 45% of the world's humid and subhumid tropics; Africa, about 30% and Asia, about 25%.

Sivakumar et al. (2005) described the agricultural climate of the arid and semiarid tropical regions in Asia, Africa and Latin America, which is characterized by low and variable rainfall and consistently high temperatures during the growing season. Climate variability—both inter- and intra-annual—is a fact of life in these regions with a traditionally low agricultural productivity. The projected climate change and

the attendant impacts on water resources and agriculture in the arid and semiarid tropical regions add additional layers of risk and uncertainty to agricultural systems that are already affected by land degradation due to growing population pressures.

It is interesting to note the observations of Sivakumar et al. (2005) that in certain agroecological zones such as the southern Sahelian zone of West Africa, where the predominant soils are sandy in nature, increased *mean* temperature could affect the *maximum* temperatures at the soil surface substantially. They pointed out that surface soil temperatures could exceed even 60°C and that under such temperatures, enzyme degradation will limit photosynthesis and growth. Increased temperatures will also result in increased rates of potential evapotranspiration. In the long term, the very establishment and survival of species in both the managed and unmanaged ecosystems in this region may be threatened, resulting in a change in the community structure.

The prospect of global climate change has serious implications for water resources and regional development (Riebsame et al., 1995). Projected temperature increases are likely to lead to increased open water and soil/plant evaporation. As a rough estimate, potential evapotranspiration over Africa is projected to increase by 5–10% by 2050. Since Africa is the continent with the lowest conversion factor of precipitation to runoff (averaging 15%), and precipitation in some areas may decrease, the dominant impact of global warming is predicted to be a reduction in soil moisture in subhumid zones and a reduction in runoff.

The general conclusion is that climate change will affect some parts of Africa negatively, although it will enhance prospects for crop production in other areas (see Downing, 1992, for case studies of agriculture in Kenya, Zimbabwe, and Senegal). Expansion of agriculture is important in the east African highlands. For example, agroecological suitability in the highlands of Kenya would increase by perhaps 20% with warming of 2.5 °C based on an index of potential food production (Downing, 1992). In contrast, semiarid areas are likely to be worse off. In eastern Kenya, 2.5 °C of warming results in a 20% decrease in calorie production.

The water and agriculture sectors are likely to be most sensitive and hence vulnerable to climate change-induced impacts in arid and semi-arid tropical Asia. Croplands in many of the countries in the region are irrigated because rainfall is low and highly variable (IPCC, 2001b). The agriculture sector here is potentially highly vulnerable to climate change because of degradation of the limited arable land. The predicted increase in frequency and/or severity of extreme events coupled with any increase in intensity of tropical cyclones could further exacerbate adverse impacts of climate change on the agricultural sector.

Sivakumar et al. (2005) referred to several studies aimed at understanding the nature and magnitude of gains/losses in yield of particular crops at selected sites in Asia under elevated CO₂ conditions (e.g., Luo and Lin, 1999). These studies suggest that, in general, areas in mid- and high- latitudes will experience increases in crop yield, whereas yields in areas in the lower latitudes will decrease. Generally climatic variability and change will seriously endanger sustained agricultural production in

tropical Asia in coming decades. The scheduling of the cropping season as well as the duration of the growing period of the crops would also be affected. Studies conducted in India, Indonesia and the Philippines confirmed that spikelet sterility and reduced yields negate any increase in dry-matter production as a result of CO₂ fertilization. Amien et al. (1996) found that rice yields in east Java could decline by 1% annually as a result of increases in temperature. Sivakumar et al. (2005) referred to studies in Asia that showed adverse effects on sorghum in rainfed areas of India, for corn yields in the Philippines and on the tea industry of Sri Lanka.

Agricultural production in lower-latitude and lower-income countries is more likely to be negatively affected by climate change (IPCC, 1998; 2001b). It is seen that climate variability and climate change, particularly in terms of frequency/intensity of droughts, have larger impacts on the subhumid than on the humid regions. If climate variability-induced disasters become more common, widespread, and persistent, many countries in the humid and subhumid tropical regions will have difficulty in sustaining viable agricultural and forest practices. A good number of researchers have all concluded that climate change would affect agriculture as a result of increased temperatures, changes in rainfall patterns and increased frequency of extreme events, which could cause changes in pest ecology, ecological disruption in agricultural areas and socioeconomic shifts in land-use practices.

Extremes in climate variability already severely affect agriculture in Latin America (IPCC, 2001b). The largest area with marked vulnerability to climate variability in Latin America is northeast Brazil. Sivakumar et al. (2005) pointed out that periodic occurrences of severe El Niño-associated droughts in northeastern Brazil have resulted in occasional famines. Under doubled-CO₂ scenarios, yields are projected to fall by 17 to 53%, depending on whether direct effects of CO₂ are considered. Lemos et al. (2002) show the difficulties of absorption of seasonal climate forecasts in this region.

In Africa, most mid-elevation ranges, plateaus, and high-mountain slopes are under considerable pressure from commercial and subsistence farming activities. Mountain environments are potentially vulnerable to the impacts of global warming. This vulnerability has important ramifications for a wide variety of human uses—such as nature conservation, mountain streams, water management, agriculture, and tourism (IPCC 1998).

Zhao et al. (2005) referred to studies on the survival rate of pathogens in winter or summer which could vary with an increase in surface temperature. Higher temperatures in winter will not only result in higher pathogen survival rates but also lead to extension of cropping area, which could provide more host plants for pathogens. Thus, the overall impact of climate change is likely to be an enlargement of the source, population, and size of pathogenic bacteria. Damage from diseases may be more serious because heat-stress conditions will weaken the disease-resistance of host plants and provide pathogenic bacteria with more favourable growth conditions.

Sivakumar et al. (2005) and Zhao et al. (2005) pointed to the environmental and social stress caused by climate change in many of Asia's rangelands and drylands. Precipitation is scarce and has a high annual variance in dryland areas of the tropics. Very high daily temperature variance is recorded with frequent sand storms and intense sunshine. The combination of climatic variability and human land use make rangeland ecosystems more susceptible to rapid degeneration of ecosystem properties. For example, because of an alteration in the amount and pattern of rainfall, the occurrence of extreme events (e.g., hurricanes, drought), and the ENSO which could become more frequent and bring more severe weather under the $2 \times \text{CO}_2$ -climate, the northern South America Savannas could fail to function as they do now (Aceituno, 1988).

Climate affects livestock in four ways: through (i) the impact of changes on availability and price of feedgrain, (ii) impacts on livestock pastures and forage crops, (iii) the direct effects of weather and extreme events on animal health, growth, and reproduction, and (iv) changes in the distribution of livestock diseases.

It was pointed out that almost two-thirds of domestic livestock are supported on rangelands, although in some countries a significant share of animal fodder also comes from crop residue. The combination of elevated temperature and decreased precipitation in arid and semiarid rangelands could cause a manifold increase in potential evapotranspiration, leading to severe water stress conditions. Many desert organisms are near their limits of temperature tolerance. Because of the current marginality of soil water and nutrient reserves, some ecosystems in semiarid regions may be among the first to show the effects of climate change. Climate change has the potential to exacerbate the loss of biodiversity in this region.

Zhao et al. (2005) mentioned that for developing countries, the impact of climate variability on livestock is generally negative in the humid and subhumid tropics, particularly in the latter. For animals, heat stress has a variety of detrimental effects with significant effects on milk production and reproduction in dairy cows, and swine fertility. Moreover, warming in the tropics during warm months would likely affect livestock reproduction and production negatively (e.g., reduced animal weight gain, dairy production, and feed conversion efficiency). Impacts however may be minor for relatively intense livestock production systems.

Livestock in humid areas in Africa are prone to disease such as those carried by the tsetse fly. With warming, its distribution could extend westward in Angola and northeast in Tanzania but with reductions in the prevalence of tsetse in some current areas of distribution.

Because of the increasing trend for meat consumption, there is a higher demand for livestock feed. Production of feed grain in Asia, especially maize, is adversely affected by climate variability and climate change.

Tropical forests represent about 40% of the world's forested area and contain about 60% of global forest biomass. As many as 16 countries of tropical Asia are situated within the humid tropical forest region. Climate change is expected to affect the boundaries of forest types and areas, primary productivity, species population

and migration, the outbreak/incidence of pests and diseases and forest degeneration in these countries.

Zhao et al. (2005) referred to the results of research from Thailand which suggest that climate change would have a profound effect on the future distribution, productivity, and health of Thailand's forests. It was estimated that the area of subtropical forest could decline from the current 50% to either 20% or 12% of Thailand's total forest cover (depending on the model used), whereas the area of tropical forests could increase from 45% to 80% of total forest cover. Estimates from Sri Lanka showed a decrease in tropical rainforest of 2–11% and an increase in tropical dry forest of 7–8%. A northward shift of tropical wet forests into areas currently occupied by tropical dry forests also is projected. In semiarid regions of Tropical Asia, tropical forests generally are sensitive to changes in temperature and rainfall, as well as changes in their seasonality.

Most tropical forests are likely to be more affected by changes in soil water availability (e.g., seasonal droughts). Some evergreen species of the humid forest clearly will be at a disadvantage in those areas that experience more severe and prolonged droughts. Significantly, drought affects the survival of individual species; those without morphological or physiological adaptations to drought often die. Species in moist tropical forests, including economically important hardwoods, are the least drought-adapted in the tropics, and their survival in some areas must be considered at risk from climate change. Droughts would favor forest fire; therefore, with a likely increase of droughts, the incidence of forest fires may also increase.

More than 50% of the world's terrestrial plant and animal species are in the frontier forests in Asia. There already are trends of increasing risks to this rich array of living species being seen in China, India, Malaysia, Myanmar and Thailand, partly due to the degeneration of their habitat (IPCC, 2001b). Since distribution of species are limited to a narrow range of environmental conditions, there are possibilities that climate change could alter these conditions which could make them unsuitable. This could cause the loss of a large number of unique species that currently inhabit the world's tropical forests.

There is high confidence that if the extent of deforestation in Amazonia expands to substantially larger areas, reduced evapotranspiration would lead to less rainfall during its dry periods. If this dry period becomes larger and more severe, it could have deleterious impacts on the forest. Many trees could die due to increased water stress. Greater severity of droughts coupled with deforestation could lead to erosion in what remains of the forests in this region. Moreover, occasional severe droughts likely to occur during the EI Niños would kill many trees of susceptible species and would result to a replacement of tropical moist forests with drought-tolerant species (Shukla et al. 1990).

There are other features of agricultural vulnerability to climate change which are also likely to vary across people, regions, continents and countries. One of these is vulnerability to food security because there would then be rapid changes in supply and demand structures most especially in the developing countries, especially in

the tropics. For example, food-importing countries like those in Africa are at risk of adverse impacts of climate change, especially because these impacts are intricately linked with changes in world markets as with changes in local and regional biophysical systems. The already deficient food production in many areas of Africa could also this way result in worsening problems of food security.

3.2. TEMPERATE REGIONS

Maracchi et al. (2005) and Motha and Baier (2005) presented overviews of impacts for Europe and North America, respectively. Increased climate variability has resulted in greater fluctuations in crop yields during recent decades. Extreme weather events such as drought, flooding, and heat waves have had severe impacts on agriculture and forestry, as have changes in drought tendencies, soil moisture availability and frost-free growing seasons. Agriculture has also played a role in greenhouse gas emissions. The clearing of forests, the draining of wetlands, and the ploughing of rangelands have led to a significant increase in atmospheric CO_2 , as organic carbon was decomposed. Nitrous oxide (N_2O) originates as a by-product of nitrogen fertilizer application and in water-logged soils. Thus, in higher latitudes, a spring burst of N_2O emissions occurs with rapid snowmelt. Heavy rains in low-lying areas also cause a N_2O burst of emissions. Methane (CH_4) emitted from agriculture is produced by the microbial breakdown of plant material and in the digestive system of cattle.

There are measures to mitigate agriculture's role in greenhouse gas emissions. Atmospheric CO_2 can be returned to the land by afforestation, conservation tillage by a cover crop, and no-till conservation practices. Soil microorganisms can remove both N_2O and CH_4 with improved pasture conditions and cover crops on cultivated land to lower the amount of inorganic nitrogen in the soil. Higher quality cattle feeds can reduce CH_4 emissions from domestic livestock.

The combined effect of climate change and enhanced CO_2 on crop production varies. Yields of C3 crops (vegetables, wheat, grapes) generally increase. Yields of C4 crops (corn, sugarcane, tropical grasses) generally decrease. However, annual variability of crop yields increase.

Distinct regional patterns by latitude were discernible in future climate scenarios for Europe and North America (Maracchi et al., 2005; Motha and Baier, 2005). Temperatures are expected to increase in nearly all areas but the largest temperature increases are projected over southern portions of both the United States and Europe. Consequently, the extreme cold of winter is expected to diminish but a greater likelihood of heat waves is projected in summer. An increase in the frequency and intensity of heavy precipitation is expected, even in southern Europe and the southern United States, despite projections of total precipitation to decrease.

Northern crop areas of both Europe and the United States will have a longer growing season and an expansion of suitable area for crop production. With higher

crop production, however, the increased risk of nutrient leaching and an accelerated breakdown of soil organic matter may affect the quality of northern agricultural lands. Lower crop yields are expected in southern crop areas due to the warmer and drier summers.

4. Adaptation and Applications

Agrometeorological adaptation strategies to increasing climate variability and climate change have been in focus already for a long time (Salinger et al., 2000). Adaptation should be viewed as a broad concept involving choices at national and international levels as well as locally. Adaptation involves more than measures; it is also a matter for national agricultural and development policies. Under the UN Framework Convention very little attention has been given to technical adaptation. The debate has centered on the need for technology transfer but adaptation technology has not been emphasized in the rush to promote technology transfer for greenhouse gas emission reductions.

Burton and Lim (2005) note that national agricultural policy is developed in the context of local risks, needs, and capacities, as well as international markets, tariffs, subsidies and trade agreements. Stakeholder participation in policy development is frequently recommended as a measure that can help to reduce the distance between national policy processes and the farm and community level.

Agriculture can be described as highly adaptable and resilient, or as resistant to change, and is related to the diffusion and success of technical innovations at the farm level. Successful adaptation over decades and centuries at this level goes a long way toward explaining the confidence now being expressed in the ability of agriculture to cope with the potential impacts of climate change. On the other hand there are concerns that the modernization of agriculture is having serious environmental and social consequences.

Prospects at the global level are good, but severe local and regional disruptions and inequalities are possible, even likely. This diagnosis suggests the need to pay more attention to national policy and global negotiations in order to alleviate inequalities between and within nations. From the perspective of climate change and development the place where local and global converge is at the level of national policy.

Some new approaches to national policy for climate change adaptation are now being developed and applied. These include the National Adaptation Programmes of Action (NAPAs) agreed at the Conference of the Parties to the Framework Convention on Climate Change (COP 7). The Adaptation Policy Framework (APF) now being elaborated builds upon past work and experience and is being developed by UNDP at a generic level. The World Health Organization is developing a set of guidelines for the assessment of adaptation to climate change in the health sector. Similar activities with partners would be timely.

One new technology allowing for adaptation measures is that of seasonal to interannual climate prediction. Harrison (2005) noted that this uses knowledge of sea surface temperature anomalies on which to base a forecast of temperature and rainfall conditions in teleconnected parts of the globe. There are two types of models used in long-range prediction where the objective is to produce a prediction of the average climatic conditions throughout a season across a region measuring several hundred kilometers along each side. Rainfall is a major concern for agrometeorology but it is variable in both space and time and many applications are more sensitive to the timing and amounts of rainfall through a season than they are to the total amount. Downscaling does not improve the accuracy of the forecast and Harrison (2005) recommends that more research is needed on improving methods for forecast validation, verification, and interpretation, and that optimal strategies be devised through more pilot projects.

According to Meinke and Stone (2005) seasonal climate forecasting can increase preparedness and lead to better social, economic and environmental outcomes for agrometeorology. However, climate forecasting is one of many risk management tools that sometimes play an important role. To apply these effectively, a participatory, cross-disciplinary research approach, that brings together institutions (partnerships), disciplines (i.e., climate science, agricultural systems science and rural sociology) and people (scientist, policy makers and direct beneficiaries) as equal partners to reap the benefits from climate forecasting, was suggested. Climate science can provide insights into climatic processes, agricultural systems science can translate these insights into technically possible solutions (management options) and rural sociology can help to determine the options that are most feasible or desirable from a socioeconomic perspective. Any future scientific breakthroughs in climate forecasting capabilities are much more likely to have an immediate and positive impact when conducted within such a framework. Seasonal to interannual climate forecasts are best applied with a good understanding of variability, both temporally and spatially, and a probabilistic approach to outcome dissemination should be considered. In practice there are serious absorption difficulties (Lemos et al., 2002).

For temperate regions, adaptation strategies for agriculture to cope with climate variability and climate change include changes in crop varieties and agronomic practices, improvements in moisture conserving tillage methods, proper irrigation management, and changes in land allocation.

5. Technologies and Strategies

There are a number of technologies and strategies that could help reduce the vulnerability of agriculture and forestry to climate variability and climate change. Stigter et al. (2005) referred to the fact that countless farming communities managed to survive and, in some cases, even to thrive by exploiting natural resource bases

which their forebears have used for generations. Through a process of innovation and adaptation, indigenous farmers have developed numerous different farming systems finely tuned to many aspects of their environment.

Traditional knowledge, indigenous practices and identified local innovations contain valuable information that should be used as a basis for improved technologies and strategies to cope with projected changes. Climate variability and related disasters can be mitigated by temporary or permanent protective measures or by avoidance strategies that try to escape the peak values or their consequences. These are all aspects of preparedness strategies.

As Stigter et al. (2005) explained, in the context of climate change, traditional knowledge and indigenous technologies that mitigate consequences of variabilities of (i) heavy moisture flows or the lack of water, (ii) changing heat flows and related temperatures, (iii) and cropping seasons need special attention. Drought being already a serious threat, indications for longer dry spells in rainy seasons and longer sequences or higher frequencies of abnormal rainfall seasons, with respect to total rainfall and rainfall distribution, make the indigenous ways of coping with drought situations even more important.

One of the popular indigenous technologies described by Stigter et al. (2005) is traditional water harvesting methods and technologies of the use of underground water. A related technology of which also the IPCC advocates more intensive use is that of water impoundment. Several useful examples are given from Indonesia, Sri Lanka, Niger, and Burkina Faso. Permaculture, water harvesting and infiltration pits, together with the use of drought tolerant crops, have been more recently extended in Zimbabwe, particularly by women, with the help of NGOs, in reply to the recurrent droughts.

Many of the same traditional adaptation strategies with agrometeorological components that we presently try to apply also hold for the situations of increasing climate variability and Stigter et al. (2005) present evidence from China to substantiate this fact.

Response farming evolved as a promising technology in the past two decades to alter cropping systems/cropping patterns in relation to fluctuations in seasonal weather. Stigter et al. (2005) suggest that response farming should not only be considered with respect to fitting the cropping seasons to variable rainfall patterns but also for fitting it to variable temperature patterns. They cite the case study from Vietnam (Van Viet, 2001) where either planting date or a combination of planting date and variety could be varied, to make sure that rice was flowering in decades for which the required optimal temperatures had been forecasted. For example the detailed knowledge available on the influence of temperature, temperature extremes and temperature distributions on growth, development and yield of rice (Salinger et al., 1997) makes this possible.

Where temperature is a limiting factor to photosynthesis, traditional farmers may react to cooling/warming by changing their cropping system. Stigter et al. (2005) give the example of changing cropping patterns from North China Plain.

They also give relevant examples of microclimate management and manipulation to cope with temperature changes, e.g., parkland agroforestry and other stabilizing intensive management of scattered or clumped or alleyed trees.

One promising new technology that offers much promise is the application of seasonal to interannual climate forecasts. Disaster preparedness strategies, both of governments and NGOs, have begun to take account of such forecasts, and there is considerable interest in assigning them an economic value. The challenge of course is to reduce the gap between the information needed by small scale farmers and that provided by the meteorological services (Blench, and Marriage 1998; Lemos et al., 2002). As Stigter et al. (2005) noted, low-income farmers are interested in a broader range of characteristics of precipitation, notably, total rainfall, patchiness of rainfall, intensity, starting date, distribution of rainfall, end of the rains and prospects for dry spells and their length. It is precisely in this area that scientific extensions and improvements of response farming approach would bring highly needed solutions (Stewart, 1988). Demonstration projects such as the CLIMAG (Climate Prediction and Agriculture) project currently being implemented in South Asia and West Africa could provide useful information for implementation of similar pilot projects in other regions.

The substantial losses in soil C due to anthropogenic activities have prompted a great deal of interest in the recent past in the concept that agricultural lands have the potential to regain some of this C and that globally between 0.4 and 0.8 Pg / Yr of C could be sequestered in agricultural soils for 50 to 100 yr through good soil management.

Desjardins et al. (2005) discussed a number of agricultural land management practices that have shown potential for increasing C content in agricultural soils. Adoption of permanent cover is one of these practices. Converting cropland into perennial forage may result in a substantial increase in C sequestration. Prevention of overgrazing is also a mitigation strategy that can improve soil carbon levels in pastures significantly.

Conservation tillage or no-till management, when combined with the use of cover crops, proper crop rotations, fertilizer strategies and manure applications, is one of the most efficient practices for sequestering C in cropland.

Reduction of summer fallow in crop rotations which results in greater cropping intensity will increase crop production and thus increase C inputs to soil and increase soil organic carbon. This will also increase water use, keeping soils dryer longer and thus reduce soil decomposition.

Most studies have shown a consistent contribution of forages to soil carbon sequestration. Perennial grasses or legumes in rotation, high yielding varieties and soil management practices that permit the return of large amounts of crop residues to the soil can potentially increase soil organic matter, thus increasing the likelihood for sequestering atmospheric CO². The use of legumes in crop rotations can also appreciably reduce the requirements for N fertilizers for various cropping systems, thereby reducing net fossil fuel use during manufacturing of N fertilizers.

Desjardins et al. (2005) also referred to the fact that most agricultural ecosystems are nitrogen-limited. Adding N fertilizer usually results in increased crop production and may therefore increase C sequestration in soils. However, in considering the net effect on the GHG budget, it is important to take into account the fact that nutrient additions via fertilizer can lead to higher N₂O emissions and may also tend to reduce the CH₄ uptake by soils. Further, there is C emitted in the manufacturing and transportation of N fertilizer that must also be accounted for.

6. Communication, Education and Training

Communicating drought information especially to remote rural populations is a major challenge for drought monitoring and prediction in Africa. Without access to reliable communication networks, the vast majority of Africa's farmers and herders do not have available the scientific and technological advances that support agricultural decision-making in richer parts of the world. Boulahya et al. (2005) working with the African Centre of Meteorological Applications for Development (ACMAD) and herders and farmers designed the RANET system. Named for its innovative linkage of radio and Internet, RANET brings new communications and information technologies together with the oral traditions of Africa to deliver scientific drought information over a distributed network owned and managed by local communities. RANET combines data from global climate data banks in the United States, seasonal rainfall predictions from the international scientific community, data and forecasts generated in Africa, along with food security and agricultural information, to disseminate a comprehensive information package via a network of digital satellite, receiving stations, computers, radio, and oral intermediaries. This is one very effective method for the communication of climate information and forecasts to rural communities, especially in Africa.

Agricultural meteorologists are concerned with many operational aspects of the effects of climate on livestock and crop production. For them to continue to make a contribution to the economy of a country they must continually sharpen their skills and remain updated on the latest information available. Walker (2005) recommends that training should include a variety of skills including transferable skills (e.g., communication, numeracy), professional skills (including cognitive skills) and information technology skills. Problem-based learning can be used to promote critical thinking, decision making and analytical skills. More use should be made of Computer Aided Learning for agricultural meteorologists' in-service training. In particular the Internet or CDs could be used to disseminate specific recently developed techniques and applications to improve the understanding of the variability in the climate and its effect on agricultural production. Computer-aided learning is becoming more accessible and user-friendly. New modules are continually being developed, and this method of learning will always expand. It is becoming an essential learning tool for agricultural meteorologists. Examples that

can address the vulnerability of farmers include crop-climate matching, the use of indices, crop modelling and risk assessment together with seasonal outlooks. A strategy needs to be formulated to address these farmers' needs and implement changes in the education and training of agricultural meteorologists.

There is also a requirement to form a network for filling the gap between state-of-art development and operational use in agrometeorological services. This can be done by the establishment of a Regional Meteorological Training Centre (RMTC) where agrometeorologists can enhance their information technology skills because of increasing demands on climate and agronomic data for climate analysis at the regional scale, the inevitable use of computer technologies such as simulation models and GIS, and the need for agrometeorological information sharing among countries for sustainable agriculture.

Finally, any education and training programme for agricultural meteorologists must include practical applications oriented toward the unique local situations, and, ways and means to maintain good services to the public despite constantly changing circumstances.

7. Research and Development

Given the range of impacts of climate variability and projected climate change on agriculture and forestry in different regions of the world (see the section on impacts above), it is imperative that development and adoption of suitable adaptation strategies to cope with these impacts in different regions should be backed up by appropriate basic research. As Pérarnaud et al. (2004) described, it is indispensable to single out two types of adaptation depending on the final user: those which can be implemented by the farmer himself (modification of sowing dates, varietal choice, use of seasonal forecasts, etc.) and those of decision makers, land and natural resource managers which necessitate investment in development and construction of infrastructures.

Needs and perspectives for agrometeorology in the 21st century were obtained from a previous WMO (CAgM workshop, where research priorities were identified as support systems to agrometeorological services (Stigter et al., 2000). PéArnaud et al. (2005) identified the following as the priority areas for research, most of which takes place in industrialized countries, and its use in order to cope with climate variability and future climate change.

7.1. IMPROVED UNDERSTANDING OF THE VARIATION OF THE CURRENT CLIMATE AND ITS IMPACT ON AGRICULTURE

To study the impacts of climate change on agriculture and forestry and improve our understanding of certain mechanisms, it is important to gather regular information

on the ecosystems (inventories of land use per species, phenological observations, production statistics, etc.), and their evolution over the past few decades on a large scale. It is also important to analyze the extended series of climatic data on national territories over a period which extends from the end of the nineteenth century to the present day. These data should also be complemented by phenological series coming either from observations of the natural vegetation or forest species, or from the cultivated species, in particular the perennial species (fruit trees, vines, etc.).

7.2. SIMULATION OF FUTURE CLIMATE

Even though the predictions on global temperature are generally consensual, disparities exist in the behavior of the hydrological cycle in the regional responses to the increase in atmospheric greenhouse gas content. Questions also remain on the response of our natural environment to global warming, e.g., land use changes (particularly the natural or cultivated vegetation), the storage of carbon (particularly in the ocean and in the continental biosphere) or the possible modifications in oceanic circulation. Research on the regionalization of climatic changes must be carried out, with focus on improving the techniques themselves, but also the evaluation of the impact of climate change on agriculture and the environment. In relation to the forecasts currently available, there is a need to enlarge the range of variables considered, e.g., global solar radiation, as well as air humidity and wind speed, variables which affect agricultural and forestry production. Also, it would be necessary to obtain information not only on the average values, but also on the extremes (for example, for rainfall or wind speed) and exceeded threshold values (the case of frost).

7.3. FORECASTING CROP PRODUCTION

Climatic change carries several kinds of impacts on agriculture, e.g., on production (in terms of quantity and also quality), on the environment, on the species and land use changes, etc. The integration of these various components represents the main challenge to the research to be done and coordinated in the near future. Predictions must increasingly rely on crop simulation models that could effectively combine the effects of CO₂ and other climate variables on the physiological processes. Retrospective evaluation of the models with series of observed data, together with their sensitivity and uncertainty analyses are essential steps to build up confidence in model predictions. Taking account of the indirect effects linked to diseases, insects, as well as weeds, however, still remains a challenge.

It is essential to apply the simulation models to a spatial unit defined according to use (simulation unit) and then aggregate the results (yield, quantity of water

consumed by the crop, etc.) on the desired regional scale. One of the greatest difficulties lies in taking account of the spatial heterogeneity of the soil, which is not always available in digital form and, might suffer from a lack of precision in terms of georeferencing. The use of crop simulation models, which are not perfect, fed with spatialized information from diverse origins with varying degrees of uncertainty, leads to the propagation of errors which may distort the final results. It is therefore appropriate to carry out theoretical research to quantify such errors and try to minimize them.

7.4. FORECASTING THE DEVELOPMENT OF PARASITES, PESTS AND WEEDS

In natural ecosystems, and also in cultivated or forest ecosystems, climate change is capable of disturbing the balance between the species, whether they are plant and/or animal, both in terms of the individual and the population. These changes will also modify the development of weeds, diseases and parasites among the crops, as well as their area of distribution. In order to forecast these changes, epidemiological models should be coupled to crop simulation models. However, development of such models necessitates the acquisition of field data and practical knowledge on the development of diseases in the field. At the present time, few such models are available and it is essential that progress is made in this direction.

7.5. BETTER UNDERSTANDING OF THE ROLE OF BIODIVERSITY

By exceeding the local species tolerance limits or altering the balance between these species, climate change is capable of having a major direct or indirect impact (fire, anthropogenic pressures) on the biodiversity of natural as well as cultivated ecosystems. Conversely, it is possible that biodiversity constitutes a stability factor in the face of climate change. Understanding the dynamics between species therefore necessitates new functional ecophysiological and behavioral studies (for animals) but also the development of specific models which enable their simulation.

7.6. PREDICTING THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON SOIL

Future changes in the climate and the composition of the atmosphere as reflected by the evolution of thermal and rainfall regimes, the vegetation, and land use, will have an effect on the soil and its dynamics. Research needs to provide answers to questions on the role of soil as a sink as well as a source of CO₂ changes in soil usage, etc. Modelling will be able to provide information on the consequences of changing agrosystems and ecosystems management practices simultaneously.

7.7. QUANTIFYING CARBON SEQUESTRATION IN FORESTS

Climate change is projected to affect forests in different ecosystems around the world and in terms of research, it is important to

- quantify the stocks and fluxes of carbon in the large forest ecosystems,
- simulate the future of the sequestration of carbon in these major forest types based on a climatic scenario with high spatial resolution,
- inventory the various forestry practices which have a significant impact on the stocks and fluxes of carbon and estimate the impact of various forestry options on the sequestration of carbon in these ecosystems and their harvested products, and
- assess the vulnerability of woodland species to allow alternative proposals to be made: replacement of species, fire prevention methods, etc.

7.8. DEVELOPING NEW CROPPING SYSTEMS

Agriculture in the 21st century will have to make its contribution to the reduction of GHG emissions (principally CO₂, CH₄, N₂O) but also and above all to adapt to climate change to continue to satisfy the vital needs of populations for food, energy, fibres, etc. There are a number of promising technologies such as minimum tillage techniques combined with the use of mulches and ground cover plants, improved agroforestry systems etc., which could increase soil carbon storage while sustaining productivity, but it is often difficult to persuade farmers to adopt these often promising solutions for various economic or social reasons. It is therefore important to use integrated approaches, which take into account the farmers' decision-making process, to design operational systems. The development of innovative systems in response to many criteria necessitates combination of experimentation on the ground and complex models with varied but coupled processes.

8. Recommendations on Adaptations

Global surface average temperature and sea level are projected to rise under all IPCC scenarios. At the same time climate variability is expected to continue on seasonal to interannual and decadal time scales owing to natural variability induced by such factors as ENSO events and the IPO. These will promote increasingly stronger impacts on agriculture and forestry. The workshop produced a number of recommendations. However, presently agronomic adaptation has been effective in mid-latitude developed countries, but less effective in lower latitude developing

countries. With increasing climate change and variability though a wide range of adaptation strategies will be essential, coupled with mitigation options.

8.1. ADAPTATION RECOMMENDATIONS

1. Whether or not there will be significant climate change, inherent climatic variability makes adaptation unavoidable. These are embedded on issues such as sustainability of land productivity, changes in erosion, degradation and environmental quality, which also require due consideration.
2. Improved management strategies are required for coping with increasing climate variability and change. These can be drawn from both traditional and new technologies.
3. Standardization of crop models for widespread agrometeorological application are needed, with more modelling on the rainfall distribution and commencement for the rainy season in tropical and subtropical regions.
4. Changes in agronomic practices, such as earlier planting dates or cultivar substitution, and methods of microclimatic modification, for example, to cool animal environments as the climate warms.
5. Development of physiological based animal models with well developed climate components are needed urgently to cover gaps in knowledge and for future projections.
6. Improvement of carbon sequestration is required from agriculture and forestry by adopting permanent land cover, utilizing conservation tillage, reducing fallow land in summer, incorporating rotations of forage and improving nutrient management with fertilizers.

8.2. ADAPTATION AND MITIGATION IN TROPICAL REGIONS

1. Monitoring of crop development and growth together with appropriate climate information will improve management.
2. Development of water conservation strategies, both from traditional and modern practices is recommended for more efficient usage.
3. Increase the planting of shelterbelts or the use of scattered trees amongst crops for the reduction of erosion and wind damage and conservation of moisture.
4. Implementation of sustainable agriculture and forestry practices will both conserve land and improve yields over the long-term.
5. Development of innovative new technologies (e.g, climate forecasting) alongside traditional methods (e.g, intercropping, mulching) will be needed for yield improvement.

6. Development of adaptation strategies such as response farming at the local community level will engage active participation of the land users.

8.3. ADAPTATION AND MITIGATION IN TEMPERATE REGIONS

1. Earlier planting and sowing of crops as temperatures increase are recommended. This will utilize the higher temperatures earlier in the growing season and result in conserving soil moisture.
2. Earlier planting with the use of long season varieties to increase crop yields is a recommended adaptation strategy in cooler climate regions where soil moisture is adequate and the risk of heat stress is low.
3. In hotter regions, the introduction of shorter season varieties will provide a measure to avoid or reduce summer heat and water stress.
4. Introduce changed land allocation for the stabilization of production and conservation of soil moisture.
5. Plan the use of shorter crop rotations and routine crop thinning in areas that experience higher precipitation.
6. Reduce the impacts of drought and erosion by utilizing larger spacing in forestry plantation planting and later thinning.
7. Increase the application of integrated pest management techniques.

8.4. MITIGATION OPTIONS

1. Prevention of overgrazing of grasslands will produce a moderate improvement in soil carbon levels.
2. Allocation of summer fallow areas is recommended for pasture and rangeland agriculture so as to reduce emissions of nitrous oxide.
3. Introduction of reduced tillage intensity and summer fallow areas, improved manure management and feed rations with improved drainage and irrigation will all contribute to less emissions of carbon dioxide, methane and nitrous oxide.
4. Introduction of forage cropping into rangeland and pasture rotations can be applied for increasing the carbon sequestration.
5. Improved nutrient management with suitable fertilizers will aid the sequestration of carbon.

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