HEAT ISLANDS

Understanding and Mitigating Heat in Urban Areas

Lisa Gartland

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List of Acronyms and Abbreviations

ACC	asphalt cement concrete
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASTM	American Society for Testing of Materials
ATLAS	Advanced Thermal and Land Applications Sensor
AVHRR	Advanced Very High Resolution Radiometer
BUR	built-up roofing
CAMx	comprehensive air quality model with extensions
CRRC	Cool Roof Rating Council
CSPE	chlorosulphonated polyethylene
dbh	diameter at breast height
DOE	US Department of Energy
EA	Energy & Atmosphere
EPA	US Environmental Protection Agency
EPDM	ethylene propylene diene monomer
EPS	expanded polystyrene
GIS	geographical information system
IPM	integrated pest management
LBNL	Lawrence Berkeley National Laboratory
LEED	Leadership in Energy and Environmental Design
MIST	mitigation impact screening tool
MR	Materials & Resources
NASA	National Aeronautics and Space Administration
NOx	nitrogen oxides
NRCA	National Roofing Contractors Association
OFP	ozone-forming potential
ORNL	Oak Ridge National Laboratory
PCC	Portland cement concrete
PM10	particles less than 10μm in diameter
PVC	polyvinyl chloride
RFP	request for proposal
RSST	repeated simple shear test
SP	single-ply
SPF	spray polyurethane foam
SRI	solar reflectance index
SS	Sustainable Sites
TPO	thermoplastic polyolefin
USDA	US Department of Agriculture
VOC	volatile organic compound

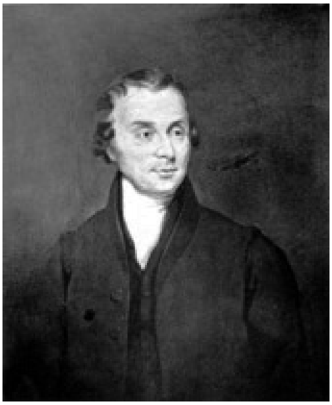
1

What is a Heat Island?

Heat island definition

Urban and suburban areas have long been observed to have heat islands, a 'reverse oasis' where air and surface temperatures are hotter than in their rural surroundings. The heat island phenomenon has been found in cities throughout the world.

The first documentation of urban heat occurs in 1818 when Luke Howard's groundbreaking study of London's climate (see Figure 1.1) found 'an artificial excess of heat' in the city compared with the country (Howard, 1833). Emilien Renou made similar discoveries about Paris during the second half of the 19th century (Renou, 1855, 1862, 1868), and Wilhelm Schmidt found these conditions in Vienna early in the 20th century (Schmidt, 1917, 1929). Study of heat islands in the US began in the first half of the 20th century (Mitchell, 1953, 1961).



Source: www.cloudman.com/luke_howard.htm.

Figure 1.1 Luke Howard (1772–1864) of London, an amateur meteorologist, was the first serious practitioner of urban climatology

Heat islands form in urban and suburban areas because many common construction materials absorb and retain more of the sun's heat than natural materials in less-developed rural areas. There are two main reasons for this heating. First, most urban building materials are impermeable and watertight, so moisture is not readily available to dissipate the sun's heat. Second, dark materials in concert with canyon-like configurations of buildings and pavement[1] collect and trap more of the sun's energy. Temperatures of dark, dry surfaces in direct sun can reach up to 88°C (190°F) during the day, while vegetated surfaces with moist soil under the same conditions might reach only 18°C (70°F). Anthropogenic heat, or human-produced heat, slower wind speeds and air pollution in urban areas also contribute to heat island formation.

In colder cities at higher latitudes and elevations, the winter warming effects of the heat island are seen as beneficial. In some urban areas during the summer, shade around buildings can even create cooler areas for parts of the day. But in most cities throughout the world, the effects of the summer heat island are seen as a problem. Heat islands contribute to human discomfort, health problems, higher energy bills and increased pollution. On top of the effects of global warming, heat islands are further reducing the habitability of urban and suburban areas. Considering that more than 75 per cent of the world's population lives in these areas (United Nations, 2002), heat island impacts are extremely consequential.

This book focuses on the negative effects of heat islands and gives strategies for reducing their impacts. In this first chapter, heat island impacts are briefly reviewed, and examples from cities around the world are used to demonstrate heat island characteristics. Subsequent chapters examine the causes of heat islands; how to measure heat islands; current land use characteristics and construction practices; and the three mitigation strategies, cool roofing, cool paving and trees and vegetation, that can cool communities. The final two chapters cover the community-wide benefits that heat island mitigation can bring, and put forward an action plan communities can follow to reduce their heat island impacts.

Impacts of heat islands

Why should we care about heat islands? Because their negative impacts affect so many people in so many ways. Heat islands do not just cause a bit of additional, minor discomfort. Their higher temperatures, lack of shade and role in increasing air pollution have serious effects on human mortality and disease. They waste money by increasing the need for energy use, for building and infrastructure maintenance, for the management of stormwater run-off and for the disposal of waste. In addition, the barren construction techniques that foster heat islands tend to be unattractive, unappealing and unhealthy for urban flora and fauna.

As shown throughout this book, the benefits of mitigating heat islands are very large. The implementation of cool roofing, cool paving and trees and vegetation bring many direct impacts to the owners and occupants of the spaces where they are implemented. These direct benefits are described for each measure in Chapters 5, 6 and 7. When implemented on a wider scale, these measures can affect entire communities, and these community benefits are presented in Chapter 8.

Characteristics of heat islands

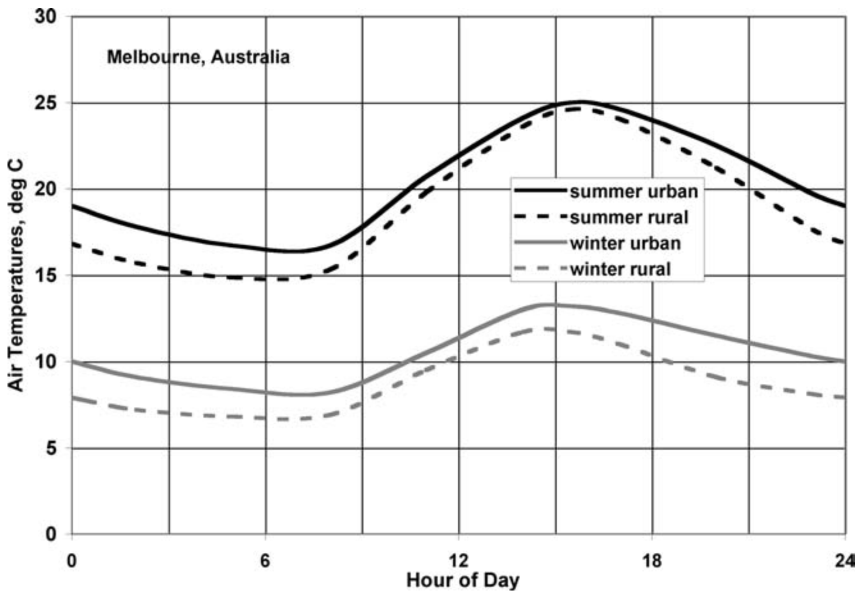
Heat islands exhibit five common characteristics:

1 When compared to undeveloped, rural areas, a heat island is warmer in general, with distinct daily patterns of behaviour. Heat islands are often warmest, relative to rural surroundings, after the sun goes down, and coolest after the sun rises. Urban air in the 'canopy layer', below the tops of trees and buildings, can be as much as 6°C (10°F) warmer than the air in rural areas.
2 Air temperatures are driven by the heating of urban surfaces, since many man-made surfaces absorb more of the sun's heat than natural vegetation does.
3 These differences in air and surface temperatures are enhanced when the weather is calm and clear.
4 Areas with the least vegetation and greatest development tend to be hottest, and heat islands tend to become more intense as cities grow larger.
5 Heat islands also display warmer air in the 'boundary layer', a layer of air up to 2000 metres (6500 feet) high. Heat islands often create large plumes of warmer air over cities, and temperature inversions (warmer air over cooler air) caused by heat islands are not uncommon.

These characteristics are described in detail in the rest of this chapter.

Hotter air temperatures

Heat islands have air temperatures that are warmer than temperatures in surrounding rural areas. The difference between urban and rural air temperatures, also called the heat island strength or intensity, is often used to measure the heat island effect. This intensity varies throughout the day and night. In the morning, the urban–rural



Note: Temperature conversion: (°C × 1.8) + 32 = °F.

Source: Morris and Simmonds, 2000.

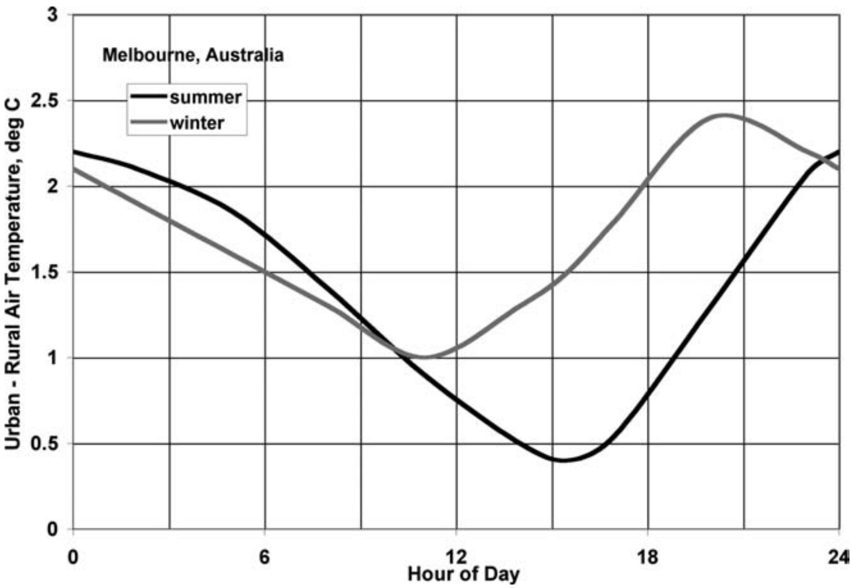
Figure 1.2 Summer and winter air temperatures in the central business district (urban) and airport (rural) of Melbourne, Australia

temperature difference is generally at its smallest. This difference grows throughout the day as urban surfaces heat up and subsequently warm the urban air. The heat island intensity is usually largest at night, since urban surfaces continue to give off heat and slow the rate of night-time cooling.

Figures 1.2 and 1.3 show air temperatures and heat island intensity for typical summer and winter days in a heat island. Figure 1.3 plots daily variations in air temperature in the central business district and at the airport of Melbourne, Australia (Morris and Simmonds, 2000). These daily profiles are averaged from hourly data for December 1997 and for January and February 1998 (summer) and for June, July and August 1998 (winter). This plot shows that temperatures are always warmer in the central business district than they are at the airport. From Figure 1.2, which plots the difference between the urban and rural air temperatures, it is seen that the heat island is strongest at night [2.4°C (4.3°F) differential at 8:00pm in winter, 2.2°C (4.0°F) at midnight in summer] and weakest during the day [1.0°C (1.8°F) at 11.00am in winter, 0.4°C (0.7°F) at 3.00pm in summer.

The daily pattern of the Melbourne heat island – with its intensity peaking overnight and gradually diminishing during the day – is characteristic of heat island behaviour in most cities of moderate climate and latitude. But the heat island intensity varies in its magnitude and the timing of its peak from city to city. Peak heat island magnitudes as large as 7°C (12°F) have been recorded (Moll and Berish, 1996). These peaks usually occur three to five hours after sunset (Oke, 1987), but are sometimes delayed until after sunrise. The timing of the peak depends on the properties of urban materials. Cities built of materials that release heat more quickly (such as dry soil and wood) reach peak heat island intensity sooner after sunset, while those made of materials that release heat more slowly (such as concrete and stone) may not reach their peak until sunrise.

In cold northern climates and some desert climates, the urban–rural air temperature difference during the day can actually be less than zero, creating a daytime 'cool island'. For



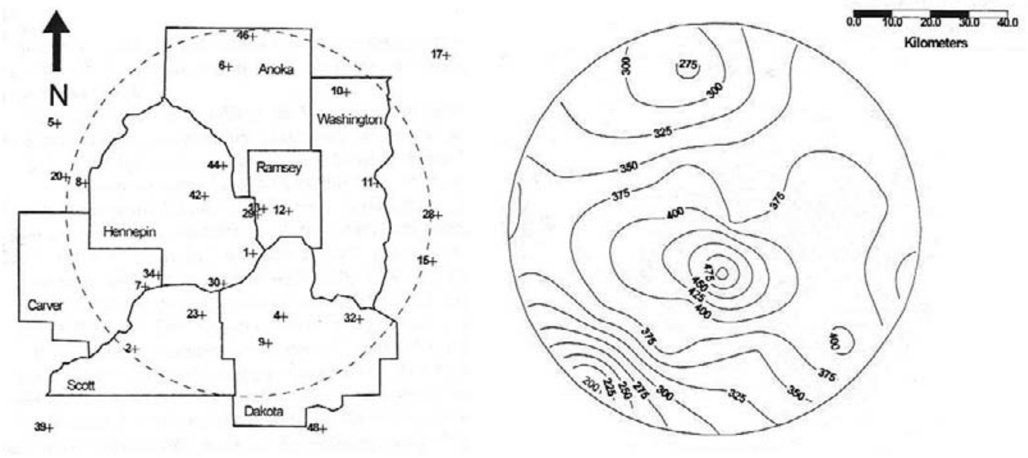
Source: Morris and Simmonds, 2000.

Figure 1.3 Summer and winter differences in air temperature between the central business district and the airport of Melbourne, Australia

example, in Reykjavik, Iceland, the heat island magnitude on summer days can be as low as *negative* 4°C (7°F) (Steinecke, 1999), so the city is actually cooler than its rural surroundings. This occurs mainly because the relatively low summer sun casts long building shadows in northern cities. In the desert city of Phoenix, Arizona, a similar cooling phenomenon, called the oasis effect, has been noted. More landscaping and irrigation in developed areas keep peak daytime temperatures 1–2°C (2–4°F) cooler than in the surrounding rural desert (Brazel et al, 2000). However, the heat island is still a factor in Phoenix, since urban night-time air temperatures run 3–8°C (5–15°F) hotter than rural temperatures, and have been showing a steady increase of about 0.5°C (0.9°F) per decade over the past half-century (Brazel et al, 2000).

Many cities have been studied using more than just the single urban–rural pair of temperatures to evaluate the heat island effect. Air temperatures have been surveyed in multiple locations throughout cities, and have shown that heat island intensity is greatest in areas with dense construction and little vegetation. For example, cooling degree–days were calculated for 26 locations around Minneapolis–St Paul (Todhunter, 1996). The higher the number of cooling degree–days, the warmer the location and the stronger the heat island is in that location. Figure 1.4 shows the measurement locations and a corresponding contour map of the Minneapolis–St Paul region's cooling degree–days. A heat island with the highest number of cooling degree–days is centred on the most urban location.

Another study of the spatial variation in heat island intensity was done in Tokyo, Japan, in 1990 (Yamashita, 1996). Temperatures were measured from moving trains along 16 rail lines in and around Tokyo, as shown in Figure 1.5. Figure 1.6 shows air temperature measurements made along the central Chuo Line in Tokyo. In summer, the temperature increase from suburban to urban locations was a fairly gradual 1.0–1.5°C (1.8–2.7°F). In winter, the temperature increases were larger at 4–5°C (7.2–9.0°F) and were more defined. Figure 1.7 maps the temperatures found along all 16 Tokyo train lines (Yamashita, 1996).

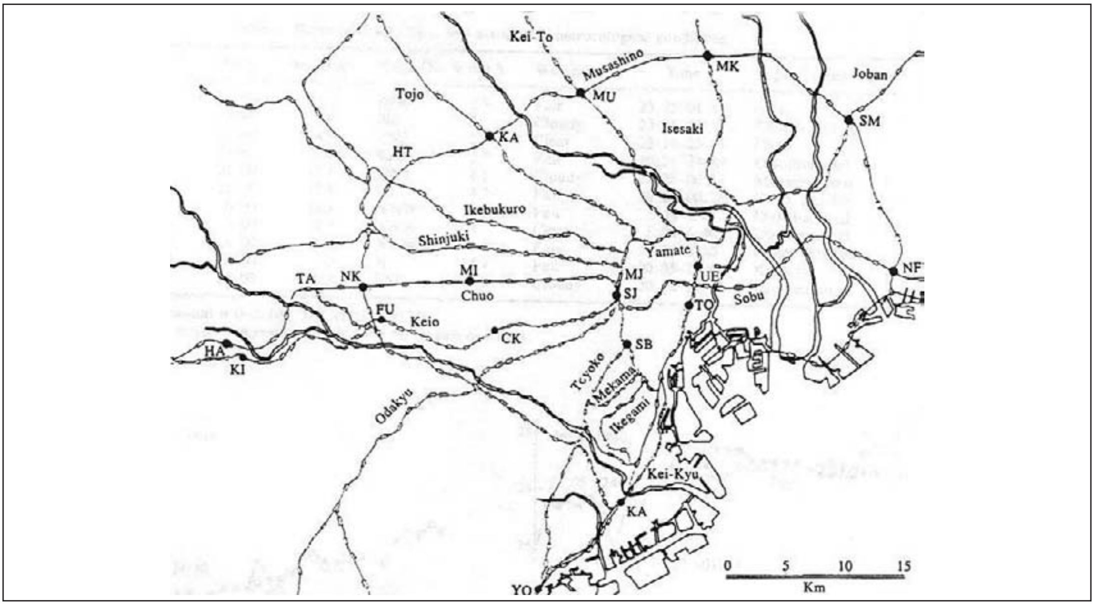


Source: Todhunter, 1996.

Figure 1.4 Minneapolis–St Paul, Minnesota Metropolitan Area: (left) locations of 26 weather stations (numbered crosses), (right) contours of cooling degree–days in degrees centigrade above the 18.3°C threshold temperature

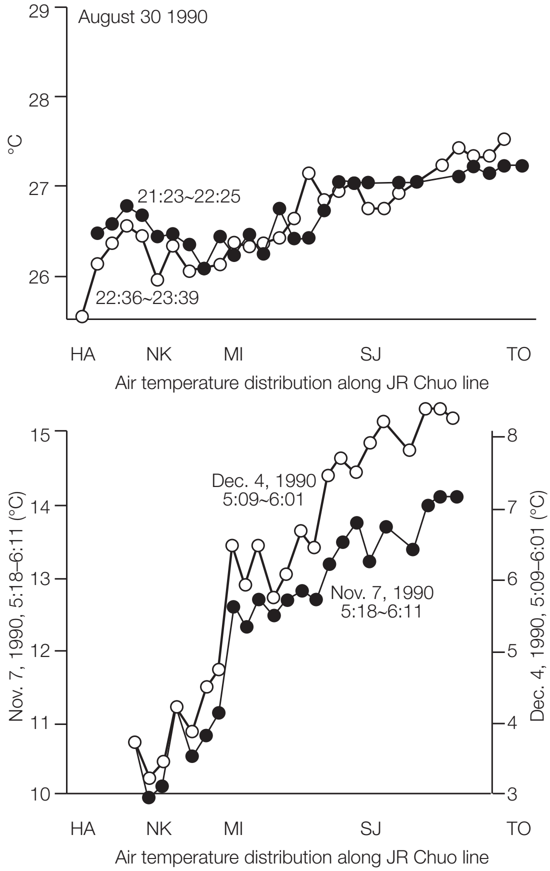
In August at night, a large heat island plateau with an intensity of 3°C (5.4°F) formed over metropolitan Tokyo. On a November morning, the heat island structure was more complex, but there was a distinct plateau over central Tokyo with an intensity of 5°C (9°F).

A study in Granada, Spain, also showed a more intense heat island over densely developed terrain. Figures 1.8 and 1.9 show results from a mobile traverse of 84 locations around the city (Montavez et al, 2000). The air temperature contours for winter nights in Granada are plotted in Figure 1.8. Areas with different land uses are designated by different patterns. The map shows air temperature peaks in areas with the largest ratios of building height to street



Source: Yamashita, 1996.

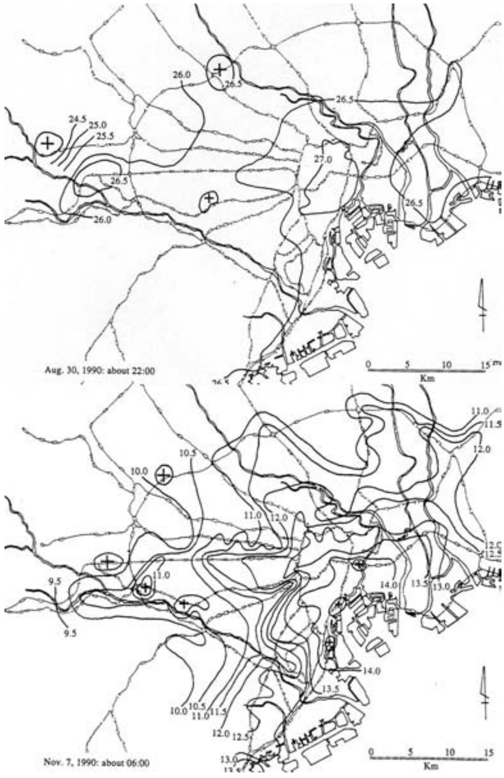
Figure 1.5 Map of Tokyo, Japan, showing the train line network along which heat island measurements were made



Note: HA, Hachioji; NK, Nishi-Kokubunji; MI, Mitaka; SJ, Shinjuku; TO, Tokyo. The distance from Hachioji to Tokyo is about 150 kilometres (about 95 miles).

Source: Yamashita, 1996.

Figure 1.6 (top) Air temperatures measured along the central Chuo Line in Tokyo, Japan, in August 1990 (~10:30pm) and (bottom) in November and December 1990 (~5:30am)



Note: The crosses show the centre points of the temperature contours.

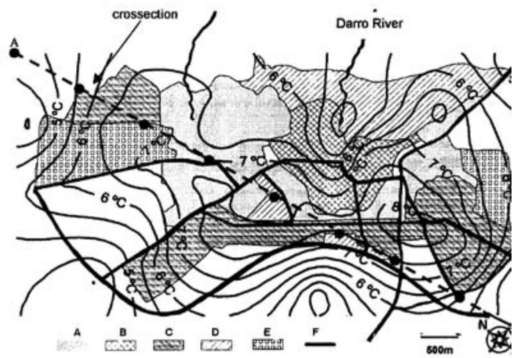
Source: Yamashita, 1996.

Figure 1.7 (top) Tokyo temperature contours derived from mobile traverse measurements made in August 1990 (~10:30pm) and (bottom) in November 1990 (~5:30am)

width (land use type C). Temperature traverses across the width of Granada are shown in Figure 1.9. Three traverses taken on the same night show how air temperatures increase from the rural areas at endpoints A and B to the urban peak in the middle of the traverse. Temperatures in urban areas are 3–3.5°C (5.4–6.3°F) hotter than temperatures in rural areas. At the centre of this traverse, a 1°C (1.8°F) temperature dip shows the cooling effect of an urban park. As the night wears on, the effect of this park is minimized by air mixing throughout the city.

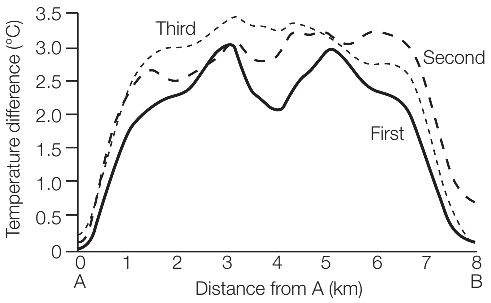
Hotter surface temperatures

Hotter surface temperatures are another distinctive characteristic of the heat island effect. Surface temperatures are much more variable than air temperatures over the course of a day. Many urban surfaces such as roofs and pavements are routinely heated by the sun to temperatures 27–50°C (50–90°F) hotter than the air. Air temperatures in a typical mid-latitude US city range from 15 to 38°C (60–100°F) on summer days, and urban surfaces can reach peak temperatures of 43–88°C (110–190°F). At night these surfaces emit this collected heat, often cooling all the way back down to the air temperature.



Source: Montavez et al, 2000.

Figure 1.8 Air temperature contours in Granada, Spain, on winter nights with clear skies and light winds. Pattern A: buildings with 7–10 floors and broad streets, B: 2–4 floors, narrow streets, C: 9–10 floors, broad streets, D: gardens, E: 7–10 floors, broad streets, F: principal roads, white: rural areas



Source: Montavez et al, 2000.

Figure 1.9 Air temperature variations along the dashed line AB in Figure 1.8 measured successively over a single winter night in Granada, Spain

Conversely, trees, grass and other vegetation tend to stay cool in the summer sun. As long as the vegetation is properly hydrated, vegetation stays at or below air temperature.

The magnitude and importance of urban surface temperatures in a heat island were not fully appreciated until they were first visualized from the air in the 20th century. Satellites and specially equipped aircraft are able to map temperatures on the Earth's surface and have found very distinguishable hot spots in and around urban areas all over the world.

The Explorer Mission 1 program of 1978 was one of the first in which satellite data were used to observe urban heat. Special equipment, called a heat capacity mapping radiometer, measured surface temperatures in the Buffalo, New York, area. Figure 1.10 (see Plate 1) shows thermal contours drawn over the visible image of Buffalo on a clear summer afternoon in 1978. Surface temperatures are hotter on city blocks and cooler in urban parks and suburban areas.

A more detailed look at urban surface temperatures can be obtained from aircraft, since they can fly closer to the Earth's surface and collect higher resolution images. An example of a flyover of Sacramento, California, is shown in Figure 1.11 (see Plate 2). This image was captured by the National Aeronautics and Space Administration (NASA) from a Lear jet equipped with the Advanced Thermal and Land Applications Sensor (ATLAS). The resolution of 10 metres per pixel allows individual buildings to be identified. For example, centred about two-thirds of the way down the image, the red spot in the rectangle of blue and green shows the roof of the California State Capitol building, surrounded by the trees and grass of its grounds. In the crook of the convergence of the American and Sacramento Rivers, the extensive red areas are industrial building rooftops, parking lots and rail yards.

Various studies have been done to determine how surface temperatures affect air temperatures in urban areas (Imamura, 1989; Kawashima et al, 2000; Watkins et al, 2002). Relationships have been found between the remotely sensed surface temperatures and the air temperatures for different cities. These relationships have been found to be highly dependent on weather conditions, so in cloudy, windy weather, the effects of surface temperatures on air temperatures are diminished. These relationships generally apply to a particular urban area only, so unfortunately, the correlation for Tokyo cannot be extended to a city with different climate, geography or development patterns.

Source: Schott and Schimminger, 1981.

Figure 1.10 Surface temperature contours (in degrees centigrade) over a map of Buffalo, New York, on 6 June 1978 at 2:00pm EDT derived during the Explorer satellite's heat capacity mapping mission (see Plate 1 for a colour version

Larger effects during clear, calm weather

The heat island effect is strongest during calm, clear weather and is weakest during cloudy, windy weather, since more solar energy is collected on clear days, and calmer winds remove heat more slowly, making the heat island more intense. Figure 1.12 shows the effect weather conditions can have on the heat island. Measurements were made at a pair of urban–rural stations in Bucharest, Romania, in 1994 (Tumanov et al, 1999). Under cloudy and windy conditions, urban–rural temperature differences are a modest 1°C (1.8°F) at night. Under calm and clear conditions, the heat island intensity is much larger, at up to 3.6°C (6.5°F).

Increases with development

As cities expand over time, the heat island also tends to expand and become more intense. The analysis of historic weather data often uncovers an intensification of the heat island coinciding with urban and suburban development. Figures 1.13 and 1.14 (Plates 3 and 4) show the effect of increasing urbanization in two Phoenix, Arizona, locations, and in Mesa and Tempe, Arizona, over the past century. Maximum and minimum air temperatures in these cities are compared to temperatures in Sacaton, a rural area in the Arizona desert. As shown in Figure 1.13, maximum temperatures in these urban and suburban areas have increased slightly or stayed about the same relative to temperatures in

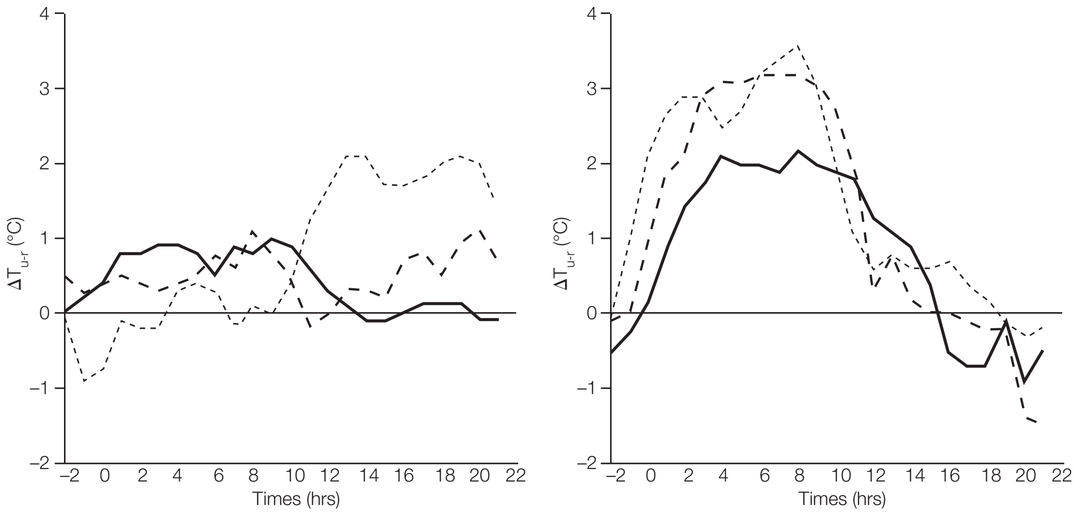
Source: Gorsevski et al, 1998.

Figure 1.11 Thermal image of downtown Sacramento, California, on 29 June 1998 at noon, derived from a flyover in a Lear jet by NASA's ATLAS program (see Plate 2 for a colour version)

Sacaton. However, minimum temperatures, recorded at night, shown in Figure 1.14 have increased by about 4°C (7°F) in Phoenix, Mesa and Tempe relative to temperatures in Sacaton. This indicates that these cities are storing more heat during the day and releasing it at night, thus increasing the intensity of the heat island over the years. These increases correspond to the development of these cities over the past century and are evidence of a link between urban development and the heat island phenomenon.

Thermal inversions

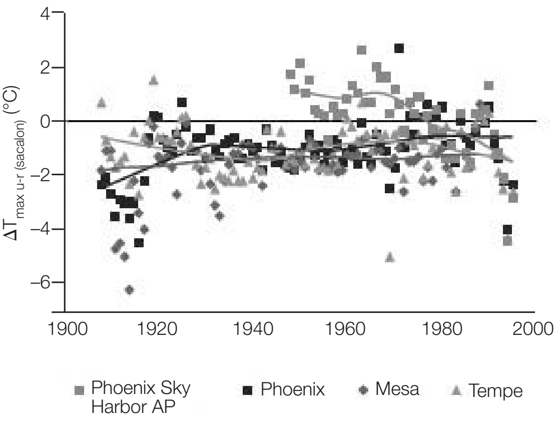
So far this chapter has been concerned with the heat island's effects on temperatures in the 'canopy layer' below the tops of buildings and trees. The heat island also affects air temperatures above the trees and buildings of urban and suburban areas. Effects are seen in the boundary layer, the lowest 2000 metres (6500 feet) or less of the Earth's atmosphere, where heat and drag from the Earth's surface create turbulence.



Source: Tumanov et al, 1999.

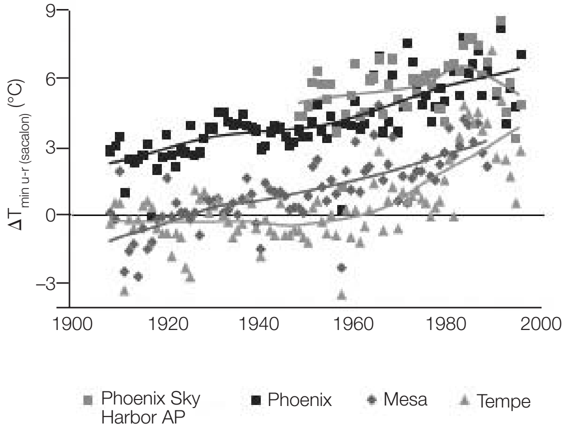
Figure 1.12 Temperature difference between the urban Filaret and rural Banasea areas of Bucharest, Romania. On the left, cloudy and windy conditions (solid – spring, dashed – summer, dotted – summer with morning clouds). On the right, calm and clear conditions (solid – winter, dashed – spring, dotted – summer). Time is relative to sunset, so 0 is sunset, 2 is two hours after sunset and –2 is two hours before sunset

Air in the atmosphere is subject to two competing tendencies. First, air pressure is lower at higher altitudes, causing air to expand and cool slightly with altitude. This occurs at a naturally occurring rate called the adiabatic lapse rate. The term 'adiabatic' means that the air does not gain



Source: Brazel et al, 2000.

Figure 1.13 Differences between the monthly averages of *maximum* temperatures at Phoenix's Sky Harbor airport, and in urban Phoenix, urban Mesa and suburban Tempe, Arizona, and the rural desert of Sacaton, Arizona, over the past century (see Plate 3 for a colour version)



Source: Brazel et al, 2000.

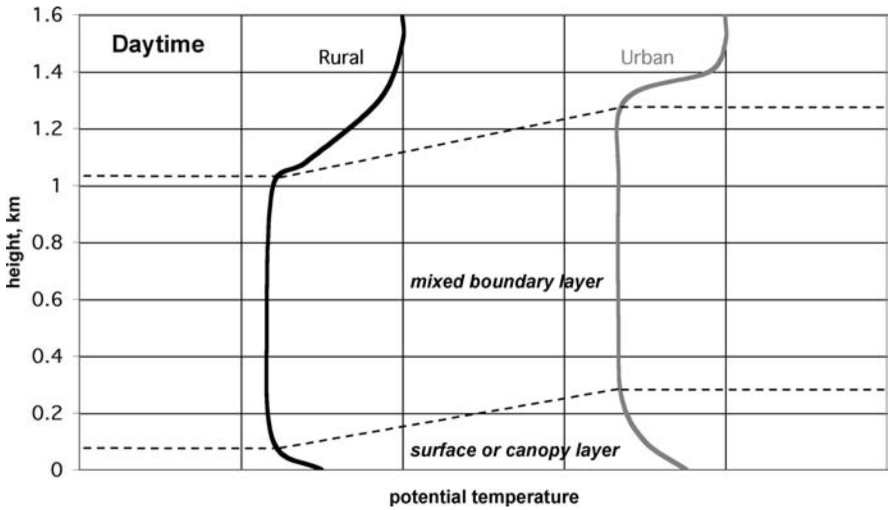
Figure 1.14 Differences between the monthly averages of *minimum* temperatures at Phoenix's Sky Harbor airport, and in urban Phoenix, urban Mesa and suburban Tempe, Arizona, and the rural desert of Sacaton, Arizona, over the past century (see Plate 4 for a colour version) or lose any energy or heat with the change in altitude. The adiabatic lapse rate varies depending on the amount of moisture in the air. It ranges between a high of 10°C per 1000 metres (5.5°F per thousand feet) for dry air to a low of 6°C per 1000 metres (3.3°F per thousand feet) for moist air. Because of this characteristic, air in the atmosphere is normally cooler at higher altitudes.

The second atmospheric tendency is for heated air to rise. During the day, solar energy heats the Earth's surfaces and these surfaces in turn heat the air above them. Warm air expands and becomes lighter, causing it to rise into the atmosphere. If enough heating occurs, a thermal inversion of warm air over cool air can occur at various levels of the atmosphere.

These two tendencies direct the behaviour of the atmosphere during the calm, clear conditions that most favour the formation of a heat island. Urban and suburban areas tend to experience more heating than rural areas. This extra heat fuels thermal inversions that trap warm air and pollution near the ground in urban areas at night.

Figures 1.15 and 1.16 show typical daytime and night-time temperature profiles in the Earth's boundary layer in both rural and urban areas. During the day, air is warmed at the Earth's surface and rises into the cooler air of the boundary layer, where it mixes with atmospheric air to form a boundary layer of constant temperature. This mixing propels the warm air upwards to the top of the boundary layer, where a thermal inversion of warmer air over cooler air forms. Because urban surfaces collect and release more heat, the boundary layer is thicker and warmer in urban areas than in rural areas.

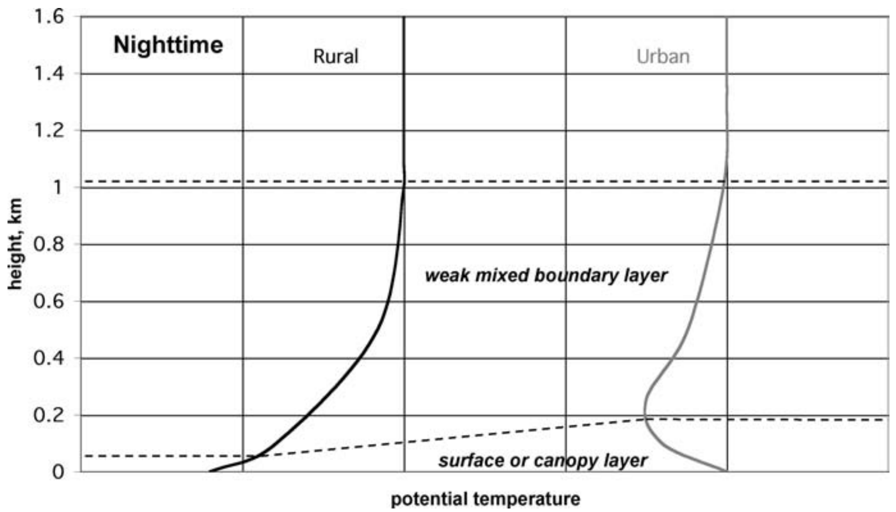
At night in rural areas, the Earth's surface is cooler than the air above it. Since the air is not being heated by the surface, warm air is no longer rising. The air instead settles into a ground level thermal inversion, or a stable mass of cool air close to the ground and warmer air above. The air over an urban area behaves differently at night. Since urban surfaces stay warmer, they continue to heat the air above them after sunset. These heating and mixing effects are weaker at night than during the day, so heated air does not rise and mix throughout the entire boundary layer. Instead, as shown in Figure 1.16, a thermal inversion (warm air over cool air) forms at the top of the canopy layer. This inversion tends to stop the rise of warmer air from the city, trapping it in the canopy layer close to the ground.



Note: kilometres × 3280 = feet.

Source: Oke, 1987.

Figure 1.15 Typical daytime potential temperature profiles over rural and urban areas; potential temperatures have been corrected for changes due to altitude

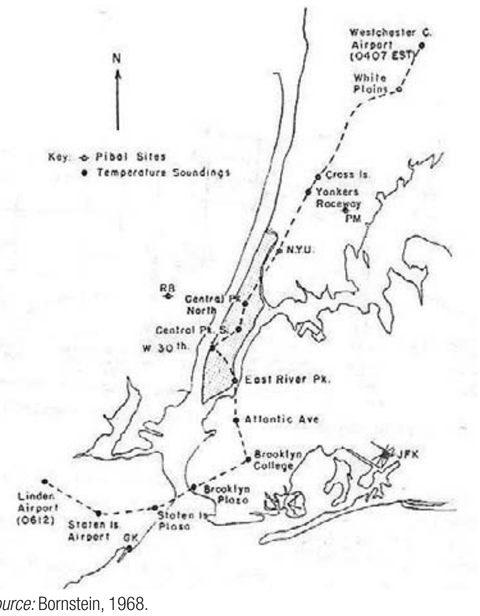


Source: Oke, 1987.

Figure 1.16 Typical night-time potential temperature profiles over rural and urban areas; potential temperatures have been corrected for changes due to altitude

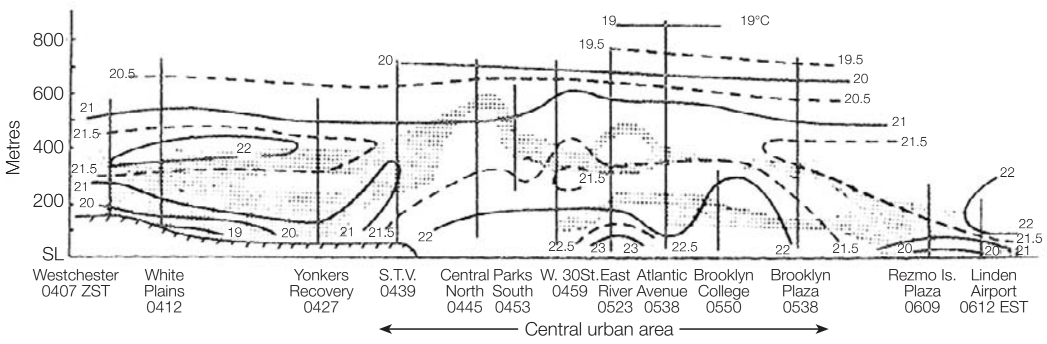
Measuring air temperatures at many locations above a city and its surroundings can give a better understanding of the heat island's effect on the local climate. A good example is a 1968 study of New York City in which a helicopter flew over the city taking vertical temperature and pressure measurements over specific locations (Bornstein, 1968). Figure 1.17 shows the flight path taken and Figure 1.18 charts the temperature profiles over the city at sunrise on a calm, clear summer day. Air temperatures close to the surface were warmest near the centre of the city and coolest in rural areas. Low-level temperature inversions were seen over the rural areas (Westchester and Linden Airport), while stronger inversions were seen at higher elevations over the urban centre.

The effects of the heat island on temperature profiles above the city have also been studied as they develop overnight. Vertical temperature measurements were made from helicopter flights over St Louis, Missouri, in 1975. Figure 1.19 shows how temperature profiles change over rural and urban areas. Overnight, the air above the rural area cools, creating a thermal inversion of warm air above cooler air close to the surface. The urban site does not cool as much as the rural site and creates a temperature inversion about 650 feet (200 metres) above the surface that traps warmer air in the canopy layer.



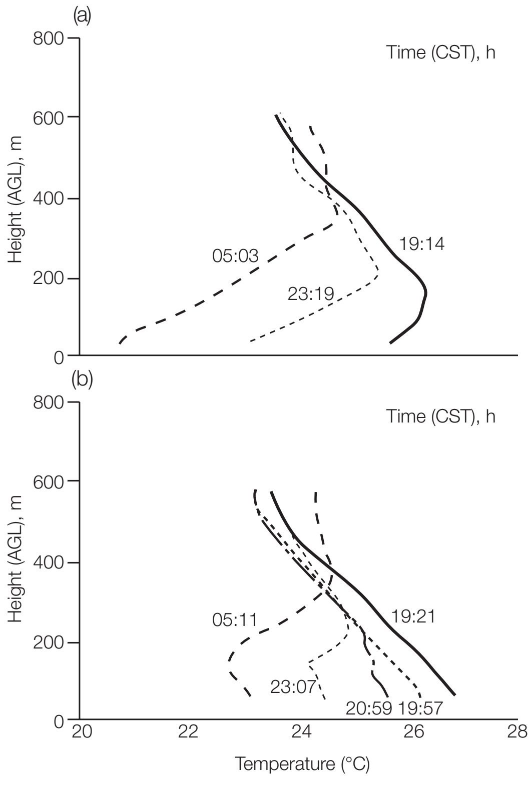
Source: Bornstein, 1968.

Figure 1.17 Map of New York City area showing the flight path taken by an instrumented helicopter on 16 July 1964



Source: Bornstein, 1968.

Figure 1.18 Actual vertical and horizontal temperature distributions in degrees centigrade at sunrise along the New York City flight path on 16 July 1964



Note: Metres × 3.28 = feet.

Source: Godowitch et al, 1985.

Figure 1.19 Rural (above) and urban (below) actual temperature profiles in St Louis, Missouri, on 26–27 July 1975 around sunrise and sunset

Note

1 Pavement: in this text pavement refers to all paved surfaces including road carriageways, parking areas, footpaths, cycle paths, driveways and so on.

References

Bornstein, R. D. (1968) 'Observations of the urban heat island in New York City'. *Journal of Applied Meteorology* **7**: 575–582

Brazel, A., N. Selover, R. Vose and G. M. Heisler (2000) 'The tale of two climates – Baltimore and Phoenix urban LTER sites'. *Climate Research* **15**: 123–135

Godowitch, J. M., J. K. S. Ching and J. F. Clarke (1985) 'Evolution of the nocturnal inversion layer at an urban and nonurban location'. *Journal of Climate and Applied Meteorology* **24**: 791–804

Gorsevski, V., H. Taha, D. Quattrochi and J. Luvall (1998) *Air Pollution Prevention Through Urban Heat Island Mitigation: An Update on the Urban Heat Island Pilot Project*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Howard, L. (1833) *The Climate of London: Deduced from Meteorological Observations Made in the Metropolis and at Various Places Around it*. London, Harvey and Darton

Imamura, R. (1989) *Air–Surface Temperature Correlations. Controlling Summer Heat Islands.* Berkeley, CA, Lawrence Berkeley Laboratory

Kawashima, S., T. Ishida, M. Minomura and T. Miwa (2000) 'Relations between surface temperature and air temperature on a local scale during winter nights'. *Journal of Applied Meteorology* **39**: 1570–1579
Mitchell, J. M. (1953) 'On the causes of instrumentally observed secular temperature trends'. *Journal of Meteorology* **10**: 244–261
Mitchell, J. M. (1961) 'The temperature of cities'. *Weatherwise* **14**: 224–229, 258
Moll, G. and C. Berish (1996) 'Atlanta's changing environment'. *American Forests* Spring: 26–29
Montavez, J. P., A. Rodriguez and J. I. Jimenez (2000) 'A study of the urban heat island of Granada'. *International Journal of Climatology* **20**: 899–911
Morris, C. J. G. and I. Simmonds (2000) 'Associations between varying magnitudes of the urban heat island and the synoptic climatology in Melbourne, Australia'. *International Journal of Climatology* **20**: 1931–1954
Oke, T. R. (1987) *Boundary Layer Climates.* New York, Routledge
Renou, E. (1855) 'Instructions météorologiques'. *Annuaire Société Météorologie de France* **3**(1): 73–160
Renou, E. (1862) 'Différences de température entre Paris et Choisy-le-Roi'. *Annuaire Société Météorologique de France* **10**: 105–109
Renou, E. (1868) 'Differences de temperature entre la ville et la campagne'. *Annuaire Société Météorologie de France* **3**: 83–97
Schmidt, W. (1917) 'Zum Einfluss grosser Städte auf das Klima'. *Naturwissen* **5**: 494–495
Schmidt, W. (1929) 'Die Verteilung der Minimumtemperaturen in der Frostnacht des 12 Mai 1927 im Gemeindegebiet von Wien'. *Fortschritte der Landwirtschaft* **2**(21): 681–686
Schott, J. R. and E. Schimminger (1981) *Data Use Investigations for Applications, Explorer Mission A (Heat Capacity Mapping Mission).* Greenbelt, Maryland, National Aeronautics and Space Administration, 129
Steinecke, K. (1999) 'Urban climatological studies in the Reykjavik subarctic environment, Iceland'. *Atmospheric Environment* **33**: 4157–4162
Todhunter, P. E. (1996) 'Environmental indices for the twin cities metropolitan area (Minnesota, USA) urban heat island – 1989'. *Climate Research* **6**: 59–69
Tumanov, S., A. Stan-Sion, A. Lupu, C. Soci and C. Oprea (1999) 'Influences of the city of Bucharest on weather and climate parameters'. *Atmospheric Environment* **33**: 4173–4183
United Nations (2002) *World Urbanization Prospects, The 2002 Revision.* New York, NY, Department of Economic and Social Affairs, Population Division, United Nations
Watkins, R., J. Palmer, M. Kolokotroni and P. Littlefair (2002) 'The London heat island – surface and air temperature measurements in a park and street gorges'. *ASHRAE Transactions* **108**(1): 419–427
Yamashita, S. (1996) 'Detailed structure of heat island phenomena from moving observations from electric tram-cars in metropolitan Tokyo'. *Atmospheric Environment* **30**(3): 429–435

2

Causes of the Heat Island

Introduction

To reduce the effects of heat islands, you must first understand their causes. In 1833, Luke Howard first hypothesized that excess heat in cities was due to humans, animals and 'fires' (various sources of combustion) in the winter. Noting that urban areas were still warmer in the summer, Howard attributed this to higher absorption of solar radiation on a city's 'collection of vertical surfaces' and a lack of moisture available for evaporation (Howard, 1833).

Howard's theories were surprisingly accurate. Further study over the past century has determined that urban surfaces are hotter than rural surfaces for two main reasons. *First*, man-made surfaces are generally composed of dark materials that readily absorb and store the sun's heat. Exacerbating this high solar absorptance, buildings and pavements form canyons that tend to trap reflected heat. *Second*, most building materials are watertight, so rainwater runs away and cannot dissipate heat by evaporation (or evapotranspiration, when plants are involved). During the day, temperatures of barren, impermeable surfaces can reach 190°F; more natural vegetated surfaces might only reach 70°F. Hotter surface temperatures lead to hotter air temperatures, especially at night, when the hot surfaces cool slowly and warm the air around them.

There are several other reasons for the heat island phenomenon. Urban heat generation from heating, cooling, transportation and industrial processes has an effect, and, as Howard surmised, this is generally more important in winter than in summer. Buildings also slow the average wind speed, delaying the transfer of heat from surfaces to the air. Higher levels of urban air pollution also play a role, since particles in the air absorb and emit heat to a city's surfaces.

The previous chapter described heat island characteristics without much explanation of their origins. Heat islands have been shown to exhibit:

- hotter air temperatures
- hotter surface temperatures
- larger effects during clear, calm weather
- increases over time
- thermal inversions.

But what causes these phenomena? As explained above, there is no single cause of the heat island. Instead, many factors combine to warm cities and suburbs. The leading urban characteristics contributing to heat island formation are listed in Table 2.1.

These characteristics can be sorted into the five main causes of heat island formation:

- reduced evaporation
- increased heat storage
- increased net radiation
- reduced convection
- increased anthropogenic heat.

Table 2.1 Urban and suburban characteristics important to heat island formation and their effect on the energy balance of the Earth's surface

Characteristic contributing to heat island formation	Effect on the energy balance
Lack of vegetation	Reduces evaporation
Widespread use of impermeable surfaces	Reduces evaporation
Increased thermal diffusivity of urban materials	Increases heat storage
Low solar reflectance of urban materials	Increases net radiation
Urban geometries that trap heat	Increases net radiation
Urban geometries that slow wind speeds	Reduces convection
Increased levels of air pollution	Increases net radiation
Increased energy use	Increases anthropogenic heat

These causes are described in detail below, but first it is useful to understand the concept of the 'energy balance' at the Earth's surface.

Energy balance

An equation called the 'energy balance' explains how energy is transferred to and from the Earth's surfaces. The energy balance is based on the first law of thermodynamics, which states that energy is never lost. For a surface on the Earth, this means that all of the energy absorbed by the surface through radiation or from anthropogenic heat goes somewhere. Either it warms the air above the surface, is evaporated away with moisture or is stored in the material as heat. The energy balance equation is:

$$\text{Convection} + \text{Evaporation} + \text{Heat storage} = \text{Anthropogenic heat} + \text{Net radiation} \quad (2.1)$$

Convection is energy that is transferred from a solid surface to a fluid (i.e. a liquid or gas), in this case from the Earth's surface to the air above it. Convection increases when wind speeds are higher, when air becomes more turbulent over rougher surfaces and when temperature differences between the surface and the air are bigger.

Evaporation is energy transmitted away from the Earth's surface by water vapour. Water from moist soil or wet surfaces changes to vapour when heated by the sun or other sources. Water vapour then rises into the atmosphere, taking the sun's energy with it. The evaporation term also includes evapotranspiration, a more complicated process plants use to keep cool. During evapotranspiration, water is drawn from the soil by the roots of the plant and is evaporated through stomata on the plant's leaves. Both evaporation and evapotranspiration increase when there is more moisture available, when wind speeds are greater and when the air is drier and warmer.

Heat storage depends on two properties of materials: their thermal conductivity and heat capacity. Materials with high thermal conductivity are more able to direct heat into their depths. Materials with high heat capacity can store more heat in their bulk. As more heat is stored, the temperature of the material rises.

Anthropogenic heat represents 'man-made' heat generated by buildings, machinery or people. In many areas, especially rural and suburban areas, the amount of anthropogenic energy is small compared to the other terms in the balance equation. In dense urban areas, the anthropogenic term is larger and can be a significant influence on heat island formation.

Net radiation encompasses four separate radiation processes taking place at the Earth's surface:

$$\text{Net radiation} = \text{Incoming solar} - \text{Reflected solar} + \text{Atmospheric radiation} - \text{Surface radiation} \quad (2.2)$$

Incoming solar represents the amount of energy radiating from the sun. This obviously varies based on the season, the time of day (zero at night), the amount of cloud cover and the atmospheric pollution levels.

Reflected solar radiation is the amount of solar energy that bounces off a surface, based on the solar reflectance of the material. Surfaces with high solar reflectance, such as bright white roofing materials, reflect most of the solar radiation that falls on them, whereas dark surfaces such as asphalt pavement absorb most of the solar radiation.

Atmospheric radiation is heat emitted by particles in the atmosphere, such as water vapour droplets, clouds, pollution and dust. The warmer the atmosphere and the more particles it contains, the more energy it emits.

Surface radiation is heat radiated from a surface itself. This term is highly dependent on the temperatures of the surface and its surroundings. A relatively warmer surface radiates more energy to its surroundings.

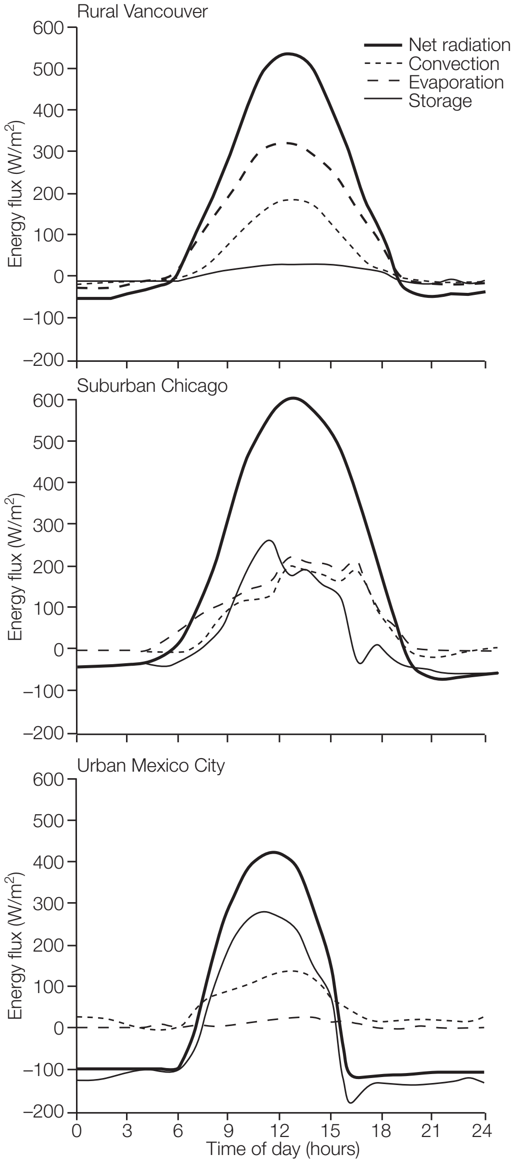
The causes of the heat island and how they influence a city's energy balance are described below.

Reduced evaporation

Figure 2.1 shows daily energy balances for rural, suburban and urban areas in Vancouver, Chicago and Mexico City. Important characteristics of these sites are listed in Table 2.2.

The most striking distinction between the three plots in Figure 2.1 is the decrease of evaporation energy from the rural area to the suburbs and finally to the urban area. This change coincides with a decrease in vegetation coverage from 100 per cent of the land area (rural), to 44 per cent (suburban) to a mere 2 per cent (urban).

Attending these shifts in evaporation energy is an increase in heat storage during the day and in heat release at night. Without the immediately available energy outlet of evaporation, urban and suburban areas must store more energy during the day. The stored energy is subsequently released back to the atmosphere at night, primarily through higher radiant emissions and to a lesser extent via increased convection. In urban Mexico City, stored heat starts to be released in late afternoon.



Source: Cleugh and Oke, 1986; Grimmond and Oke, 1995; Oke et al, 1999.

Figure 2.1 Daily energy balance measurements under clear sky conditions in a rural Vancouver area during the summer of 1983, a suburban Chicago area during July 1992 and an urban Mexico City area during December 1993

Table 2.2 Characteristics of the land use, weather and daily energy balance of a rural Vancouver area, a Chicago suburb, and a Mexico City urban area

	Rural Vancouver	Suburban Chicago	Urban Mexico City
Land use (2-D view)			
Vegetation and water	100%	44%	2%
Buildings	0%	33%	43%
Impervious pavements	0%	23%	55%
Weather			
Rainfall during study	Yes	Yes	No
Incoming solar (W/m^2/day)	5380	7000	4920
Daily energy balance ratios			
Net radiation/incoming solar	0.66	0.60	0.15
Convection/incoming solar	0.20	0.21	0.23
Evaporation/incoming solar	0.45	0.28	0.03
Heat storage/incoming solar	0.04	0.19	0.31
Heat release/incoming solar	0.03	0.08	0.42

Source: Cleugh and Oke, 1986; Grimmond and Oke, 1995; Oke et al, 1999.

Note that the evaporative energy flux at the urban Mexico City site may be understated. Mexico City had no rainfall during the study period, whereas Vancouver and Chicago had enough rainfall to keep vegetated or permeable areas fairly moist. But since the vegetated area of the Mexico City site is very small and irrigation was probably available, it seems safe to say that rainfall might not have changed the site's evaporation by very much.

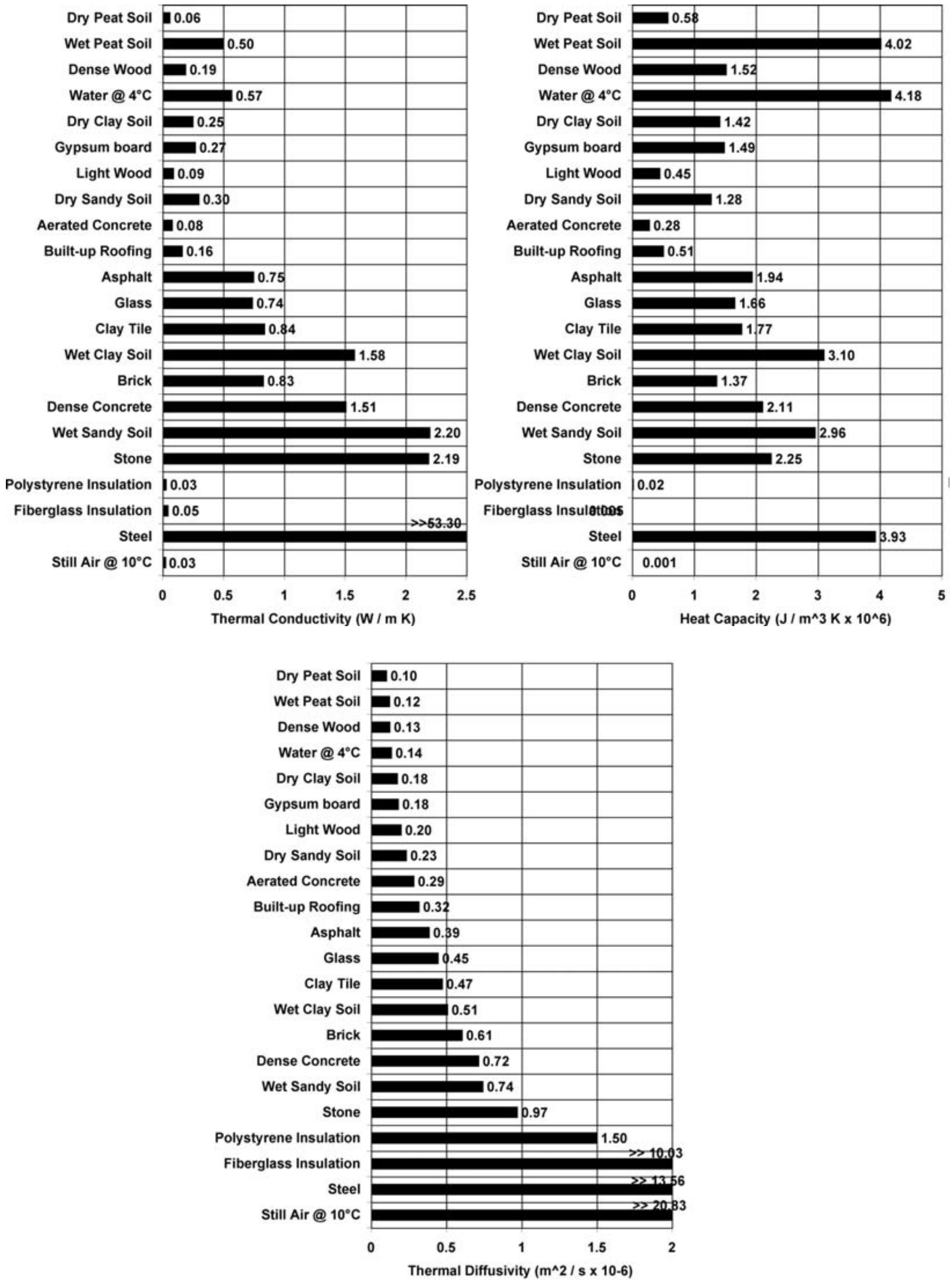
It should be noted that not all cities have reduced evaporation levels, yet they still experience heat island behaviour due to other causes. Urban areas such as Phoenix, Arizona (Balling and Brazel, 1988; Brazel et al, 2000), and Negev, Israel (Pearlmutter et al, 1999), tend to have higher levels of evaporation than the surrounding desert since they have been substantially landscaped with trees and grass that are regularly watered and irrigated.

Increased heat storage

Compounding the lack of moisture, construction materials have properties that tend to exacerbate the heat island problem. Two material properties are important to heat storage: thermal conductivity and heat capacity. Materials with high thermal conductivity tend to conduct heat into their depths. Materials with high heat capacity are able to store more heat in their volume.

A combination of these properties, called thermal diffusivity, is an important indicator of how easily heat can penetrate into a material. Thermal diffusivity is found by dividing a material's thermal conductivity by its heat capacity. High values of thermal diffusivity mean that heat reaches deeper into a material layer, and temperatures stay more constant over time. Low values mean that a thinner layer is heated, and temperatures tend to fluctuate more rapidly.

Figure 2.2 plots the values of thermal conductivity, heat capacity and thermal diffusivity for various materials. Values of thermal conductivity and heat capacity tend to vary considerably from material to material, but there is a striking progression in thermal diffusivity, moving mainly from materials found in nature, such as soils and wood, to man-made construction materials such as pavements and insulation. Rural areas tend to be composed of materials of lower thermal diffusivity, while urban areas have higher diffusivities. This enhances the storage of heat during the day and its slow release at night.



Source: Oke, 1987; ASHRAE, 1993.

Figure 2.2 Thermal conductivity, heat capacity and thermal diffusivity of various materials

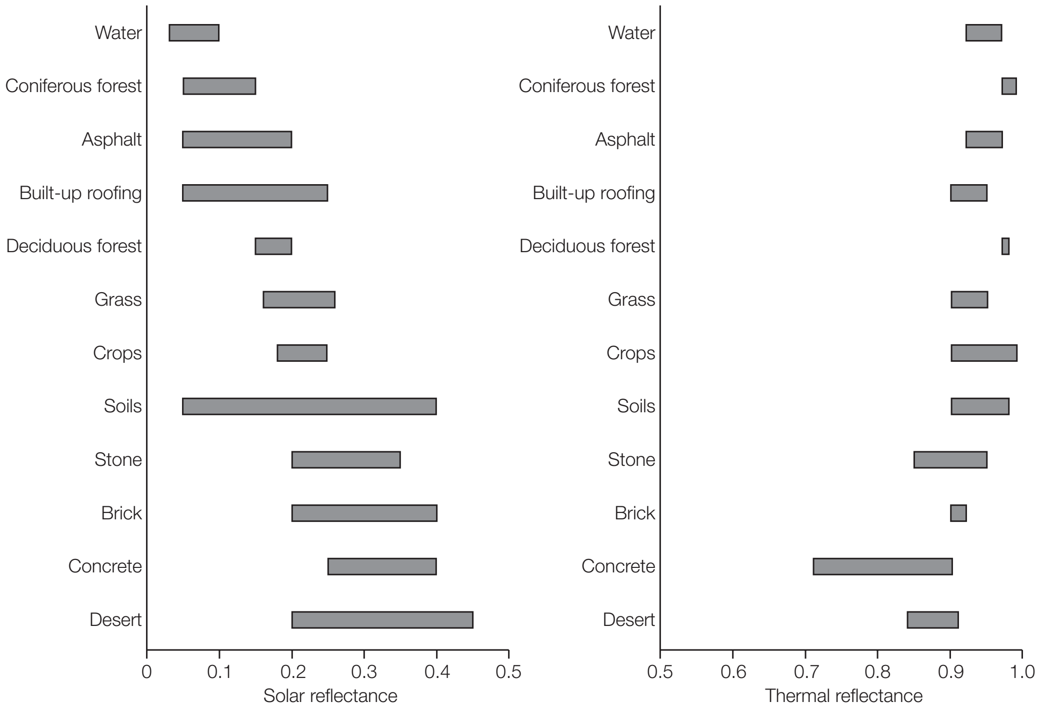
Increased net radiation

The net radiation collected by an urban setting is generally greater than that collected in a rural area. The difference is due to many factors, including lower solar reflectance of urban materials, restrictive urban geometries and the higher air pollution levels in cities. The net radiation term, defined in Equation 2.2, includes the incoming radiation from the sun and atmosphere, as well as the outgoing radiation reflected and emitted from surfaces.

Most urban materials reflect less incoming solar energy than materials commonly found in rural areas. Figure 2.3 shows the range of solar reflectance values for materials found in urban and rural settings. Two prominent materials have low values of solar reflectance: asphalt paving and built-up roofing. The prevalent use of these materials lowers the overall solar reflectance of communities. For example, the reflectance in urban areas of St Louis, Missouri, was 4 per cent lower than in surrounding rural areas (Vukovich, 1983). This means that 4 per cent more of the sun's energy is absorbed in urban areas, and this tends to increase net radiation levels during daylight hours.

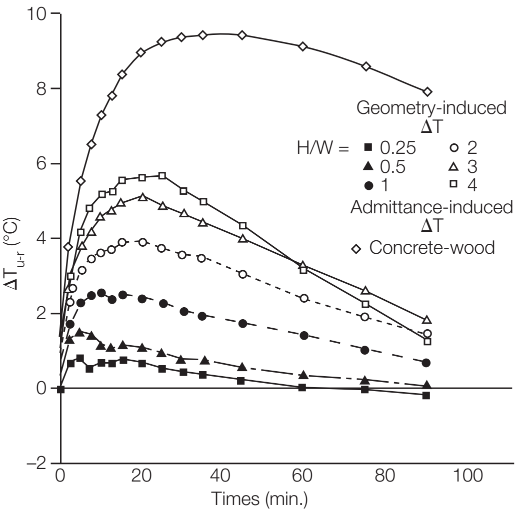
Figure 2.3 also shows the range of thermal emittance for various materials. Emittance is 0.85 or higher for most materials, although some concrete mixes can have lower values. Metals are not included in Figure 2.3, but their thermal emittance is quite low, ranging from 0.20 to 0.60 depending on surface finish. Low thermal emittance reduces the ability of a material to radiate heat. Extensive use of concrete or metal surfaces can reduce the overall urban thermal emittance, which tends to increase net radiation levels in urban areas.

Urban geometry also has an effect on a community's net radiation levels. Heat radiates from surfaces diffusely, or evenly in all directions. For a ground surface surrounded by buildings, a lot of radiation is captured by building walls instead of escaping to the atmosphere. This is yet another factor that tends to increase net radiation



Source: Oke, 1987.

Figure 2.3 Solar reflectance and thermal emittance of various natural and construction materials



Source: Oke, 1981.

Figure 2.4 Change in heat island intensity (urban minus rural air temperature) just after sunset (time=0) for varying ratios of building height to width in a scale model experiment, and for a concrete slab versus a wood slab (representing a rural area)

levels in urban areas. So-called urban canyons make it harder for urban areas to cool off, especially after the sun has set. Figure 2.4 shows results from a scale model test in which the building height to width ratios were varied (Oke, 1981). The temperature difference between urban and rural areas is much larger after sunset in areas with tall buildings, and urban air cools more slowly throughout the night. These results have been verified by numerical modelling (Arnfield, 1990; Voogt and Oke, 1991) and by field observations in various cities (Oke and Maxwell, 1975; Oke, 1981; Voogt and Oke, 1991; Mills and Arnfield, 1993).

Another factor affecting net radiation is air pollution. Pollution affects the radiation budget of urban areas in two ways. First, during the day air pollution decreases the amount of solar radiation reaching the Earth's surface. Before air pollution controls became widespread, solar radiation reductions of 50 per cent were found in many cities (Landsberg, 1981). Today, pollution still reduces solar energy significantly in many cities. Aerosol pollutants in particular block the sun's energy. For example, a study in Mexico City found that aerosols decrease the city's solar energy gain by up to 22 per cent (Jauregui and Luyando, 1999).

Air pollution also increases the amount of long-wave, infrared radiation emitted from the atmosphere to the Earth. Pollution particles do reflect a lot of radiation, both from the sun and from the Earth. But they also tend to absorb more radiation as well. This raises the atmosphere's temperature and increases the amount of energy it emits. Various studies have found atmospheric radiation levels to increase by up to 15 per cent in the presence of air pollution (Landsberg, 1981).

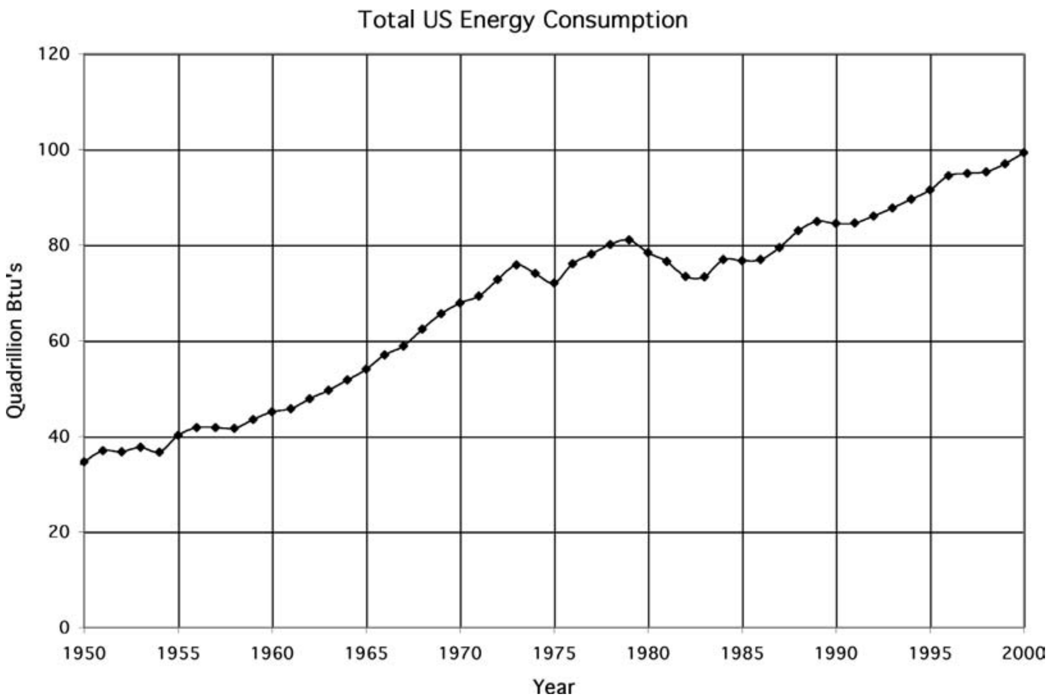
These two effects from pollution, reduced solar radiation and increased atmospheric emission, work in opposition on the net radiation term. Pollution levels and types vary tremendously, and so during daylight hours it is hard to say exactly what pollution's net effects are. But at night, when solar energy is not a factor, urban air pollution definitely increases net radiation levels.

Reduced convection

It has already been shown that heat islands are more intense during calm, clear weather (Landsberg, 1981; Tumanov et al, 1999). In large measure, this is because less heat is convected from surfaces to the air when wind speeds are low. Lower wind speeds tend to increase heat storage during the day and slow the release of heat at night.

Cities also tend to have slower winds than rural areas. Buildings in urban and suburban areas act as wind breaks, slowing wind speeds by up to 60 per cent (Landsberg, 1981). However, in some instances wind speeds can increase around the bases of high-rise buildings. Winds can be funnelled down the sides of buildings to the street under certain conditions (Bosselmann et al, 1995).

Heat islands have also been found to create their own breezes. Hot air tends to rise above the city, drawing in cooler air from the



Source: EIA, 2000.

Figure 2.5 Energy consumption in the US from 1950 to 2000

surroundings. Two coastal cities – Houston, Texas, and Tokyo, Japan – have been found to pull cool air in from the sea as they heat up during the day (Yoshikado, 1990; Nielsen-Gammon, 2000).

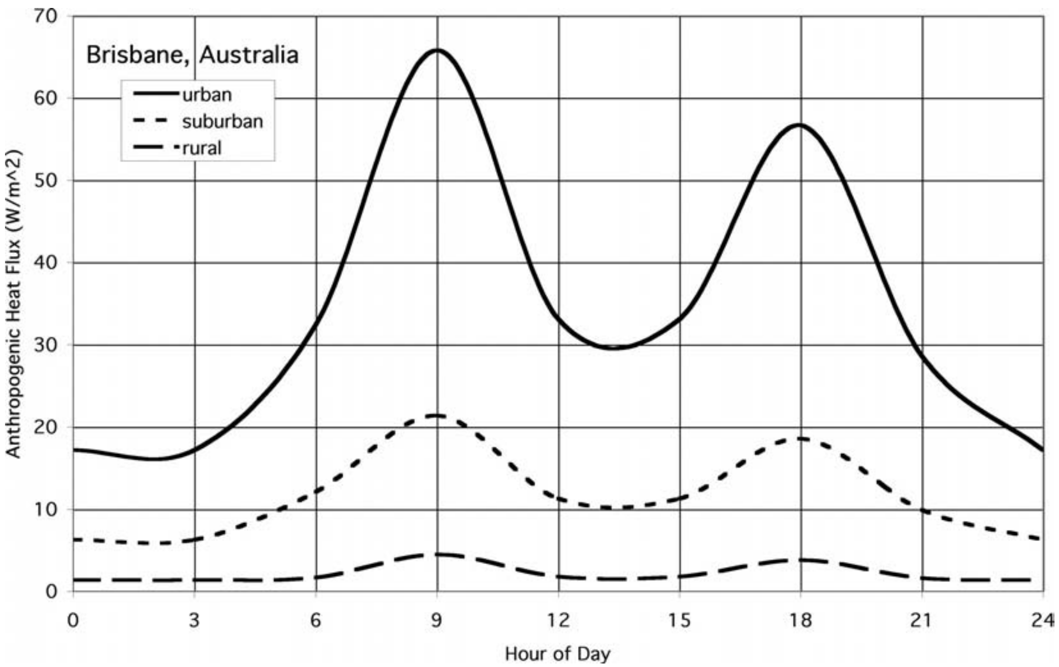
Occurrences of slowing wind speeds and/or induced breezes are difficult to predict, and these effects tend to cancel each other out. Careful study of individual cities can clarify the effect of city winds on the heat island and vice versa.

Increased anthropogenic heat

Anthropogenic heat is generated by human activity and comes from many sources, such as buildings, industrial processes, cars and even people themselves. To determine how much anthropogenic heat is produced in any region, all energy use (commercial, residential, industrial and transportation) must be tallied. The sum is then divided by the region's area to enable comparisons of different cities to be made.

Anthropogenic heat gains are usually larger in winter than in summer. According to estimates made before 1980, anthropogenic heat gains were assumed to range between 20 and $40W/m^2$ in the summer and between 70 and $210W/m^2$ in the winter (Taha, 1997) and follow a daily double-humped pattern similar to that of Figure 2.6. More recent work shows that anthropogenic heat gains are now significantly higher due to increasing energy use, and especially due to increased use of air conditioning in summer.

Figure 2.5 shows the increase in annual energy consumption in the US from 1950 to 2000. From 1980 to 2000, US energy consumption increased by 25 per cent. This increase has been concurrent with metropolitan area growth, so the anthropogenic heat gain for cities, which is now spread over larger areas, will be somewhat less than 25 per cent. Some of this increased energy use is due to increased use of air condi-



Source: Khan and Simpson, 2001.

Figure 2.6 Daily anthropogenic energy generation in urban, suburban and rural areas of Brisbane, Australia, in December 1996

tioning during the summer, so it's likely that summertime levels of anthropogenic heat gain have increased more than wintertime levels.

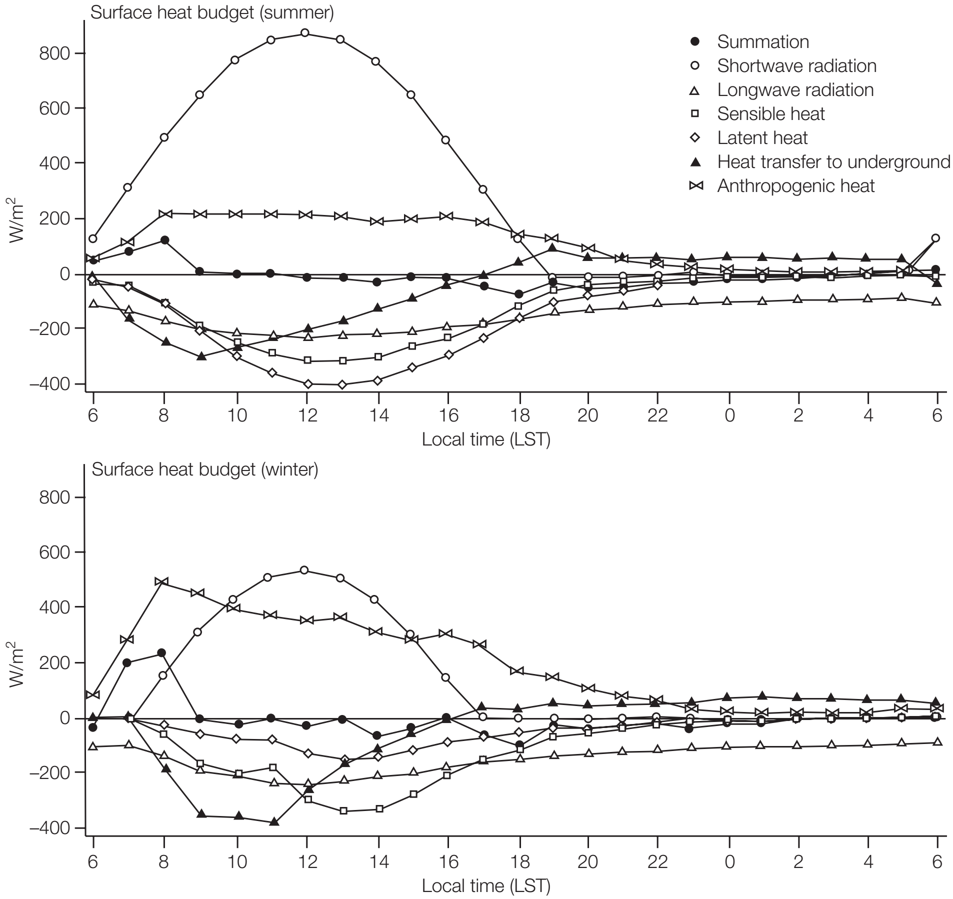
More recent estimates of anthropogenic heat gains include estimates of urban, suburban and rural areas in Brisbane, Australia, during December (summer) 1996 (Khan and Simpson, 2001). The daily pattern shown in Figure 2.6 has higher heat gains in the morning and afternoon and a peak urban value of about 65W/m^2. This value is higher than the 20–40W/m^2 of the pre-1980 assumptions.

On the extreme end of anthropogenic heat gain, a study of the most densely populated and energy intensive urban regions in Tokyo, Japan, has found levels as high as 400W/m^2 in the summer and up to 1590W/m^2 in the winter (Ichinose et al, 1999). Figure 2.7 plots Tokyo's overall daily energy balance, and shows that anthropogenic heat gain is equal to about 40 per cent of the incoming solar energy in summer and 100 per cent of the winter solar energy.

Interplay of heat island causes

The heat island is a fairly complex phenomenon. This is in large part due to the complicated nature of urban areas and weather patterns. But it is also due to the way these factors interact. Factors that increase heat island intensity create high surface temperatures. High surface temperatures in turn increase heat lost from surfaces and can also stimulate city breezes, both of which tend to reduce the heat island intensity.

Heat islands in urban areas tend to display typical characteristics, but the intensity and timing of heat islands vary at each location. The heat island in each community ultimately finds its own balance between temperatures and energy flows, based on the area's terrain, construction and weather conditions.



Source: Ichinose et al, 1999.

Figure 2.7 Summer and winter energy balance in Tokyo, Japan, showing anthropogenic heat gains in relation to other energy terms

References

Arnfield, A. J. (1990) 'Canyon geometry, the urban fabric and nocturnal cooling: A simulation approach'. *Physical Geography* **11**(3): 220–239

ASHRAE (1993) *Handbook of Fundamentals*. Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers

Balling, R. C. Jr. and S. W. Brazel (1988) 'High-resolution surface temperature patterns in a complex urban terrain'. *Photogrammetric Engineering and Remote Sensing* **54**(9): 1289–1293

Bosselmann, P., E. Arens, K. Dunker and R. Wright (1995) 'Urban form and climate: Case study, Toronto'. *Journal of the American Planning Association* **61**(2): 226

Brazel, A., N. Selover, R. Vose and G. M. Heisler (2000) 'The tale of two climates – Baltimore and Phoenix urban LTER sites'. *Climate Research* **15**: 123–135

Cleugh, H. A. and T. R. Oke (1986) 'Suburban–rural energy balance comparisons in summer for Vancouver, BC'. *Boundary Layer Meteorology* **36**: 351–369

EIA (2000) *Energy Consumption by Source, 1949–2001*. Washington DC, US Energy Information Administration

Grimmond, C. S. B. and T. R. Oke (1995) 'Comparison of heat fluxes from summertime observations in the suburbs of four North American cities'. *Journal of Applied Meteorology* **34**: 873–889

Howard, L. (1833) *The Climate of London: Deduced from Meteorological Observations Made in the Metropolis and at Various Places Around it*. London, Harvey and Darton

Ichinose, T., K. Shimodozono and K. Hanaki (1999) 'Impact of anthropogenic heat on urban climate in Tokyo'. *Atmospheric Environment* **33**: 3897–3909

Jauregui, E. and E. Luyando (1999) 'Global radiation attenuation by air pollution and its effects on the thermal climate in Mexico City'. *International Journal of Climatology* **19**: 683–694

Khan, S. M. and R. W. Simpson (2001) 'Effect of a heat island on the meteorology of a complex urban airshed'. *Boundary Layer Meteorology* **100**: 487–506

Landsberg, H. E. (1981) *The Urban Climate*. New York, NY, Academic Press

Mills, G. M. and A. J. Arnfield (1993) 'Simulation of the energy budget of an urban canyon – II. Comparison of model results with measurements'. *Atmospheric Environment* **27B**(2): 171–181

Nielsen-Gammon, J. W. (2000) *The Houston Heat Pump: Modulation of a Land–Sea Breeze by an Urban Heat Island*. College Station, TX, Department of Atmospheric Sciences, Texas A&M University**:** 5

Oke, T. R. (1981) 'Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations'. *Journal of Climatology* **1**: 237–254

Oke, T. R. (1987) *Boundary Layer Climates*. New York, Routledge

Oke, T. R. and G. B. Maxwell (1975) 'Urban heat island dynamics in Montreal and Vancouver'. *Atmospheric Environment* **9**: 191–200

Oke, T. R., R. A. Spronken-Smith, E. Jauregui and C. S. B. Grimmond (1999) 'The energy balance of central Mexico City during the dry season'. *Atmospheric Environment* **33**: 3919–3930

Pearlmutter, D., A. Bitan and P. Berliner (1999) 'Microclimate analysis of "compact" urban canyons in an arid zone'. *Atmospheric Environment* **33**: 4143–4150

Taha, H. (1997) 'Urban climates and heat islands: Albedo, evapotranspiration and anthropogenic heat'. *Energy and Buildings* **25**

Tumanov, S., A. Stan-Sion, A. Lupu, C. Soci and C. Oprea (1999) 'Influences of the city of Bucharest on weather and climate parameters'. *Atmospheric Environment* **33**: 4173–4183

Voogt, J. A. and T. R. Oke (1991) 'Validation of urban canyon radiation model for nocturnal long-wave radiation fluxes'. *Boundary Layer Meteorology* **54**: 347–361

Vukovich, F. M. (1983) 'An analysis of the ground temperature and reflectivity pattern about St. Louis, Missouri, using HCMM satellite data'. *Journal of Climate and Applied Meteorology* **22**: 560–571

Yoshikado, H. (1990) 'Vertical structure of the sea breeze penetrating through a large urban complex'. *Journal of Applied Meteorology* **29**: 878–891

3

Measuring and Modelling Heat Islands

The ideal way to measure any city's heat island would be to examine regional weather patterns both with and without the city in place. Clearly, it is impossible to remove and replace cities, so in the real world, five basic methods are used to measure the effects of development on urban climate:

- fixed stations
- mobile traverses
- remote sensing
- vertical sensing
- energy balances.

Measuring a heat island's effects on regional climate is useful and interesting, but cannot tell us how effective mitigation measures would be at reducing a heat island's impacts. That is where modelling becomes necessary. Many different types of models are being used to predict how well mitigation measures can reduce urban temperatures, energy use and air pollution. Models have been developed to look at individual buildings, urban canyons and larger urban areas. This chapter reviews various techniques for measuring and modelling heat islands.

Measuring heat islands

Here we present the five different approaches commonly used to investigate heat islands: (1) fixed stations, (2) mobile traverses, (3) remote sensing, (4) vertical sensing and (5) energy balances.

Fixed stations

The simplest and most common method of analysing a heat island is to compare existing weather data from two or more fixed locations. Most cities throughout the world have weather stations with years of accumulated information about air temperatures, wind speeds, cloud cover, humidity and precipitation levels. A few stations also include some measure of solar radiation, in terms of watts per square metre or a percentage of the maximum solar radiation available.

There are many weather stations located throughout most communities, including those operated by national weather service organizations, local universities, television stations and utility companies. Long-term archives of weather data have become more accessible with the advent of computer technology and the internet. Hourly, daily, monthly or annual values can be accessed and examined fairly easily for little or no cost.

Fixed station data has most commonly been used in three different ways: (1) comparing data from a single pair of urban and rural weather stations, (2) studying data from multiple stations to find regional, two-dimensional impacts and (3) investigating a large set of historical data to evaluate heat island trends over time as a region develops.

If a single pair of urban and rural stations is being used to assess the heat island, it is important to choose analysis locations wisely. The urban site should attempt to typify a region's construction practices, and the rural site should best represent the surrounding natural terrain as it existed before human development. It is also ideal if these sites have the same altitude, terrain and general climate, but this is not always possible.

Understanding the climate at each weather station is very important. The urban–rural locations chosen are often located in the central business district of a city and at the airport, but there is some scepticism about how well these sites represent the heat island. First, these two locations may have quite different climates, independent of any urban effects. Second, weather stations are often located on towers or rooftops, well above the ground or street level conditions experienced by most people.

In general, for heat islands the ideal place to measure air temperature is in the 'canopy layer'. The canopy layer is defined as the volume of air below the tops of buildings and trees. Standard measurements of canopy layer temperatures are made at a standing person's chest height, usually at a height of 1.5 metres (5 feet) above the ground.

Many 'urban' weather stations are located on the tops of buildings and do not reflect canopy layer conditions. If canopy layer instrumentation is used instead, it must be remembered that conditions can vary dramatically from one side of a street to the other due to building shade and wind patterns.

For measurements in rural areas, airports may not accurately represent historical rural conditions. They are often not sheltered from winds, and natural vegetation may have been eliminated in favour of runway space. Suburbs are also encroaching upon many airports, so measurements may be affected by upwind development. Airport weather stations are often located on towers, so measurements may not represent ground-level conditions.

Once the best available locations have been chosen, a fairly simple analysis can show urban–rural differences between locations over hours, days, seasons and years. Data are often averaged for each hour over several days or weeks in order to make a comparison of average daily temperature patterns. An example of this type of analysis for Melbourne, Australia, is shown in Figures 1.2 and 1.3 of Chapter 1. Another example of single pair data analysis, shown in Figure 1.12, compares the heat island in Bucharest, Romania, during clear and cloudy weather conditions.

Measurements from urban–rural pairs of weather stations can also be used to evaluate changes in heat island intensity over time. In this case, it is important to watch out for changes in the weather station's instrumentation or location, or changes in structures close to the station over the time period of interest. Refer back to Chapter 1, where Figures 1.13 and 1.14 (Plates 3 and 4) show how the heat islands of Phoenix and Mesa, Arizona, intensified, mostly at night, over an entire century of urban development.

A more rigorous analysis of a heat island includes data from numerous fixed stations in and around a city. If enough stations are available, two-dimensional contour maps of a city's temperatures can be generated. Figure 1.4 shows an analysis using data from 26 weather stations in Minneapolis–St Paul, Minnesota. The study of weather data from a collection of stations over time can often demonstrate an intensification of the heat island coinciding with urban and suburban development.

If the region is not well represented by existing stations, additional fixed stations can be temporarily located in the gaps to collect data at important locations. An additional weather station should include at least the measurement of temperature, humidity, wind speed and wind direction. Instrumentation to measure solar radiation levels, such as a pyranometer, is also very useful.

Mobile traverses

There are frequently too few fixed stations available in the right locations around a city to yield a clear two-dimensional picture of the heat island. Setting up temporary stations to collect data at additional fixed locations can be difficult and expensive. Taking a mobile traverse is an economical way to study the heat island of an urban area and its suburban and rural surroundings.

A mobile traverse entails travelling on a predetermined path throughout a region, stopping at representative locations to take readings using just a single set of weather instrumentation. Methods of transport have varied. In smaller study areas, researchers have walked or cycled between measurement locations (Spronken-Smith and Oke, 1998). In larger areas, researchers have travelled by public transport or car (Chandler, 1960; Hutcheon et al, 1967; Yamashita, 1996; Stewart, 2000). An example of a mobile traverse via railway for Tokyo, Japan, is illustrated in Figures 1.5–1.7.

Mobile traverses can be undertaken at any time of day or night, although sometimes this is dependent upon traffic conditions. Most studies perform traverses at night during calm, clear weather in order to measure maximum heat island intensities. A night-time traverse of Granada, Spain, shown in Figures 1.8 and 1.9, illustrates how temperatures rise in more densely constructed areas.

There are a few drawbacks to using the mobile traverse method to measure heat islands. One is the inability to record simultaneous measurements at different locations. It is possible to use two or more sets of travelling equipment at the same time, but this at least doubles the equipment cost. Most traverses can be completed in less than an hour, but conditions can vary significantly in that time. Temperatures often need to be adjusted to a baseline time by comparing mobile measurements with data from one or more fixed locations.

Care must be taken when making mobile traverse measurements. If travelling by public transport or car, it is important to keep the instrumentation away from sources of heat. Temperatures along roadways can be unduly influenced by engine or pavement heat, or by wind from traffic. Stepping a few feet off the road may give a more representative reading of an area's conditions. It is also important to give measurement equipment enough time to reach equilibrium with its surroundings before taking readings.

Remote sensing

Fixed stations and mobile traverses are generally used to monitor the *air* temperatures around a city. Remote sensing can be used to find temperatures and other characteristics of *surfaces*, for example, roofs, pavements, vegetation and bare ground, by measuring the energy reflected and emitted from them. Specialized equipment on aeroplanes or satellites is used to take pictures of the visible and invisible energy radiating from cities and their surroundings. Figure 1.10 (Plate 1) shows the heat island in Buffalo, New York, in 1978, one of the first times satellite imagery was used to map surface temperatures.

Since they are constantly circling the Earth, satellites do not record continuous information over a daily period. They usually pass over an area twice a day, so daytime and night-time thermal characteristics can be compared and seasonal variations examined. Care must be taken to choose days with clear weather for study.

Specialized airplane flights can be done at any time of day, so they can be more useful at capturing daily patterns of heat island behaviour. But these flights are expensive to perform and often need special permission to fly at lower altitudes than is normally allowed. Figure 1.11 (Plate 2) shows surface temperatures in Sacramento, California, measured using special remote sensing equipment in a NASA Lear jet.

The advantage of using remote sensing is its power to visualize temperatures over large areas. However, remote sensing shows only a birds-eye view of urban temperatures, leaving out temperatures of walls and vegetation and temperatures under the trees. These vertical and shaded surfaces are just as important to the urban heat island as the surfaces seen from above. Some work has been done in Vancouver, British Columbia, to add this vertical information to remotely sensed data to yield a true three-dimensional, or 'complete', surface temperature (Voogt and Oke, 1997).

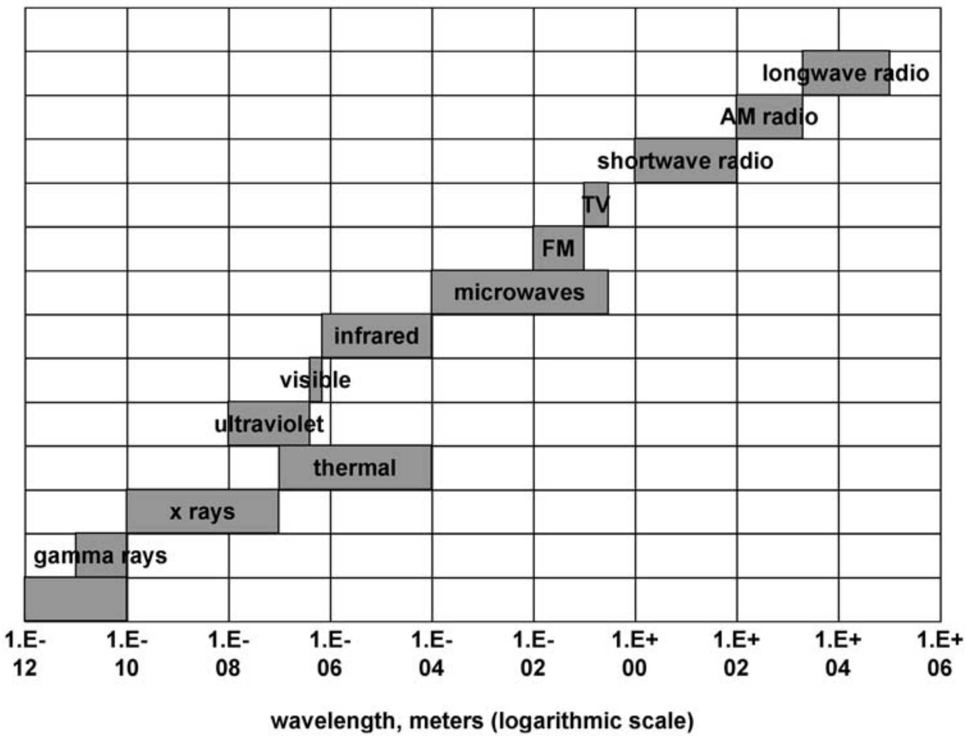


Figure 3.1 Wavelengths of electromagnetic radiation

Remote sensing instrumentation typically takes measurements at five different energy wavelengths. These measurements can be used to determine how hot or cold the surfaces are, and to show what the surface looks like and how reflective it is. The physics behind these energy measurements is explained in detail below, for the technically minded.

Physics of radiative energy measurements

Radiative energy is transmitted by electromagnetic particles, called photons, which act very much like waves. As shown in Figure 3.1, radiative energy is classified according to its wavelength. The wavelengths of interest for remote sensing of surface temperatures are in the thermal band, and include some of the ultraviolet and all of the visible and infrared wavelengths (i.e. wavelengths from about 10^{-7} to 10^{-4} metres, or 0.1 mm to 100 mm).

All surfaces emit thermal energy according to Planck's Law, which states that the maximum energy that can be emitted by a perfect surface, called a black body, is dependent on the fourth power of the surface's temperature:

$$\text{Blackbody emitted energy} = \sigma T^4 \tag{3.1}$$

where σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}\text{W/m}^2\text{K}^4$). No real surfaces are perfect black bodies, however, so for an actual surface:

$$\text{Actual emitted energy} = \varepsilon\sigma T^4 \tag{3.2}$$

where ε is the surface emittance, a value between 0 and 1. The emittance for most materials on the Earth ranges between 0.8 and 0.95, although emittances for bare metals can vary from 0.2 to 0.6, depending on their surface finish.

Thermal energy is always emitted in a characteristic wavelength curve, shown for three temperatures by the red, blue and green curves in Figure 3.2 (Plate 5). As surfaces get hotter, this curve's peak gets bigger and covers a set of shorter wavelengths (i.e the curve moves to the left in Figure 3.2). The peak wavelength for each temperature is defined by Wien's Law as:

$$\text{Maximum wavelength} = \mathbf{Y}_{max} = 2.88 \times 10^{-3}/T \quad (3.3)$$

Where the temperature, T, must be in degrees Kelvin.

Figure 3.2 plots the energy emitted from a black body at the boiling point of water (100°C or 212°F, red curve), at the freezing point of water (0°C or 32°F, blue curve) and at the midpoint between these two temperatures (50°C or 120°F, green curve), with peak values at about 90, 45 and 20W/m^2, at wavelengths of about 7.5, 9.0 and 10.5µm, respectively. These curves represent a typical range of energy emissions for surfaces in cities and rural areas.

The orange curve in Figure 3.2 shows energy from the sun, with its much hotter surface, that reaches the Earth's surface on a clear day. This curve peaks at about 1400W/m^2 at a wavelength of 0.5µm (note that this curve's units are given on the right-hand axis in Figure 3.2). Figure 3.3 (Plate 6) expands this curve to show the ultraviolet, visible and infrared components of the sun's energy. This curve is not smooth, but has a few dips that indicate where various energy wavelengths are absorbed by the Earth's atmosphere. Water vapour filters energy at various infrared wavelengths, while ozone is responsible for filtering almost all of the ultraviolet energy.

The five vertical blue lines in Figure 3.2 (two of these lines are also shown in Figure 3.3) designate the five wavelength bands usually measured remotely from satellites or aircraft. These wavelengths were measured by the advanced very high resolution radiometer (AVHRR) instrumentation used by National Oceanic and Atmospheric Administration satellites since 1978 (Hastings and Emery, 1992). The three bands on the right measure emitted thermal energy, and the two bands on the left measure reflected solar energy.

The three energy emission measurements can be used to derive surface temperatures, since the shape of black-body emission curves are known. Of course, it is not quite that simple: real

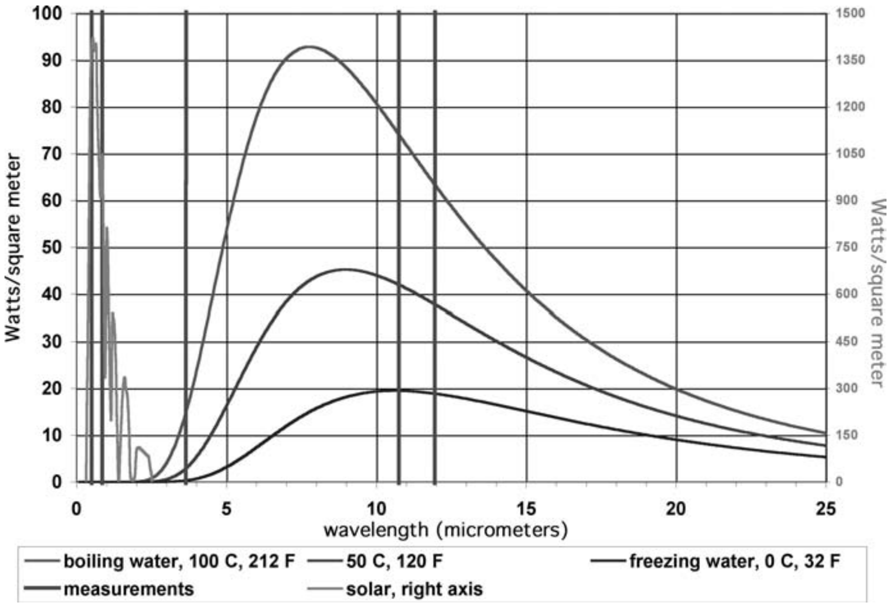


Figure 3.2 Black body emissions at different temperatures, solar energy reaching the Earth and the five energy wavelengths typically measured by remote sensing (see Plate 5 for a colour version)

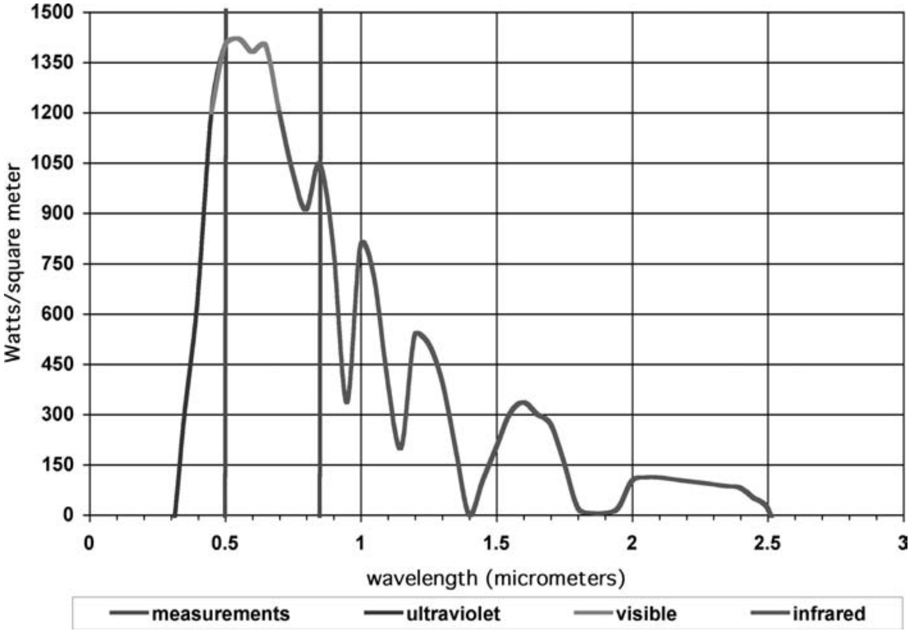


Figure 3.3 Solar energy reaching the Earth in the ultraviolet, visible and infrared wavelengths, plus the two energy wavelengths that are typically used to measure reflected solar energy (see Plate 6 for a colour version)

surfaces on Earth are not black bodies, so thermal emittance must be estimated for the area being studied. The Earth's atmosphere also filters out various energy wavelengths, so the measured energy must be adjusted accordingly.

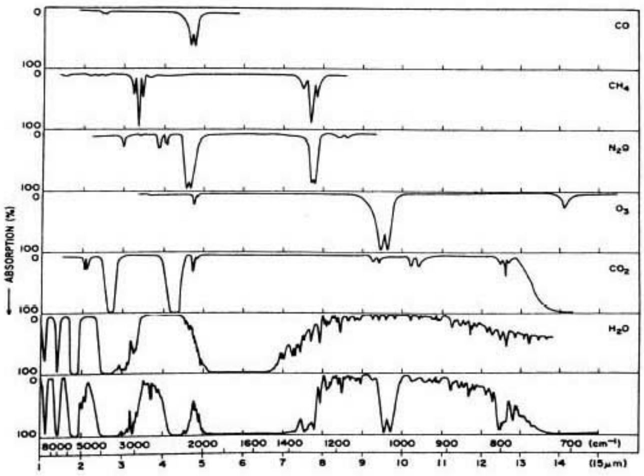
Note that to minimize the corrections needed, the radiative energy measurements are made at wavelengths that are less affected by atmospheric absorption. Figure 3.4 shows how different atmospheric gases absorb infrared energy. As noted previously, water vapour in the atmosphere is the biggest absorber of infrared energy, filtering out much of the solar infrared under 2.5mm (as also seen in Figure 3.3) as well as the energy between 2.5 and 3.5μm, around 4.5mm, from 5 to 8μm, around 9.5μm and at around 12.5μm. The effect of all gases combined is shown in the bottom section of Figure 3.4. The three measurements used to find surface temperatures are made at wavelengths of 4.7, 10.8 and 12mm, where less atmospheric absorption takes place.

Measurements at the two lowest bands (centred at about 0.5 and 0.85μm) measure the visible light and the reflected solar energy of the surfaces. These are useful for characterizing the type of surfaces being viewed, and especially for determining how much vegetation is present (Goward et al, 1985; Brest, 1987; Gallo et al, 1993a, 1993b; Owen et al, 1998).

Vertical sensing

We have already seen how the air in the urban canopy layer is affected by the heat island. But the air above the canopy layer is also affected. The Earth's surface has an influence on the lowest 10 kilometres (32,000 feet) of the Earth's atmosphere, called the troposphere. Most of these effects are confined to a shallower region of 1–1.4 kilometres (3200–4600 feet) called the boundary layer, where heat and drag from the surface create turbulence. The boundary layer is thickest during the day when hot surfaces heat the air, which then rises into the cooler atmosphere and mixes. At night the Earth's surface tends to be cooler than the atmosphere, and the boundary layer contracts.

Scientists have found significant differences in the boundary layers over rural and urban

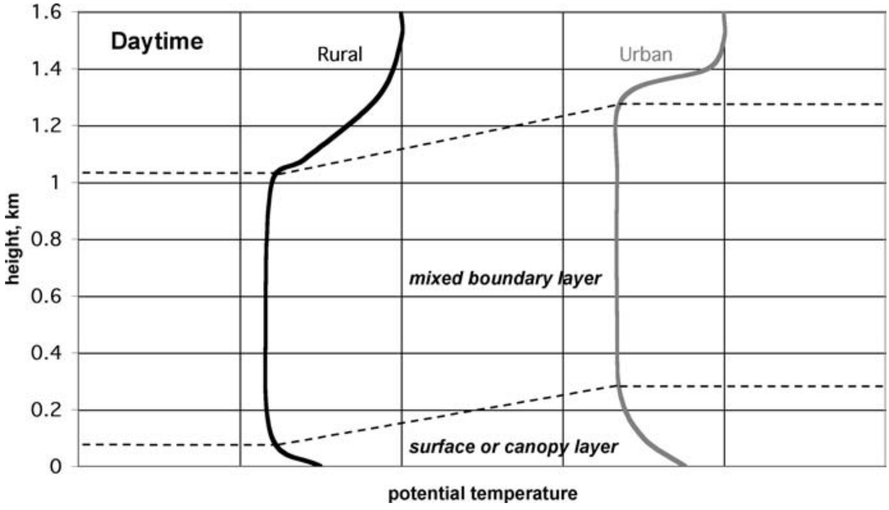


Source: Sokolik, 2002.

Figure 3.4 Absorption of infrared energy by different constituents of the Earth's atmosphere (carbon monoxide, methane, nitrogen dioxide, ozone, carbon dioxide and water vapour) plus all constituents combined (bottom)

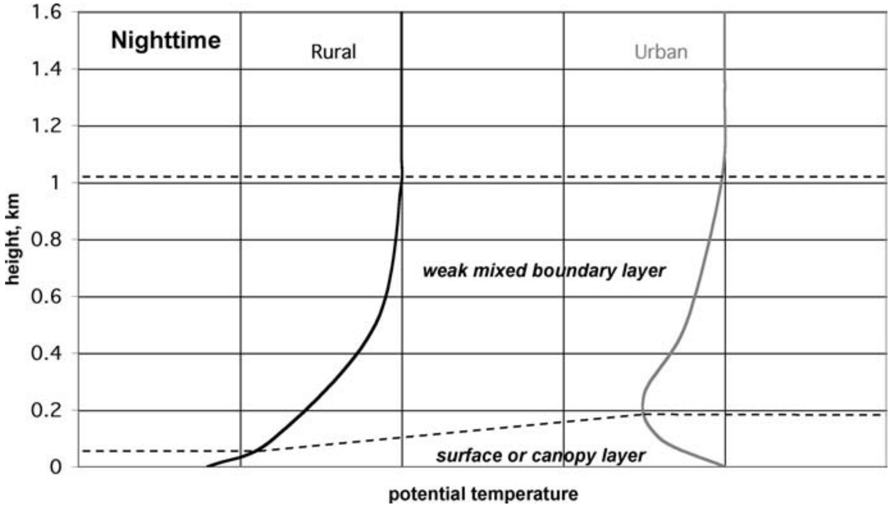
areas. These differences are measured using various methods to measure temperatures and other properties at various altitudes above the Earth's surface. These methods include sending instrumented balloons aloft, installing monitoring equipment on radio towers or flying at different altitudes in an instrumented helicopter or airplane.

Figure 3.5 shows typical daytime temperature profiles in the boundary layers over rural and urban areas. Warmer urban surfaces create a thicker boundary layer, above which the temperature reverts to that of the rest of the troposphere. The temperature inside the boundary layer is approximately constant because turbulent eddies keep the air well mixed.



Source: Oke, 1987.

Figure 3.5 Typical daytime potential temperature profiles over rural and urban areas; potential temperatures have been corrected for changes due to altitude



Source: Oke, 1987.

Figure 3.6 Typical night-time potential temperature profiles over rural and urban areas; potential temperatures have been corrected for changes due to altitude

Figure 3.6 shows typical night-time temperature profiles over rural and urban areas. In rural areas at night, the surface is cooler than the air above it, creating a stable layer of cooler air below warmer air. At night in urban areas, slowly cooling urban surfaces cause heated air to form an inversion above the canopy layer.

Taking vertical measurements around a city and its surroundings can give a better understanding of the heat island's effect on the local climate. Figures 1.17 and 1.18 show temperatures over the New York City region at sunrise on a summer day in 1968 using an instrumented helicopter to take measurements. The effects of the heat island on vertical temperature profiles have also been studied as they develop over time. Figure 1.19 shows how a thermal inversion forms at night over urban areas of St Louis, Missouri, from data collected on a tall radio tower.

Energy balances

Measuring the energy flowing in and out of surfaces is a sophisticated way of measuring heat island effects. This method also gives further understanding into the origins of the heat island.

The theory of the energy balance equation is covered in detail in the beginning of Chapter 2. To quickly review, the energy balance equation is based on the first law of thermodynamics, which states that the energy in and out of any surface must be conserved. In the case of a surface on the Earth, this equation is generally written as:

$$\text{Convection} + \text{Evaporation} + \text{Heat storage} = \text{Anthropogenic heat} + \text{Net radiation} \quad (3.4)$$

Energy entering the Earth's surfaces comes from two sources: (1) anthropogenic, or man-made, sources such as buildings, machinery and people or (2) net radiation, the amount of the sun's energy that is absorbed, not reflected or emitted away. At any moment in time, the net radiation and anthropogenic heat must be either convected away by the wind, dissipated by the evaporation of moisture or evapotranspiration from vegetation, or stored in the surface itself. For a more detailed explanation of this equation and these terms, refer back to Chapter 2.

Energy balance experiments use a lot of equipment to measure the energy flowing into and out of surfaces. Four separate measurements can be made to evaluate the net radiation term:

- incoming solar radiation (short wave) using a pyranometer or albedometer
- reflected solar radiation (short wave) using a pyranometer or albedometer
- atmospheric radiation (long wave) using a radiometer
- surface radiation (long wave) using a pyrgeometer.

The net radiation would then be calculated as:

$$\text{Net Radiation} = \text{Incoming solar} - \text{Reflected solar} + \text{Atmospheric radiation} - \text{Surface radiation} \quad (3.5)$$

Alternatively, the net radiation into the surface can be measured directly using only one instrument:

- net radiation using a net radiometer, which combines upward and downward facing pyranometers and pyrgeometers to compute net radiation between 0.3 and 50mm

Convection, evaporation and heat storage are measured using the following equipment:

- convection using an eddy covariance system, with a sonic anemometer and fine wire thermocouples to measure the wind and temperature fluctuations used to calculate sensible (convective) heat flows
- evaporation using an eddy covariance system, with a sonic anemometer and hygrometer to measure the wind and humidity variations used to calculate latent (evaporative) heat flows
- heat storage using a heat flux meter.

To reduce equipment costs, energy balance experiments generally do not measure every term. Sometimes heat storage is not measured, but is calculated from the energy balance equation. At other times the convection and evaporation terms are not measured, and a combined term for convection and evaporation is found from the energy balance equation. This second method is really most appropriate only if moisture is not expected to be an important factor.

In addition to the energy terms, and in order to compare data from different sites and times, local weather variables should also be measured:

- air temperature using thermocouples
- humidity using temperature/relative humidity sensors
- wind speed using an anemometer.

It is important to note that anthropogenic heat generated by the surface being tested is not accounted for with this measurement scheme. This term usually gets buried in the heat storage term. In most cases, anthropogenic heat is small in comparison to the rest of the energy terms, so this experimental method is reasonably accurate.

Modelling heat islands

Models of heat islands are used both to help understand how the heat island works and to estimate how effective it would be to apply different mitigation measures. Models exist to look at the heat island's effects on individual buildings, a single street or neighbourhood, or an entire urban region. The following section looks at the five main types of models used to evaluate heat islands and their potential to be alleviated:

- building energy models
- roof energy calculators
- canyon and comfort models
- ecosystem models
- regional models.

Building energy models

Building energy models are used to predict how much energy a building will use for heating and cooling. These models are quite sophisticated, looking at a building's location, geometry, construction, lighting and appliances, heating and cooling systems, and daily patterns of operation in order to estimate its energy use. These models are used to evaluate all sorts of energy efficiency measures, but for heat island mitigation they are used to evaluate the effects of installing a cool roof, planting shade trees or putting cool paving around a building.

The most commonly used building energy model is DOE-2, a program developed over decades by the US Department of Energy. Although this program was superseded in 2001 by the more advanced EnergyPlus program, EnergyPlus is currently more difficult to run and only a handful of user interfaces are available. The final DOE-2.1E version of DOE-2 has many user interfaces available that simplify its use, so it still serves as the basis of calculations for the majority of energy conservation work.

DOE-2 does suffer from some limitations that underestimate the savings from cool roofing. The program does not correctly calculate convective heat transfer from the roof due to wind, it does not account for radiative heat transfer in an attic or plenum[1] space, and it assumes that roof insulation properties stay constant with temperature. It has been found to under-predict the energy savings from a cool roof by as much as 50 per cent (Gartland et al, 1996). Nevertheless, this program has served as the basis for many estimates of building energy savings due to heat island mitigation (Konopacki et al, 1996; Konopacki and Akbari, 2000, 2001, 2002).

Roof energy calculators

There are three roof calculator tools available on the internet: (1) a tool developed for the US Environmental Protection Agency's Energy Star program, (2) another tool developed by Oak Ridge National Laboratory for the US Department of Energy and (3) EnergyWise from the National Roofing Contractor Association.

Energy Star roofing comparison calculator

DOE-2 also serves as the basis for the US Environmental Protection Agency tool used specifically to estimate cool roof energy savings, the Energy Star roofing comparison calculator (Akbari and Konopacki, 2003; Cadmus Group, 2007). This web-based calculator estimates the energy and money that can be saved by using Energy Star roofing products. It was developed to study air-conditioned buildings of at least 3000 square feet. Input to the calculator includes the age, type and location of the building; the efficiency of heating and cooling systems; the local cost of energy; and information about the roof area, insulation and type of roof. Annual electricity savings and cost savings are found, and the effects of any heating penalty are given.

There are some drawbacks to using the Energy Star calculator. The foremost problem is its lack of accuracy. The equations used were derived from multiple runs of DOE-2 for different building scenarios, although no documentation is provided to check the accuracy of this derivation. As stated before, DOE-2 under-predicts cool roof energy savings. It would be helpful if the calculator estimates were compared or calibrated to energy savings found in actual buildings.

Another drawback is that the Energy Star calculator does not estimate reductions in electricity demand. Utility bills for commercial and industrial buildings usually charge for peak electricity demand as well as for the electricity actually used. The demand savings can be significant and should be accounted for in savings estimates.

The Energy Star calculator also gives some incorrect information on solar reflectance. Contrary to the options listed, beige roof membranes typically have solar reflectance of about 20 per cent, not 45 per cent, and there are no red concrete tiles available with solar reflectance of 70 per cent.

ORNL/DOE cool roof calculator

Another web-based calculator was developed by Oak Ridge National Laboratory (ORNL) for the US Department of Energy. The ORNL calculator (ORNL-BEP, 2001; ORNL, 2007) has two versions: one for buildings with low-slope roofs and the other for buildings with steep-slope roofs. The equations for this calculator are based on a roof heat transfer model that was calibrated to match results from a roof and ceiling test assembly (Wilkes, 1991). Input to the model includes building location, roof insulation level, solar reflectance and thermal emittance of the proposed roof, and the cost of energy and efficiency of the heating and cooling systems. Output from the calculator includes the annual dollar savings in comparison to a black roof and the annual heating energy penalty. The calculator also has an option to calculate the demand savings achieved by reducing peak electricity use.

The ORNL calculator does present some misleading information about the solar reflectance and thermal emittance of roofing materials. 'High', 'average' and 'low' values of solar reflectance are given incorrectly as 80, 50 and 10 per cent; most traditional materials have solar reflectance values between 5 and 25 per cent. Most cool materials are bright white with a solar reflectance of 70–85 per cent. Very few cool coloured materials have 'average' solar reflectance. Even more inaccurate are the thermal emittance categories of 'high', 'average' and 'low', listed as 90, 60 and 10 per cent. Thermal emittance for most non-metallic roofing materials ranges between 80 and 95 per cent, the thermal emittance of metallic-surfaced materials ranges between 20 and 60 per cent and no known roof materials have thermal emittance as low as 10 per cent.

EnergyWise roof calculator

Like the DOE/ORNL calculator, the EnergyWise calculator (Bailey, 2006) is based on roof component tests. Developed by the National Roofing Contractors' Association (NRCA), this calculator goes into much more detail about the different roof layers used than the other two roof calculators do. This is useful for seeing how different insulation levels or configurations affect energy use.

But for the evaluation of cool roofing, this tool has some serious drawbacks. The options for defining the solar characteristics of the roof surface are extremely limited. You can only specify whether or not the roof meets American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) 90.1 criteria (solar reflectance over 70 per cent and thermal emittance over 75 per cent). There is no way to enter actual solar reflectance and thermal emittance values. Designers of the program say that it is only intended to serve as an ASHRAE 90.1 compliance tool, and that it is not designed to estimate the energy savings of cool roofs (Crowe, 2007). The EnergyWise tool also currently calls for cooling energy cost input using obscure units (dollars per gallon), but the program designers intend to fix this in the near future (Crowe, 2007).

Canyon and comfort models

The next step up from studying individual buildings is to study a configuration of buildings surrounding a street. These are called urban canyon models. These models are based on energy balance equations that represent the heat transfer between pavements and building walls. Models take into account the canyon's geometry, wind patterns and solar loads, accounting for shade during certain parts of the day.

Canyon models were first used to help clarify the mechanisms responsible for heat islands (Nunez and Oke, 1976, 1977; Oke, 1981; Arnfield, 1982). Urban canyon models have also been used to evaluate how the geometry of urban areas affects urban climate (Barring et al, 1985; Arnfield, 1990; Todhunter, 1990; Sakakibara, 1996), and how urban climate affects the energy use of buildings (Santamouris, 2001; Santamouris et al, 2001; Georgakis, 2002).

Urban canyon models seem ideally suited to estimating the effects of cooling surfaces or adding vegetation, although not too much work of this type has been done yet. One interesting study used urban canyon models to see what the effects of cool roofing and vegetated walls were on the conditions at the base of urban canyons in Athens, Greece (Alexandri and Jones, 2006). Landscaping the walls was found to have the dominant effect, but cooling the roof and walls together reduced air temperatures in the canyon by 6–8°C (10–15°F).

Comfort models use equations that are similar to urban canyon models to evaluate human comfort under different conditions. The OUTCOMES model is one such tool that calculates an energy balance for a human being, based on the weather and the characteristics of the surroundings. OUTCOMES has been used to see how human comfort is improved by shade trees (Grant et al, 2002; Heisler and Wang, 2002; Calzada, 2003; Heisler, 2003).

Ecosystem models

Ecosystem models look at the effects of vegetation in urban areas. There are two main models available: CITYgreen, developed by American Forests, and i-Tree, from the US Department of Agriculture (USDA) Forest Service.

CITYgreen

CITYgreen (American Forests, 2002) is a geographical information system (GIS)-based model that evaluates how a region's trees and vegetation reduce stormwater run-off, improve air quality, decrease energy use and store carbon. Urban planners, regulatory agencies, urban foresters, developers and others use CITYgreen to assess the economic benefits of urban vegetation.

i-Tree

i-Tree (USDA Forest Service, 2007) is a suite of tools for assessing the costs and benefits of urban trees. Its two main components are UFORE, a tool for assessing the environmental effects of trees, and STRATUM, a tool that weighs tree costs and benefits. The complete package helps urban foresters compile field data, inventory trees and estimate tree management costs and the value of trees in terms of energy conservation, air quality improvement, CO_2 reduction, stormwater control and property values.

Regional models

Regional models can be used to evaluate the effects of heat island mitigation on regional air temperatures and air pollution. Researchers have been able to model heat island effects using a combination of meteorological and photochemical modelling techniques.

MM5-CAMx

Two models can be used together to evaluate heat island effects on larger regions. MM5, a model developed by Pennsylvania State University and the National Center for Atmospheric Research (Dudhia, 1993), is used for meteorological modelling. MM5 is most commonly used to simulate the climate and weather of mesoscale regions of at least several square miles. The comprehensive air quality model with extensions (CAMx) (Yarwood et al, 1996) is used to simulate the air quality of a region.

To evaluate the effects of heat island mitigation measures, the input for these models must be extensively manipulated. Temperature, energy use, emissions and smog formation are very interdependent, so the two models must be run iteratively. In other words, modelling the effects of heat island mitigation is a huge undertaking. But as difficult as it is, researchers are making progress at seeing how heat island mitigation measures can reduce temperatures, smog formation and particulate pollution in different urban areas (Douglas et al, 2000; Emery et al, 2000; Taha et al, 2000, 2002; Rose et al, 2003; Sailor, 2003; Taha, 2005).

MIST

In addition to complicated meteorological and photochemical modelling, a much simpler tool has been developed to predict the potential regional impacts of heat island mitigation. The mitigation impact screening tool (MIST) (Sailor and Dietsch, 2005) is a web-based tool that can approximate how increasing a region's solar reflectance and vegetation will reduce temperature, smog and energy consumption. Based on detailed modelling of 20 cities in the US, MIST will estimate mitigation impacts in 200 different locations in the US.

Note

1 US plenum refers to an air-filled space in a structure, especially in ventilation systems.

References

Akbari, H. and S. Konopacki (2003) *Streamlined Energy-Savings Calculations for Heat-Island Reduction Strategies*. Berkeley, CA, Lawrence Berkeley National Laboratory

Alexandri, E. and P. Jones (2006) *Sustainable Urban Future in Southern Europe – What About the Heat Island Effect?* ERSA 2006, Volos, European Regional Science Association

American Forests (2002) *CITYgreen 5.0 User Manual*. Washington DC, American Forests

Arnfield, A. J. (1982) 'An approach to the estimation of the surface radiative properties and radiation budgets of cities'. *Physical Geography* **3**: 92–122

Arnfield, A. J. (1990) 'Canyon geometry, the urban fabric and nocturnal cooling: A simulation approach'. *Physical Geography* **11**(3): 220–239

Bailey, A. P. (2006) 'Saving energy with the right roofs. NRCA and other industry groups introduce a comprehensive energy-conservation program'. *Professional Roofing* February: 34

Barring, L., J. O. Mattsson and S. Lindqvist (1985) 'Canyon geometry, street temperatures and urban heat island in Malmö, Sweden'. *Journal of Climatology* **5**: 433–444

Brest, C. L. (1987) 'Seasonal albedo of an urban/rural landscape from satellite observations'. *Journal of Climate and Applied Meteorology* **26**: 1169–1187

Cadmus Group (2007) 'Energy Star roofing comparison calculator'. Available at http://roofcalc.cadmusdev.com/

Calzada, J. R. (2003) *Vegetation Influences on the Human Thermal Comfort in Outdoor Spaces*. Barcelona, School of Architecture of Barcelona: 6

Chandler, T. J. (1960) 'Wind as a factor of urban temperatures – A survey in north-east London'. *Weather* **15**: 204–213

Crowe, J. (2007) EnergyWise questions, email communication to L. Gartland, 2 October

Douglas, S. G., A. B. Hudischewskyj and V. Gorsevski (2000) *Use of the UAM-V Modeling System as an Air Quality Planning Tool for Examining Heat Island Reduction Strategies*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Dudhia, J. (1993) 'A non-hydrostatic version of the Penn State/NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front'. *Monthly Weather Review* **121**: 1493–1513

Emery, C., H. Taha and G. Gero (2000) *City of Los Angeles Cool Communities Program, Technical Review of Air Quality Modeling*. Technical Review of Air Quality Modeling, Los Angeles, CA, Environmental Affairs Department

Gallo, K., A. L. McNab, T. R. Karl, J. F. Brown, J. J. Hood and J. D. Tarpley (1993a) 'The use of a vegetation index for assessment of the urban heat island effect'. *International Journal of Remote Sensing* **14**(11): 2223–2230

Gallo, K., A. L. McNab, T. R. Karl, J. F. Brown, J. J. Hood and J. D. Tarpley (1993b) 'The use of NOAA AVHRR data for the assessment of the urban heat island effect'. *Journal of Applied Meteorology* **32**: 899–908

Gartland, L., S. Konopacki and H. Akbari (1996) *Modeling the Effects of Reflective Roofing*. Berkeley, CA, Lawrence Berkeley National Laboratory: 8

Georgakis, C. (2002) *Temperature and Wind Velocity in the Urban Environment*. Athens, Group of Building Environmental Physics, University of Athens: 21

Goward, S. N., G. D. Cruickshanks and A. S. Hope (1985) 'Observed relation between thermal emission and reflected spectral radiance of a complex vegetated landscape'. *Remote Sensing of Environment* **18**: 137–146

Grant, R. H., G. M. Heisler and W. Gao (2002) 'Estimation of pedestrian-level UV exposure under trees'. *Photochemistry and Photobiology* **75**(4): 369–376

Hastings, D. A. and W. J. Emery (1992) 'The advanced very high resolution radiometer (AVHRR): A brief reference guide'. *Photogrammetric Engineering and Remote Sensing* **58**(8): 1183–1188

Heisler, G. M. (2003) OUTCOMES modeling. email communication to E. Wong and L. Gartland, 25 June, Syracuse, NY

Heisler, G. M. and Y. Wang (2002) *Applications of a Human Thermal Comfort Model*. Fourth Symposium on the Urban Environment, Norfolk, VA, American Meteorological Society

Hutcheon, R. J., R. H. Johnson, W. P. Lowry, C. H. Black and D. Hadlet (1967) 'Observations of the urban heat island in a small city'. *Bulletin of the American Meteorological Society* **48**(1): 7–9

Konopacki, S. and H. Akbari (2000) *Energy Savings Calculations for Heat Island Reduction Strategies in Baton Rouge, Sacramento and Salt Lake City*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Konopacki, S. and H. Akbari (2001) *Energy Impacts of Heat Island Reduction Strategies in Toronto, Canada*. Berkeley, CA, Lawrence Berkeley National Laboratory

Konopacki, S. and H. Akbari (2002) *Energy Savings for Heat Island Reduction Strategies in Chicago and Houston (Including Updates for Baton Rouge, Sacramento, and Salt Lake City)*. Berkeley, CA, Lawrence Berkeley National Laboratory: 48

Konopacki, S., H. Akbari, S. Gabersek, M. Pomerantz, L. Gartland and M. Moezzi (1996) *Energy and Cost Benefits from Light-Colored Roofs in 11 US Cities*. Berkeley, CA, Lawrence Berkeley National Laboratory

Nunez, M. and T. R. Oke (1976) 'Long-wave radiative flux divergence and nocturnal cooling of the urban atmosphere. II: Within an urban canyon'. *Boundary Layer Meteorology* **10**: 121–135

Nunez, M. and T. R. Oke (1977) 'The energy balance of an urban canyon'. *Journal of Applied Meteorology* **16**(1): 11–19

Oke, T. R. (1981) 'Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations'. *Journal of Climatology* **1**: 237–254

Oke, T. R. (1987) *Boundary Layer Climates*. New York, Routledge

ORNL (2007) 'ORNL/DOE cool roof calculator'. Available at http://www.ornl.gov/sci/roofs+walls/facts/SolarRadiationControl.htm

ORNL-BEP (2001) *DOE Cool Roof Calculator*. Oak Ridge, TN, Oak Ridge National Laboratory, Building Envelopes Program

Owen, T. W., T. N. Carlson and R. R. Gillies (1998) 'An assessment of satellite remotely sensed land-cover parameters in quantitatively describing the climate effect of urbanization'. *International Journal of Remote Sensing* **19**(9): 1663–1681

Rose, L. S., H. Akbari and H. Taha (2003) *Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas*. Berkeley, CA, Lawrence Berkeley National Laboratory: 61

Sailor, D. (2003) *Streamlined Mesoscale Modeling of Air Temperature Impacts of Heat Island Mitigation Strategies*. New Orleans, LA, Mechanical Engineering, Tulane University

Sailor, D. and N. Dietsch (2005) *The Urban Heat Island Mitigation Impact Screening Tool (MIST)*. Washington DC, US Environmental Protection Agency, Heat Island Reduction Initiative

Sakakibara, Y. (1996) 'A numerical study of the effect of urban geometry upon the surface energy budget'. *Atmospheric Environment* **30**(3): 487–496

Santamouris, M. (2001) *Energy and Climate in the Urban Built Environment*. London, James & James

Santamouris, M., N. Papanikilaou, I. Livada, I. Koronakis, C. Georgakis, A. Argiriou and D. N. Assimakopoulos (2001) 'On the impact of urban climate on the energy consumption of buildings'. *Solar Energy* **70**(3): 201–216

Sokolik, I. (2002) *Remote Sensing of Atmospheres and Oceans, Lecture # 7 Notes, Course ATOC/ASEN 5235*. Boulder, CO, Program in Atmospheric and Oceanic Sciences, University of Colorado

Spronken-Smith, R. A. and T. R. Oke (1998) 'The thermal regime of urban parks in two cities with different summer climates'. *International Journal of Remote Sensing* **19**(11): 2085–2104

Stewart, I. D. (2000) 'Influence of meteorological conditions on the intensity and form of the urban heat island in Regina'. *The Canadian Geographer* **44**(3): 271–285

Taha, H. (2005) *Urban Surface Modification as a Potential Ozone Air-Quality Improvement Strategy in California. Phase One: Initial Mesoscale Modeling*. Sacramento, CA, California Energy Commission

Taha, H., S. C. Chang and H. Akbari (2000) *Meteorological and Air Quality Impacts of Heat Island Mitigation Measures in Three US Cities*. Berkeley, CA, Lawrence Berkeley National Laboratory

Taha, H., H. Hammer and H. Akbari (2002) *Meteorological and Air Quality Impacts of Increased Urban Surface Albedo and Vegetative Cover in the Greater Toronto Area, Canada*. Berkeley, CA, Lawrence Berkeley National Laboratory

Todhunter, P. E. (1990) 'Microclimatic variations attributable to urban canyon asymmetry and orientation'. *Physical Geography* **11**(2): 131–141

USDA Forest Service (2007) *i-Tree Software Suite v1.2, Tools for Assessing and Managing Community Forests*.

Washington DC, United States Department of Agriculture Forest Service
Voogt, J. A. and T. R. Oke (1997) 'Complete urban surface temperatures'. *Journal of Applied Meteorology* **36**: 1117–1132
Wilkes, K. (1991) *Thermal Model of Attic Systems with Radiant Barriers*. Oak Ridge, TN, Oak Ridge National Laboratory
Yamashita, S. (1996) 'Detailed structure of heat island phenomena from moving observations from electric tram-cars in metropolitan Tokyo'. *Atmospheric Environment* **30**(3): 429–435
Yarwood, G., R. E. Morris, M. A. Yocke, H. Hogo and T. Chico (1996) *Development of a Methodology for Source Apportionment of Ozone Concentration Estimates from a Photochemical Grid Model*. 89th AWMA Annual Meeting, Nashville, TN, 23–28 June

4

From Heat Islands to Cool Communities

In this chapter, land use characteristics are studied to see how typical construction fosters heat islands. Urban and suburban areas have very high percentages of roofing and paving and surprisingly low amounts of trees and vegetation. The trend in most areas is towards larger cities with fewer trees.

The types of roofing and paving materials used are mostly solid and dark, and they readily absorb and retain heat. The lack of trees also reduces the amount of cooling through evapotranspiration. These traditional materials and patterns of development contribute to the heat island effect. We investigate how three heat island mitigation strategies – the use of cool roofing, cool paving, and trees and vegetation – can be used to reverse the warming trends in our cities and suburbs.

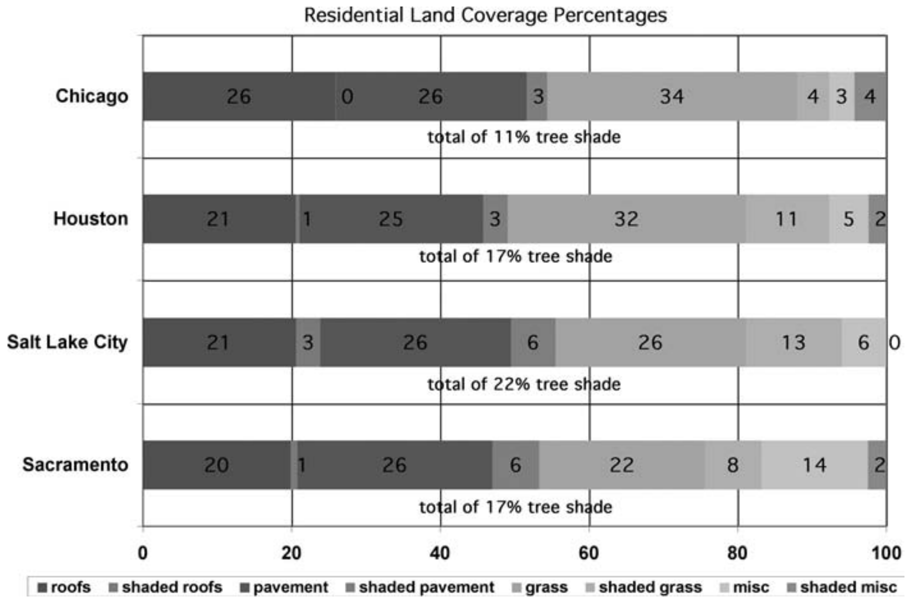
Typical land use characteristics

Lawrence Berkeley National Laboratory performed 'urban fabric analyses' by studying satellite images and using consistent methods to identify land cover in four cities in the US (Akbari and Rose, 1999, 2001a, 2001b; Rose et al, 2003). The land coverage patterns found in Chicago, Houston, Salt Lake City and Sacramento show some interesting characteristics. Figure 4.1 (Plate 7) shows how much roofing, paving and vegetation cover a sample of residential areas in these cities. Figure 4.2 (Plate 8) shows coverage in non-residential areas, including commercial, industrial, office and downtown spaces. Table 4.1 summarizes numerical data from both figures.

As expected, non-residential areas tend to have more paving, less grass and fewer trees than residential areas. Perhaps surprisingly, roofing covers approximately the same percentage of residential and non-residential land areas. When added together, roofing and paving cover a massive 46–52 per cent of residential areas and 58–67 per cent of non-residential areas in these four cities. Vegetation, including tree shade and grass, covers only 39–49 per cent of residential areas and 16–30 per cent of non-residential areas.

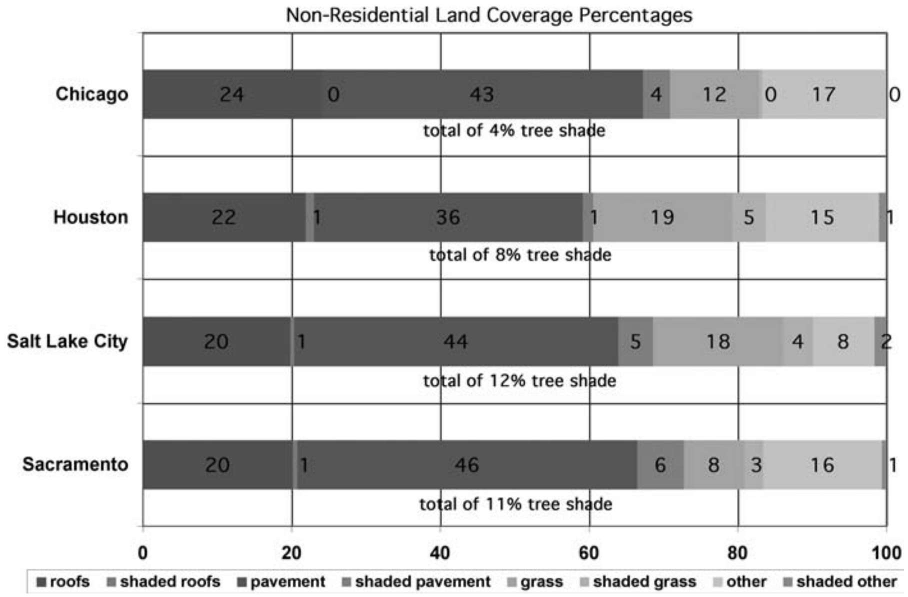
The overall average of the land cover for all four cities is shown in Figure 4.3. Looking down from above the trees, solid surfaces are found to cover more than half of these cities. Roofs, roads, parking lots, sidewalks and driveways cover 20, 15, 12, 5 and 3 per cent of the land, respectively, for a total of 56 per cent impervious coverage. Trees cover only 12 per cent of the area, and grass another 22 per cent, so just 34 per cent of the average city is vegetated.

Other studies have confirmed these low levels of vegetation in cities in the US. The USDA Forest Service compared urban tree coverage to rural coverage. They found that tree canopies cover 27 per cent of 306,560 square kilometres (108,500 square miles) of urban land



Source: Akbari and Rose, 1999, 2001a, 2001b; Rose et al, 2003.

Figure 4.1 Coverage of roofing, paving and vegetation in residential areas of Chicago, Houston, Salt Lake City and Sacramento (see Plate 7 for a colour version)



Source: Akbari and Rose, 1999, 2001a, 2001b; Rose et al, 2003.

Figure 4.2 Coverage of roofing, paving and vegetation in non-residential areas of Chicago, Houston, Salt Lake City and Sacramento (see Plate 8 for a colour version)

Table 4.1 Ranges of roofing, paving and vegetative land cover in residential and non-residential areas of Chicago, Houston, Salt Lake City and Sacramento

	Residential areas	Non-residential areas
Roofing, unshaded	20–26%	20–24%
Paving, unshaded	25–26%	36–46%
Grass, unshaded	22–34%	8–19%
Other, unshaded	3–14%	8–17%
Tree cover	11–22%	4–12%
Total Impermeable, unshaded	46–52%	58–67%
Total Vegetative	39–49%	16–30%

Source: Akbari and Rose, 1999, 2001a, 2001b; Rose et al, 2003.

in the 48 contiguous United States compared to 33 per cent coverage in non-urban land (Dwyer et al, 2001). An area's natural vegetative state was found to be an important factor for tree coverage. Cities located in naturally forested areas averaged 34 per cent tree cover, cities in grasslands averaged 18 per cent tree cover and cities in deserts averaged only 9 per cent tree cover (Dwyer et al, 2001).

The trend in most cities throughout the world is towards increasing urban growth and decreasing tree and vegetation cover. One striking example is the growth of Atlanta, Georgia. As shown in Figure 4.4 (Plate 9), Atlanta has been expanding into surrounding forested land since 1972, covering about 65 per cent of this forest with roads and buildings (Dwyer et al, 2001). As a result, average summer temperatures in Atlanta's urban areas increased by at least 3.3°C (6°F) between 1973 and 1997, and the area of its heat island expanded threefold (Moll and Berish, 1996; Quattrochi et al, 1997; American Forests, 2001).

Urbanization does not always decrease tree cover in cities. Human settlement can have varying effects on vegetation over time. For example, tree coverage in Oakland, California, increased from less than 5 per cent in 1900 to over 20 per cent in the year 2000 (Dwyer et al, 2001). But prior to 1900, the region's vegetation was decimated by extensive logging of redwoods during the gold rush, as well as by the felling of native oaks by early settlers. The increases in tree coverage after 1900 stemmed from reforestation of the Oakland hills and city expansion into the flatlands, with trees planted along streets and around residences for beautification.

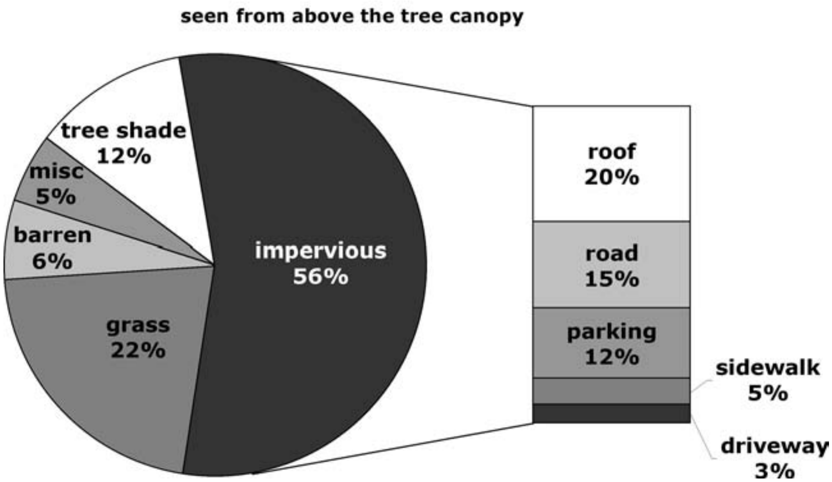
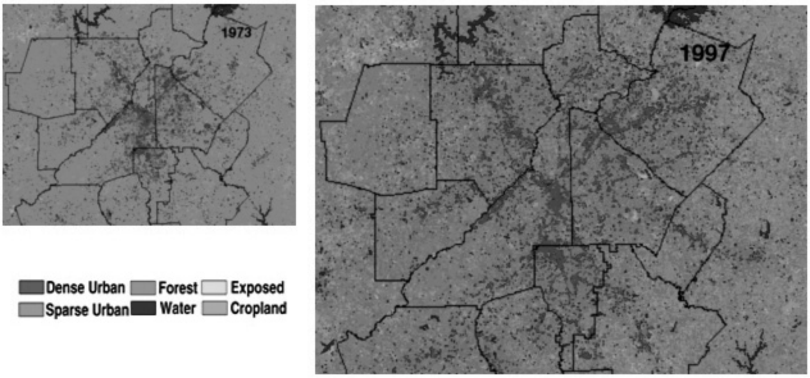


Figure 4.3 Average land cover in Chicago, Houston, Sacramento and Salt Lake City



Source: American Forests, 2001.

Figure 4.4 Satellite images of Atlanta, Georgia, metropolitan area showing changes in land cover between 1973 and 1997 (see Plate 9 for a colour version)

Los Angeles also has an interesting history regarding tree cover. Settlers in the early 1900s planted orchards, but from the 1930s to the end of the century, buildings and pavement relentlessly replaced these irrigated orchards. Maximum temperatures in Los Angeles first fell about 1.5°C (3°F), then rose more than 3°C (5°F), mirroring these vegetation trends (Akbari et al, 1996).

Typical roofing materials

Roofing covers about 20 per cent of urban and suburban areas, and is the hottest feature seen in thermal images of cities. Refer back to Figure 1.11, the thermal image of Sacramento, California, and note that roofs can be easily identified as red rectangles, representing a temperature of at least 50°C (125°F). In fact, most roofing materials commonly reach temperatures of 65–90°C (150–190°F). Their solar reflectance ranges between 5 and 25 per cent, which means they absorb 75–95 per cent of the sun's energy.

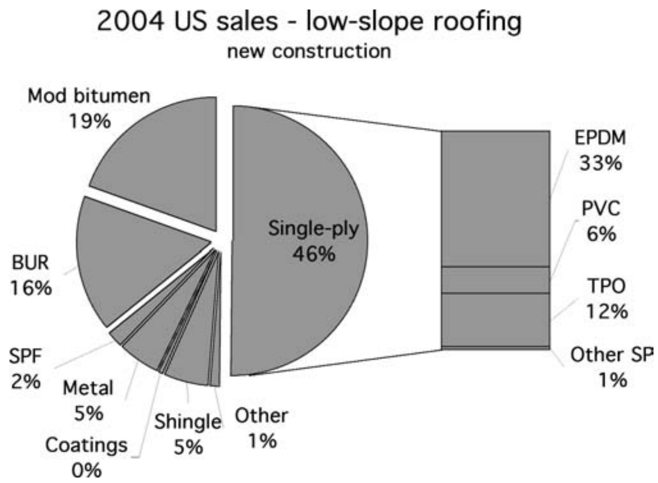
The roofing market is really two different markets: one for low-slope roofs and another for steep-slope roofs. Low-slope roofs are almost flat and are defined as having a slope of less than one in twelve, just enough to allow water to drain away. These roofs are found mainly on large commercial, industrial and office buildings. Steep-slope roofs have a slope of more than one in twelve. Steep-slope roofs are found mainly on residential buildings and play a visible role in a home's appearance. These two markets use very different sets of materials.

Figures 4.5 and 4.6 show the breakdown of materials used in the low-slope market in the US. Unfortunately, the majority of low-slope roofing in use today can be classified as 'hot' roofing. The three most common materials, used on over 70 per cent of low-slope roofs in the US, absorb 75 per cent or more of the sun's energy.

Ethylene propylene diene monomer (EPDM) accounts for almost one-third of all low-slope roofing sales in the US. EPDM is a large single ply, or sheet, and is made of synthetic rubber. It is usually black, and absorbs about 95 per cent of the sun's energy.

Modified bitumen, comprising almost 20 per cent of US low-slope sales, is a membrane made from asphalt and plastic polymers that is fixed to the roof over an asphalt adhesive layer. It is usually dark grey in colour and absorbs 80 per cent or more of the sun's heat.

Built-up roofing (BUR), about 20 per cent of US low-slope sales, consists of layers of felt or fibreglass saturated with asphalt. BUR must be protected from the sun, so it is usually topped by a cap sheet layer with small coloured granules or by a layer of aggregate, i.e. small rocks. Granules or aggregate are typically tan or grey, absorbing 75 per cent or more of the sun's heat.



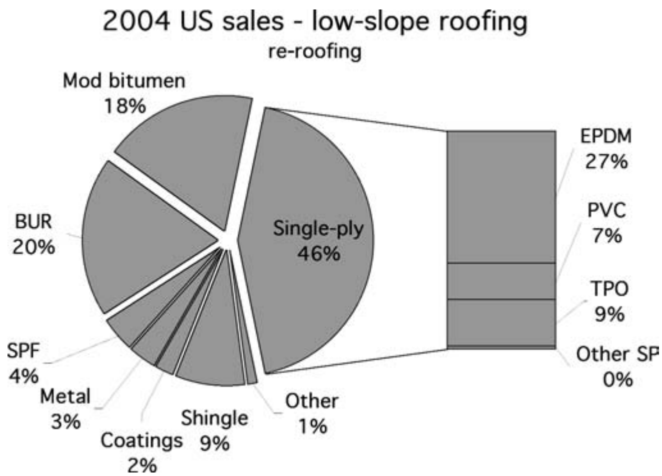
Note: EPDM, ethylene propylene diene monomer; PVC, polyvinyl chloride; TPO, thermoplastic polyolefin; SP, single-ply; Mod, modified bitumen; BUR, built-up roofing; SPF, spray polyurethane foam.

Figure 4.5 Types of low-slope roofing used in the US for new building construction, 2004

Figures 4.7 and 4.8 show the breakdown of materials used for new construction and re-roofing of steep-slope roofs in the US.

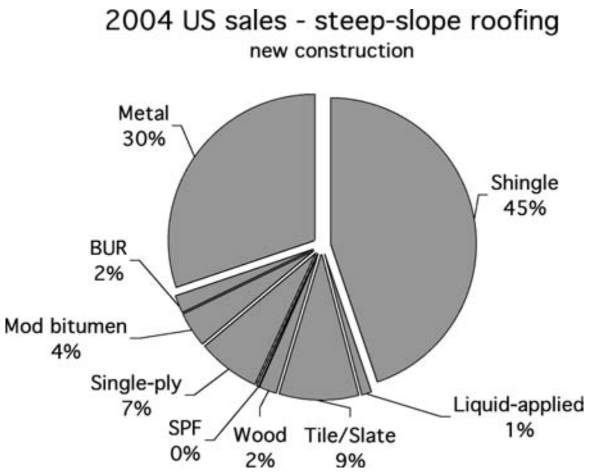
Shingles[1] make up about 50 per cent of steep-slope roofing sales in the US. Shingles, like BUR, are made of felt or fibreglass saturated with asphalt and covered with granules. Granule colours for asphalt shingles come in various shades of brown/tan, grey/black, green and red. The solar reflectance of shingles ranges between 5 and 25 per cent, and temperatures can reach 65–90°C (150–90°F) in the sun.

Metal roofing constitutes about 25 per cent of the steep-slope market in the US. Metal can be bare or coated, but in both cases it gets hot in the sun. When coated, metal roofs come in various shades of green, blue, red and brown, and have solar reflectance values and temperatures similar to those of shingles. Bare metal roofing can have a somewhat higher solar reflectance,



Note: EPDM, ethylene propylene diene monomer; PVC, polyvinyl chloride; TPO, thermoplastic polyolefin; SP, single-ply; Mod, modified bitumen; BUR, built-up roofing; SPF, spray polyurethane foam.

Figure 4.6 Types of low-slope roofing used in the US for re-roofing of existing buildings, 2004



Note: EPDM, ethylene propylene diene monomer; PVC, polyvinyl chloride; TPO, thermoplastic polyolefin; SP, single-ply; Mod, modified bitumen; BUR, built-up roofing; SPF, spray polyurethane foam.

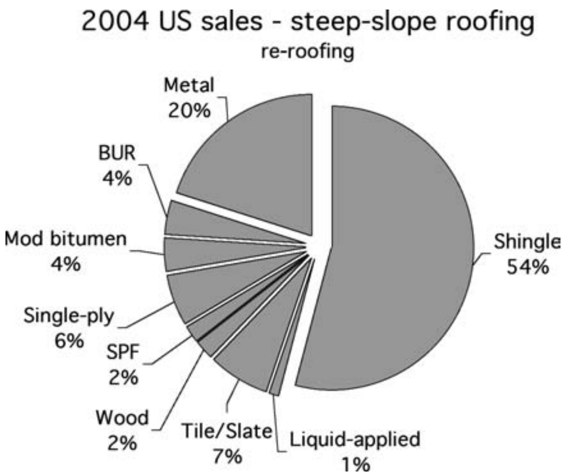
Figure 4.7 Sales of steep-slope roofing in the US for new building construction, 2004

usually ranging between 20 and 60 per cent. But bare metal roofing tends to retain heat, i.e. it has a low thermal emittance, and generally heats up to 50–70°C (120–160°F) in the sun.

Cool roofing materials

The good news is that new 'cool' roofing materi- als are making inroads into the roofing market. Surface temperatures of cool roof materials generally stay below 50°C (120°F) in even the hottest, sunniest summer weather. Traditional roof materials can heat up to 90°C (190°F). Cooler roof surfaces help reduce the heat island, since they release less heat to the air during the day and overnight.

Cool roofing materials have two properties that keep them cooler than traditional hot materials during peak summer weather:



Note: EPDM, ethylene propylene diene monomer; PVC, polyvinyl chloride; TPO, thermoplastic polyolefin; SP, single-ply; Mod, modified bitumen; BUR, built-up roofing; SPF, spray polyurethane foam.

Figure 4.8 Sales of steep-slope roofing in the US for re-roofing of existing buildings, 2004

- high solar reflectance
- high thermal emittance (over 85 per cent).

High solar reflectance means that these materials reflect away the sun's energy much more easily than traditional materials, whose solar reflectance is 25 per cent or lower (Berdahl and Bretz, 1997). The definition of 'high' solar reflectance is somewhat subjective. For low-slope roofs, the US Environmental Protection Agency (Ryan, 2007) specifies a solar reflectance of 65 per cent or higher. Other agencies, such as the State of California (CEC, 2006), define a 70 per cent minimum solar reflectance for low-slope roofs. For steep-slope roofs, the US EPA defines a minimum solar reflectance of 25 per cent, while California requires a 40 per cent minimum.

The coolest materials also have high thermal emittance to help them radiate away any collected heat. The thermal emittance of most materials is greater than 85 per cent, but bare metallic surfaces tend to have emittance values ranging between 20 and 60 per cent. Thermal emittance requirements also vary. The US EPA does not require any minimum thermal emittance to qualify roofs as Energy Star products (Ryan, 2007). California allows a cool roof with a low thermal emittance to make up for this shortcoming by having a higher solar reflectance (CEC, 2006).

In the low-slope market, single-ply materials such as polyvinyl chloride (PVC) and thermoplastic polyolefin (TPO) are usually bright white in colour, have solar reflectance values greater than 70 per cent and stay below 50°C (120°F). Spray polyurethane foam (SPF) is a spray-on insulation, usually topped with a highly reflective protective coating, that also stays cool. Highly reflective cool roof coatings are also being used to extend the life of underlying low-slope roofing materials.

The steep-slope market has not made as much progress with cool materials. New high-reflectance pigments are available and are slowly but surely being adopted for use in metal roof coatings. These pigments reflect the sun's invisible infrared energy, keeping metal roofs cooler without substantially changing their colour. Such pigments could also be used to coat the granules on asphalt shingles, but their adoption by the shingle industry has so far been negligible. Much more information about cool roofing materials can be found in Chapter 5.

Typical paving materials

As described above, pavement covers between 25 and 50 per cent of cities and is often the dominant feature of our urban environments. The thermal characteristics of pavement have a lot of influence on the formation of heat islands.

The two most commonly installed types of pavement are asphalt cement concrete, referred to here as asphalt, and Portland cement concrete, referred to as concrete. Asphalt is black or dark grey when installed, with 5–10 per cent initial solar reflectance. Over time, asphalt lightens and its solar reflectance increases to 10–20 per cent. Asphalt can heat to 65°C (150°F) or more in the summer sun and is the second hottest feature in the urban landscape, behind traditional roofing materials.

Concrete pavements start out light grey, with a 30–40 per cent solar reflectance. Over time, concrete becomes dirtier and its solar reflectance lowers to 25–35 per cent. Concrete pavements stay much cooler than asphalt, often staying below 50°C (120°F) in even the hottest, sunniest conditions.

The asphalt and concrete paving industries are fierce competitors and are not extremely forthcoming with market data. But it is clear that asphalt paving has the largest market share in the US. Table 4.2 gives estimates for the market shares of asphalt and concrete for different pavement applications. Asphalt tends to have lower installation costs and be easier to install, while concrete tends to last longer, support heavier traffic loads, need less maintenance, and have lower life-cycle costs (Packard, 1994; Ting et al, 2001; Hawbaker, 2003). Most agencies responsible for paving, such as government transportation departments and developers, are more interested in keeping initial costs low and are less motivated by life-cycle considerations.

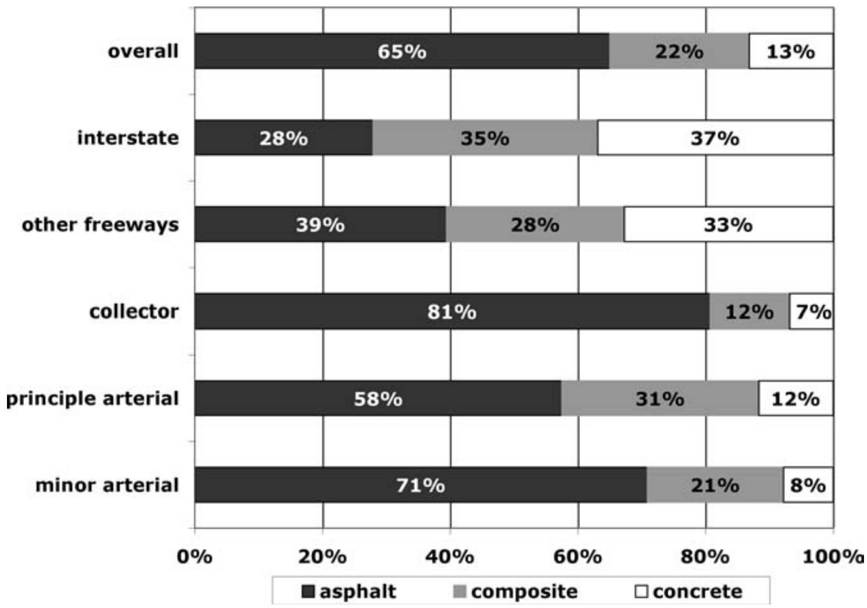
Table 4.2 Estimated market share of asphalt and concrete pavements in the US

Pavement application	Asphalt market share	Concrete market share
Highways	70%	30%
Urban roads	85%	15%
Driveways	40%	60%
Sidewalks	10%	90%
Parking lots	85%	15%
Pathways and trails	80%	20%
Pedestrian spaces/open malls	25%	75%

Source: Hawbaker, 2002.

An analysis of US highway statistics confirms asphalt's dominant market share for roads and highways (USDOT, 2000). Figure 4.9 shows what percentage of US roads are paved with asphalt (termed flexible pavement in the statistics), what percentage are concrete (termed rigid pavement), and what roads use a composite, generally a road first laid with concrete and subsequently re-surfaced with asphalt.

Highways are more likely to be paved with concrete, or to at least have a concrete base, while city streets are more likely to be paved with asphalt. This is partly due to the need for highways to support heavier loads. It may also be due to more stable funding of federal and state transportation agencies, responsible for most highway paving, to cover the higher initial costs in favour of lower life-cycle costs.



Source: USDOT, 2000.

Figure 4.9 Percentage of road surfaces in the US covered with asphalt, concrete and a composite of concrete and asphalt, corrected for the number of lanes per road type

Cool paving materials

Cool paving reduces pavement temperatures by 19.5°C (30°F) or more (Asaeda et al, 1996; Pomerantz et al, 2000; Gartland, 2001). The hottest pavements tend to be impermeable and dark in colour, with solar reflectance under 25 per cent. There are two ways to cool pavements: (1) by making them lighter in colour, thus raising solar reflectance to 25 per cent or higher, and/or (2) by making them permeable, allowing water to drain through during rainstorms and evaporate back out during hot, sunny weather. Evaporating water removes heat from the paving material, keeping it cooler, much like the evapotranspiration process of plants.

Thermal emittance is not as important a factor in the surface temperature of pavement as it is in roofing. Asphalt pavements generally have thermal emittance values of 85 per cent or higher, while the thermal emittance of concrete pavements ranges between 70 and 90 per cent. But the effects of thermal emittance are outweighed by the effects of solar reflectance. For dry, impermeable pavements, solar reflectance is the biggest factor affecting the temperature. Since pavement colour has the largest effect on solar reflectance, the lightest coloured pavements are usually the coolest.

Asphalt pavements are not normally cool pavements, but they can be cooled in various ways. Light pigments or light-coloured aggregates (rocks in the pavement mixture) can be added to the asphalt mix. These additives can increase the solar reflectance of the pavement by up to 30 percentage points. For example a typical pavement with solar reflectance of 15 per cent can potentially bring its reflectance up to 45 per cent by using lighter-coloured aggregates and pigments in its mix. Lighter pigments and lighter aggregates can also be added to emulsion seal coats and chip seals used during routine asphalt resurfacing and maintenance (Cartwright, 1998; Ting et al, 2001). Asphalt pavements can also be finished in a variety of brick- or stone-like textures, using light coloured coatings to simulate the look of other materials.

Concrete pavements tend to be lighter in colour than asphalt pavements, with solar reflectance values that may qualify typical concretes as cool pavements. However, they can be cooled even further by the use of lighter coloured aggregates and cement binders. Laboratory tests of specially lightened concretes revealed solar reflectance values as high as 80 per cent (Levinson and Akbari, 2001). Concrete can be also be applied over existing asphalt pavements through processes called white-topping or ultra-thin white-topping, which uses fibre reinforcement to strengthen the pavement, keeping it thinner and reducing its curing time (Hurd, 1997).

Another way to keep pavements cool is to make them porous or permeable. This allows water to drain through small openings when it rains, storing water in the soil or supporting materials beneath the pavement. During dry, sunny conditions, stored water evaporates and cools the pavement. For porous pavements to stay cool over time there must be a water source, either in the form of regular rainstorms or through periodic watering.

Both asphalt and concrete can be constructed as porous pavements. With 'open-graded' asphalt and porous concrete, the smallest particles of sand and rock are left out of the concrete mix. This leaves a void space between the larger rocks and allows water to drain through the pavement. These void spaces must be carefully sized to avoid getting clogged by dirt and other materials. Both asphalt and concrete versions of porous pavements have been used on roads and parking lots (Smith, 1999; Maes and Youngs, 2002).

Other cool pavement options are available, such as block pavers and resin-based pavements, but these are much less common than traditional asphalt or concrete pavements. Block pavers are lattice blocks made of plastic, metal or concrete. These blocks are laid in place over a graded and prepared base and are filled with rocks or soil; the soil can then be planted with grass or wild flowers. The blocks provide structural support, while still allowing water to drain and subsequently to evaporate. Porous block pavers have been used successfully in low traffic areas such as alleyways, driveways, parking lots and fire lanes (Cote et al, 2000; Chicago, 2002).

Resin-based pavements use tree resins to bind the pavement together, in place of the asphalt or cement binders used in asphalt and concrete pavements. The resin is clear, so resin-based pavements assume the colour of the aggregate, sand and dirt of the rest of the pavement mixture. These aggregates are often taken straight from the site, allowing the pavements to blend in with the natural environment. Resin-based pavements have been used successfully as hiking and biking paths in parks and other environmentally sensitive areas. More detailed information about cool paving can be found in Chapter 6.

Thermal properties of materials

The reflectance and emittance of common urban and rural materials are shown in Figure 2.3. Two prominent materials have low solar reflectance: asphalt paving and built-up roofing. The prevalent use of roofing and paving materials in cities and suburbs increases the amount of solar radiation amassed by urban areas.

Roofing and paving materials have additional characteristics that exacerbate the heat island problem. As was presented in Chapter 2, and is worth noting again here, thermal conductivity and heat capacity are also important. Materials with high thermal conductivity tend to store and release more heat. Figure 2.2 plots the values of common natural materials and construction materials. Man-made construction materials such as pavement and insulation tend to store more heat during the day, and release it slowly at night.

Cooling with trees and vegetation

Trees and vegetation cool their vicinity in two ways: (1) evapotranspiration converts the sun's energy into vaporized water instead of heat, keeping vegetation and air temperatures lower, and (2) trees and vegetation shade surfaces from the sun's heat, keeping them cooler and reducing the energy they store.

More than 75 per cent of the world's residents live in urban areas (United Nations, 2002), and urban trees are the only trees most people see from day to day. According to analyses by the United States American Forests and Lawrence Berkeley National Laboratory, many US cities have less than 25 per cent tree cover in residential areas and less than 15 per cent tree cover in commercial areas (Akbari and Rose, 1999, 2001a, 2001b; American Forests, 2002; Rose et al, 2003). The United States Department of Agriculture (USDA) Forest Service counted about 3.8 billion trees in urban areas in the US, or 17 trees for each urban inhabitant (Dwyer et al, 2001).

American Forests estimates that planting 634.4 million more trees in the US, about three more trees for each urban inhabitant, could bring significant benefits to urban areas (American Forests, 2002). According to their calculations, many US cities have less than 25 per cent tree cover in residential areas and less than 15 per cent tree cover in commercial areas (American Forests, 2002). American Forests recommends increasing average tree cover in cities to the levels listed in Table 4.3. Overall, cities with abundant water should have tree cover of 40 per cent, while drier cities should have 25 per cent tree cover. American Forests has determined that the addition of trees to reach these levels is a practical and cost-effective way to reduce energy savings, air pollution and stormwater run-off in urban and suburban areas.

Independent analyses of Chicago and Sacramento confirm the American Forests recommendations for additional tree coverage. A study of Chicago estimated that 38 per cent of the land area could be classified as 'available growing space' for trees, but only 11 per cent percent of Chicago was actually covered by trees. The remaining 27 per cent represents land where more trees could potentially be planted, most commonly in residential yards; the strips of

Table 4.3 Recommended tree coverage for cities in the US

	Cities east of the Mississippi River and in the Pacific Northwest	Cities in the southwest and dry west
Suburban residential[a]	50%	35%
Urban residential[a]	25%	18%
Central business district[a]	15%	9%
Overall	40%	25%

Note: a Suburban residential areas are defined as having a density of up to five dwelling units per acre, urban residential areas have density of five or more dwelling units per acre, and central business districts are assumed to combine commercial and industrial uses.

Source: American Forests, 2002; Moll and Kollin, 2002.

land alongside highways (legal surveyed land/area set aside for highways and roads); and on commercial, industrial and institutional land (McPherson et al, 1993). Similar work in Sacramento estimated that trees could cover an additional 15 per cent of the city, increasing shading to 20 per cent of roofs, 20 per cent of roads, 50 per cent of sidewalks and 30 per cent of parking lots (Akbari and Rose, 1999).

Trees and vegetation can be most useful when planted in strategic locations around buildings (McPherson and Simpson, 1999; Sarkovich, 2002). Planting deciduous species to the south, southwest, east and southeast has been found to be most effective at cooling buildings, especially if these trees shade windows and part of the building's roof. Planting evergreen species to the north helps block winter winds.

Shading pavement in parking lots and streets is also an effective way to cool a community. Trees can be planted around the perimeters or in medians (unpaved space used to separate opposing lanes of traffic, streets from sidewalks, or parked cars from each other) inside the parking lots or along the length of streets. Many cities have ordinances requiring street and parking lot landscaping. These ordinances are not intended just for beautification, but also have the specific intention of keeping these areas cooler.

Many playgrounds, school yards and sports fields are devoid of shade from trees or vegetation. People, and especially children, congregating in these areas can often use some respite from the sun's heat and damaging ultraviolet rays. A couple of strategically placed trees can make these areas more comfortable and healthy.

Keep in mind that trees are not the only vegetation option. There are many areas where trees do not fit or grow too slowly to be effective in the short term. Another promising landscaping option is to grow vines on trellises. Vines need less soil and space, grow very quickly and can often be supported on a wire or string.

Green roofing, or garden roofing, is another important option for shading and landscaping urban areas. It is impossible to shade all rooftops by planting trees around buildings, but effective roofing systems have been developed to grow everything from simple turf to full-scale gardens on the tops of buildings.

Detailed information about the use of trees and vegetation can be found in Chapter 7.

Potential for cooling

Chapter 8 reviews how the use of cool roofing, cool paving and more trees and vegetation can make a big difference to urban temperatures. A theoretical study of Sacramento, California, looked at what would happen if the amount of trees and vegetation were doubled and cool roofing and paving materials were used. The average surface temperature during the hottest periods was lowered by 16°C (29°F), and air temperatures were decreased by 1.2°C (2.2°F) on hot afternoons.

Note

1 US shingle refers to a small thin piece of building material, often tapered, for use as tiles on a roof or in wall-cladding.

References

Akbari, H. and L. S. Rose (1999) *Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California*. Berkeley, CA, Lawrence Berkeley National Laboratory: 48

Akbari, H. and L. S. Rose (2001a) *Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Chicago, Illinois*. Berkeley, CA, Lawrence Berkeley National Laboratory

Akbari, H. and L. S. Rose (2001b) *Characterizing the Fabric of the Urban Environment: A Case Study of Salt Lake City, Utah*. Berkeley, CA, Lawrence Berkeley National Laboratory: 51

Akbari, H., A. Rosenfeld, H. Taha and L. Gartland (1996) *Mitigation of Summer Heat Islands to Save Electricity and Reduce Smog*. American Meteorological Society Annual Meeting, Atlanta, GA, American Meteorological Society

American Forests (2001) *Urban Ecosystem Analysis for the Atlanta Metro Area*. Washington DC, American Forests: 8

American Forests (2002) 'National urban tree deficit.' Available at http://www.americanforests.org/graytogreen/treedeficit/

Asaeda, T., V. T. Ca and A. Wake (1996) 'Heat storage of pavement and its effect on the lower atmosphere'. *Atmospheric Environment* **30**(3): 413–427

Berdahl, P. and S. Bretz (1997) 'Preliminary survey of the solar reflectance of cool roofing materials'. *Energy and Buildings* **25**(2): 149–158

Cartwright, P. (1998) 'Blue diamond materials and excel paving provide colored asphalt for union station project'. *California Asphalt* November/December: 8–9

CEC (2006) *2005 Building Energy Efficiency Standards for Residential and Non–Residential Buildings*. Sacramento, CA, California Energy Commission

Chicago (2002) *Urban Heat Island Initiative: Alley Reconstruction*. Chicago, IL, City of Chicago: 1

Cote, M. P., J. Clausen, B. Morton, P. Stacey and S. Zaremba (2000) *Jordan Cove Urban Watershed National Monitoring Project*. Boston, MA, US Environmental Protection Agency, Office of Ecosystem Protection: 8

Dwyer, J. F., D. J. Nowak, M. H. Noble and S. M. Sisinni (2001) *Connecting People with Ecosystems in the 21st Century: An Assessment of Our Nation's Urban Forests, A Technical Document Supporting the 2000 USDA Forest Service RPA Assessment*. Washington DC, US Department of Agriculture, Forest Service: 119

Gartland, L. (2001) *Cool Roof Energy Savings Evaluation for City of Tucson Thomas O. Price Service Center Administration Building One*. Tucson, AZ, City of Tucson

Hawbaker, L. (2002) Concrete market share, email communication with L. Gartland, 28 June

Hawbaker, L. (2003) *Responsible Roads…The Key to Unlock Asset Management for Streets and Local Roads*, paper no LVR8-1151, p21, 8th International Conference on Low-Volume Roads, Reno, NV, 22–25 June

Hurd, M. K. (1997) 'Ultra-thin whitetopping'. *Concrete Construction* February

Levinson, R. and H. Akbari (2001) *Effects of Composition and Exposure on the Solar Reflectance of Portland Cement Concrete*. Berkeley, CA, Lawrence Berkeley National Laboratory: 51

Maes, L. and A. Youngs (2002) *Pervious Concrete Parking Lot Offers Cost-Saving and Environmental Benefits to City of Cerritos*. Cerritos, CA, Southern California Ready Mixed Concrete Association, California Cement Promotion Council: 2

McPherson, E. G. and J. R. Simpson (1999) *Reducing Air Pollution through Urban Forestry*. 48th Annual Meeting of the California Forest Pest Council, Sacramento, CA, 18–19 November

McPherson, E. G., D. J. Nowak and P. L. Sacamano (1993) *Chicago's Evolving Urban Forest: Initial Report of the Chicago Urban Forest Climate Project*. Radnor, PA, US Department of Agriculture Forest Service, Northeastern Forest Experiment Station: 55

Moll, G. and C. Berish (1996) 'Atlanta's changing environment'. *American Forests* Spring: 26–29

Moll, G. and C. Kollin (2002) 'Trees: The green infrastructure'. *IQ Report* **34**(11)

Packard, R. G. (1994) 'Pavement costs and quality: A consumer's report'. *Concrete International* **16**(8)

Pomerantz, M., B. Pon and H. Akbari (2000) *The Effect of Pavements' Temperatures on Air Temperatures in Large Cities*. Berkeley, CA, Lawrence Berkeley National Laboratory: 20

Quattrochi, D., J. Luvall, S. Q. Kidder, C. P. Lo, H. Taha, R. D. Bornstein, R. R. Gillies, K. Gallo and M. G. Estes (1997) *Project ATLANTA, A Remote Sensing-Based Study of Past and Future Land Use*

Change Impacts on Climate and Air Quality of the Atlanta, Georgia, Metropolitan Region. Huntsville, AL, Global Hydrology and Climate Center, National Aeronautics and Space Administration: 67

Rose, L. S., H. Akbari and H. Taha (2003) *Characterizing the Fabric of the Urban Environment: A Case Study of Greater Houston, Texas*. Berkeley, CA, Lawrence Berkeley National Laboratory: 61

Ryan, S. J. (2007) *Final Energy Star Version 1.0 Specification for Roof Products* Washington DC, US Environmental Protection Agency

Sarkovich, M. (2002) *SMUD's Urban Heat Island Mitigation Efforts. Special Panel on Heat Island Mitigation (not in proceedings)*, American Council for an Energy Efficient Economy, Summer Study on Energy Efficiency in Buildings, Pacific Grove, PA, 21 August, Sacramento Municipal Utility District

Smith, R. (1999) 'All's finally quiet at Sutter's mill'. *California Asphalt* January/February: 22

Ting, M., J. Koomey and M. Pomerantz (2001) *Preliminary Evaluation of the Lifecycle Costs and Market Barriers of Reflective Pavements*. Berkeley, CA, Lawrence Berkeley National Laboratory: 67

United Nations (2002) *World Urbanization Prospects, the 2002 Revision*. New York, NY, Department of Economic and Social Affairs, Population Division, United Nations

USDOT (2000) *Highway Statistics 1999*. Washington DC, US Department of Transportation: 192

5

All About Cool Roofing

Introduction

Traditional roof materials tend to bake in the sun, heating up to temperatures of 50–90°C (150–190°F). Hot roof materials create problems for the buildings beneath them, including:

- hotter indoor temperatures
- reduced indoor comfort
- more energy used for cooling
- more money spent on utility bills
- more wear on cooling systems
- faster deterioration of the roof.

Hot roofs also create problems for their communities, including:

- greater electricity demand, especially during peak afternoon hours
- more potential for brownouts and blackouts on the power grid
- increased power plant emissions
- hotter urban and suburban temperatures
- increased smog formation due to the combination of higher emissions and temperatures
- more roofing waste sent to landfills.

Replacing hot roof materials with cool materials can help alleviate these problems. Cool roof materials stay cooler in the sun, usually heating up to a peak of only 40–60°C (100–140°F). The coolest roofing materials have two important characteristics:

- high solar reflectance (also called albedo), the percentage of solar energy reflected by a surface (it is recommended that white roofs should have solar reflectance values greater than 70 per cent, coloured roofs should have solar reflectance values greater than 40 per cent, and that all roofs should have thermal emittance values greater than 80 per cent)
- high thermal emittance, the percentage of energy a material can radiate (not reflect) away.

This chapter explains what makes a roof cool and identifies the various types of cool roofing materials available today. The many benefits of cool roofs are then described.

Cool roofing definition

As just stated, cool roofing materials need to have both high solar reflectance and high thermal emittance. Before describing reflectance and emittance further, it is useful to understand a bit more about energy from the sun, since this is what heats up roofing materials.

Solar properties

Figure 5.1 (Plate 10) shows the typical solar energy that reaches the Earth's surface on a clear summer day. Its intensity varies over wavelengths

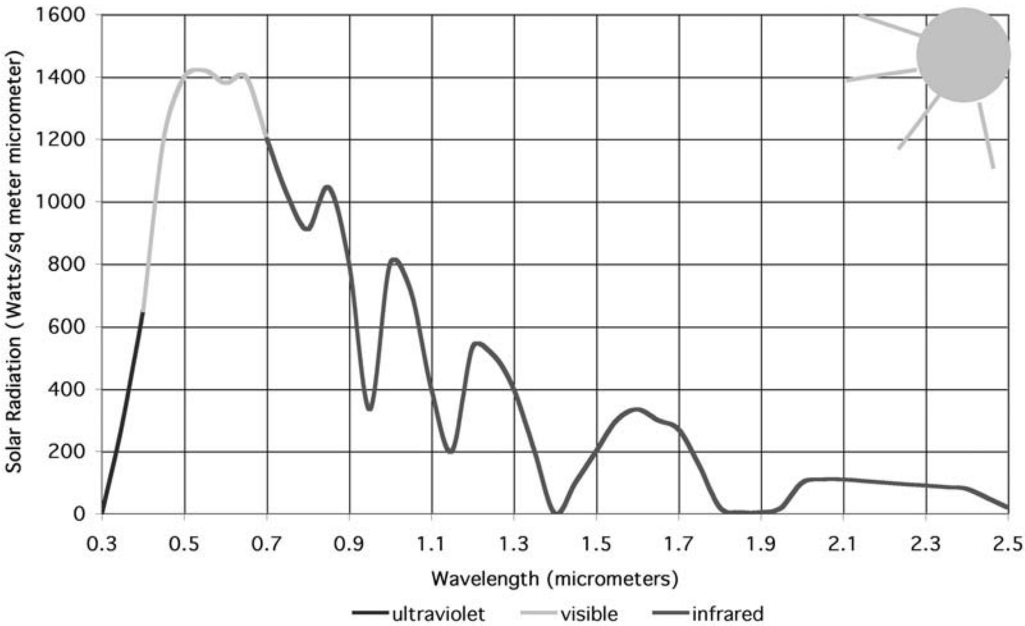


Figure 5.1 Solar energy versus wavelength reaching the Earth's surface (see Plate 10 for a colour version)

from 0.3 to 3.0μm with a peak at about 0.6μm. These wavelengths are classified into three ranges – ultraviolet, visible and infrared. Ultraviolet energy, responsible for causing sunburn, falls in the shortest wavelengths and contributes just 3 per cent of the sun's energy. Visible light delivers 40 per cent of the sun's energy over wavelengths from 0.4 to 0.7μm. Visible light ranges in colours from red to violet (remember ROYGBIV for red, orange, yellow, green, blue, indigo and violet), which combine into an almost white light. The remaining 57 per cent of the sun's energy, making up the wavelengths from 0.7 to 2.5μm, is infrared energy that is felt as heat.

Adding up the area under the curve of Figure 5.1, which combines the contributions from ultraviolet, visible and infrared wavelengths, gives a peak solar energy of about 1200W/m^2. This is the maximum energy that reaches the ground at noon on a clear day during the summer. For comparison, this is equivalent to the heat from twelve 100W incandescent light bulbs hitting the ground every square metre, or about every square yard.

Solar reflectance

Solar reflectance is an overall measure of how well a material reflects all components of the sun's energy. Materials do not always reflect energy at different wavelengths uniformly, but often reflect more at one wavelength and less at another. By measuring how much energy a material reflects at each wavelength between 0.3 and 2.5μm and then calculating a weighted average of those values, the solar reflectance can be found. ASTM standard E 903 (ASTM, 1992) has more details about this calculation.

Traditional roofing materials reflect the sun's energy poorly, with overall solar reflectance values between 5 and 25 per cent. Figure 5.2 (Plate 11) shows the reflective properties of typical roof materials (Berdahl and Bretz, 1997). A black asphalt shingle reflects about 5 per cent of the energy across all wavelengths. A green shingle performs a bit better, with a 14 per cent overall solar reflectance. Note the variation in reflectance of the green material between 0.4 and 0.6μm; this variation in the reflection of visible light is what gives the material its colour.

The most reflective of the traditional roof materials comes in a light grey colour, often called white by roofers' marketing departments. However, this light grey material has only a 25 per cent overall solar reflectance. Remember that solar energy hitting a roof can be as great as 1200W/m^2, so at 25 per cent reflectance, 900 of those watts are absorbed into the roof.

The coolest roof materials tend to reflect more energy in the visible and infrared wavelengths. Figure 5.2 shows the solar reflectance of one of the coolest materials available, a cool white coating (Berdahl and Bretz, 1997). This coating has a very high reflectance in the visible portion of the solar spectrum, hence its bright white colour. The reflectance of the material falls off in the infrared, but its overall solar reflectance is still 75 per cent. This means that instead of absorbing 900W/m^2, the cool roof absorbs only 300W/m^2. Hundreds of bright white coatings and single-ply roof materials with a similar high solar reflectance are readily available in today's market.

Bright white coatings are able to achieve their high solar reflectance mainly by using titanium dioxide (TiO_2), a pigment that reflects the energy of all the sun's wavelengths. Other pigments have been discovered that reflect high amounts of infrared energy, but not visible energy. These pigments have less effect on a material's colour, and have brought about a whole new class of cool roofing materials – cool colours.

Figure 5.2 shows two examples of these cool coloured materials. The cool green material uses a pigment mixture of chromium oxide (Cr_2O_3) and titanium dioxide and achieves an overall solar reflectance of 48 per cent. This is much higher than the 15 per cent of a traditional green roof material (Berdahl and Bretz, 1997). The cool red material uses ferrous oxide (Fe_2O_3) and titanium dioxide to make a red coating with a solar reflectance of 43 per cent. Traditional red materials have solar reflectance of only 10–20 per cent. Figure 5.2 shows that both of these materials achieve most of their reflectance gains in the infrared wavelengths. The solar reflectance of cool coloured materials is expected to range between 30 and 60 per cent, depending on the type of pigment used and the darkness of the colour chosen. Examples of cool coloured materials on the market today are given later in this chapter.

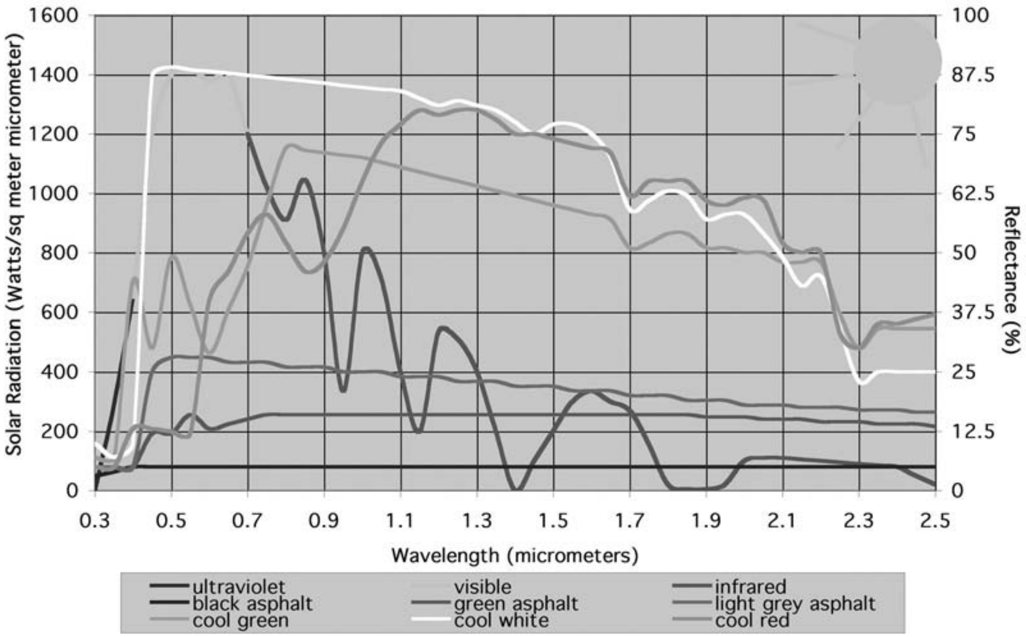


Figure 5.2 Solar reflectance of different roof materials (see Plate 11 for a colour version)

Thermal emittance

The effect of solar reflectance, i.e. that a material stays cooler if it absorbs less solar energy, is fairly obvious. The effect of thermal emittance on materials is not so obvious. Materials with high thermal emittance are able to radiate heat away from themselves to stay cool. Materials with low thermal emittance trap energy on a molecular level at long wavelengths between 5 and 40μm. These long wavelengths correspond to relatively low temperatures, off to the right on our chart of solar wavelengths in Figures 5.1 and 5.2. Energy that cannot be emitted from a material raises a material's temperature.

Most roofing materials, and most materials in general, have thermal emittance values of 80 per cent or higher. But an important class of materials, metals, tends to have lower emittance. The thermal emittance of bare metallic surfaces ranges from 20 to 60 per cent, depending on the finish (smooth or rough) and condition (shiny and clean, dirty, or rusty). This low thermal emittance prevents bare metal roofs and metallic coatings from being cool materials, despite their high solar reflectance.

An example of the effect of thermal emittance on temperature is a wrench left out in the hot sun. The wrench is likely to scorch your hand when you pick it up, despite its being very shiny and reflective, and thus having a high solar reflectance. But a wrench, being made of metal, has low thermal emittance. The wrench reflects most of the sun's heat away, but cannot radiate away the energy that it absorbed. Similarly, a tin roof heats up because it cannot cool itself through radiation as other materials can. Tennessee Williams had the physics right when he wrote *Cat on a Hot Tin Roof*!

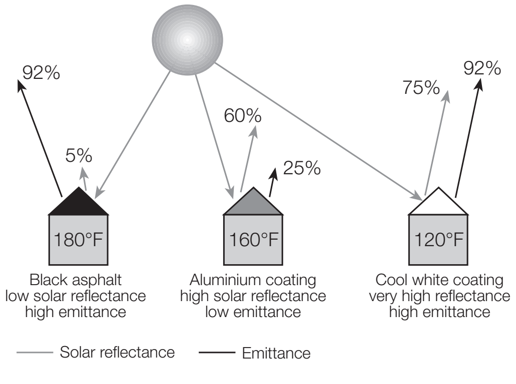


Figure 5.3 Combined effects of solar reflectance and emittance on roof temperature (see Plate 12 for a colour version)

Note that only the thermal emittance of the *uppermost surface* of the roof is important. A bare metal roof has low emittance, but coating that metal with any non-metallic material, such as paint, immediately raises its emittance. Conversely, you can coat a non-metallic roof with a metallic coating and immediately lower its emittance.

As illustrated in Figure 5.3 (Plate 12), solar reflectance and thermal emittance work together to affect surface temperatures. Traditional roof surfaces have low reflectance (5–25 per cent) and high emittance (over 80 per cent), and heat up to 65–90°C (150–190°F) at midday during the summer. Bare metal or metallic surfaced roofs have high reflectance (50 per cent or higher if clean) and low emittance (20–60 per cent), yet still warm to 60–75°C (140–170°F). Cool roofs with both high reflectance (greater than 70 per cent) and high emittance (over 80 per cent) warm to only 35–60°C (100–140°F) in the summer sun.

Many people use the terms 'reflective', 'high-albedo', 'light-coloured' or 'white' interchangeably when referring to 'cool' materials. It is important to remember that these conditions by themselves do not guarantee a material stays cool in the sun. Truly cool materials must have both high solar reflectance and high thermal emittance. For example, metallic materials such as aluminium coatings can be highly 'reflective' and have 'high albedo', but are not cool because of their low thermal emittance. An asphalt shingle can be labelled 'white' or 'light-coloured', but still have low solar reflectance and get hot in the sun.

Measurement and labelling of cool roof materials

The introduction of infrared-reflecting pigments makes it especially difficult to judge how cool a

Table 5.1 Test methods to evaluate the solar properties of roofing materials

Property measured	Test method	Equipment used	Test location
Solar reflectance	E 903 Standard Test Method for Solar Absorptance, Reflectance and Transmittance of Materials Using Integrating Spheres (ASTM, 1992)	Integrating sphere spectrophotometer	Laboratory
Solar reflectance	E 1918 Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field (ASTM, 1997b)	Pyranometer	Field
Solar reflectance	C 1549 Standard Test Method for Determination of Solar Reflectance near Ambient Temperature Using a Portable Solar Reflectometer	Pyranometer	Field
Thermal emittance	E 408 Standard Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques (ASTM, 1990)	Reflectometer or emissometer	Laboratory
Thermal emittance	C 1371 Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers (ASTM, 1998)	Emissometer	Field
Solar reflectance index	E 1980 Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces (ASTM, 1999)	Calculation method	–

material may be. You cannot simply look at a material – it must have its solar reflectance and thermal emittance measured. Five standard American Society for Testing of Materials (ASTM) methods are commonly used to measure solar properties. Solar properties are not required to be tested, but two voluntary programs exist under which manufacturers can test and register their products: the Energy Star program and the Cool Roof Rating Council program. These test methods and voluntary programs are described below.

Test methods

Solar reflectance and thermal emittance can be measured using standard test methods that have been developed and validated by the ASTM. These methods are listed in Table 5.1. Solar reflectance and thermal emittance can be tested either in the laboratory or in the field. Laboratory measurements are usually made to find the properties of new material samples. The equipment needed for laboratory measurements is quite expensive, so these measurements are often made by independent laboratories for a fee. Field measurements are useful for evaluating how well a roof material has withstood the test of time, weather and dirt build-up. Equipment for field testing tends to be less expensive, although it yields lower accuracy. Sometimes field testing is performed by the manufacturer or by another interested party with the right equipment.

The last method listed in Table 5.1 is not an actual test, but outlines a way to calculate the solar reflectance index, or SRI. SRI is a term used occasionally when referring to cool roofing materials. This value incorporates both the solar reflectance and thermal emittance into a single value to represent a material's performance in the sun. This index tells us how hot a surface would get relative to a standard black and standard white surface. In physical terms, this is like laying a roof material in the sun next to a perfect black surface and a perfect white surface and measuring the temperatures of all three surfaces. The SRI is a value between zero (as hot as the black surface) and 100 (as cool as the white surface). When calculating SRI, surface temperatures are not actually measured; instead, ASTM E 1980 lays out equations for finding the SRI from previously measured values of solar reflectance and thermal emittance.

Cool roof labelling

Manufacturers are not required to measure or label their roof products' solar reflectance or thermal emittance, but two programs currently exist to facilitate manufacturers who want to certify that their products are cool. Since 1998, the United States Environmental Protection Agency has listed roof products under their Energy Star program. The Cool Roof Rating Council has had a testing and labelling program in place since 2003.

Energy Star program

Under the Energy Star program, manufacturers test their products' solar reflectance according to either ASTM E 903 or ASTM E 1918. The roof product can then qualify as an Energy Star product if it meets the criteria laid out in Table 5.2.

To ensure the long-term integrity of reflective products, the Energy Star program not only requires tests of materials after three years in service, but also requires products to have warranties comparable to those offered for non-reflective roof products (Schmeltz and Bretz, 1998; EPA, 2000).

There are three things to note about the Energy Star criteria. First, the solar reflectance criteria are different for low-slope and steep-slope roofing, but these criteria vary by a wide margin. There are hundreds products for low-slope roofs that meet Energy Star criteria of 65 per cent solar reflectance. Unfortunately, only a handful of products for steep-slope roofs currently meet Energy Star's 25 per cent solar reflectance criteria. The use of cool coloured pigments for steep-slope roofs has not yet been embraced by the roofing industry.

Second, thermal emittance is not a qualifying criterion for Energy Star. Under the original version of the program (which ran through 2007), thermal emittance did not even need to be tested or reported. Under version 2.0 of Energy Star, which took effect on 31 December 2007, thermal emittance must be measured (via test methods ASTM C 1371 or E 408) and reported. However, thermal emittance levels are not used to decide whether a material qualifies as an Energy Star product, even under Energy Star version 2.0.

Products with low emittance – bare metals or metallic coatings – can therefore qualify for an Energy Star rating even if they are not especially cool. For low-sloped roofs this is not a big problem, since metallic materials with low emittance often have trouble meeting the 65 per cent solar reflectance requirement. But products with low emittance can generally qualify for Energy Star ratings under the steep-slope roof criteria, requiring only a 25 per cent solar reflectance. Bare metal or metallic coating on the Energy Star list should be chosen cautiously for use as a cool roof product.

One other caveat about the Energy Star program is that it allows manufacturers to administer their own tests. While this keeps costs down for manufacturers, it also allows a certain amount of misuse of the testing system, uninten-

Table 5.2 Energy Star roof product program qualifying criteria

Type of roof product[a]	New solar reflectance	Three-year solar reflectance[b]
Low-slope	65% or higher	50% or higher
Steep-slope	25% or higher	15% or higher

Note: [a] A low-slope roof product is intended for use on a roof with a slope of less than 1 in 6; a steep-slope product is intended for a roof with slope of more than 1 in 6

[b] Three-year solar reflectance is measured on a roof that has been in service for three years or more.

tional or otherwise. Energy Star states that they spot check values and randomly test products themselves to verify reported values. However, there was one instance (since corrected) when a solar reflectance greater than 100 per cent was published on the Energy Star list. The latest information about Energy Star roof products, including testing, labelling and the products list, can be found on the Energy Star website at http://www.energystar.gov.

Cool Roof Rating Council products list

The Cool Roof Rating Council, or CRRC, also runs a program that measures and labels the solar properties of roofing materials. CRRC was incorporated in 1998 as a non-profit educational organization. Its mission, as stated on its website, is to:

- implement and communicate fair, accurate and credible radiative energy performance rating systems for roof surfaces
- support research into energy-related radiative properties of roofing surfaces, including the durability of those properties
- provide education and objective support to parties interested in understanding and comparing various roofing options.

With these aims, CRRC began its own roof product testing and labelling program in 2002. Their program differs from the Energy Star program in some important ways. First, the CRRC requires that everyone who does material property testing be accredited through CRRC's own training programs. Manufacturers can become accredited testers themselves, as two manufacturers have done so far. There are also four independent laboratories that are accredited through the CRRC.

Second, the CRRC has always required that both the solar reflectance and thermal emittance of roof materials be tested and reported. Solar reflectance can be measured using ASTM E 903, E 1918 or C 1549, or by using CRRC's own test method #1. Thermal emittance must be tested using ASTM C 1371. In addition, CRRC also requires re-testing after three years of weathering. Three-year testing is performed only at accredited test farms located in three different climates (hot/humid, cold/temperate and hot/dry).

Third, the CRRC list does not require products to meet any minimum requirements. Any product that has been correctly tested can be added to the CRRC list, regardless of its thermal properties. This means that products on the CRRC list are not necessarily 'cool', but only that their material properties have been verifiably tested. Consumers can then make their own decisions about acceptable limits.

Finally, CRRC has set up a classification system for coloured roof products. Manufacturers can designate their various materials into one of 18 colour family groups, based on Hunter colour values for lightness, redness/greenness and yellowness/blueness. This allows manufacturers to test just one representative colour in a colour family group, instead of being required to test each individual colour they offer.

Types of cool roofing

The roofing market is divided into two segments that use very different product types: the low-slope roof market and the steep-slope roof market.

A low-slope roof is a roof that is essentially flat, with only enough slope to provide good drainage. A low-slope roof is usually defined as having a slope of no more than one in twelve. Low-slope roofs are found on the majority of commercial and industrial buildings, such as offices, warehouses and retail buildings, as well as on many multi-family buildings and some residences.

Steep-slope roofs have inclines greater than one in twelve. These roofs are found most often on residential buildings, and the roofing materials are generally visible from below. The most common roofing materials used on steep-slope roofs include composite shingles, metal roofing,

roofing tiles and roofing shakes (shakes[1] are wooden shingles made from split logs). So far the coolest options for steep-slope roofs are specially pigmented cool tiles and cool coated metal roofing.

Cool low-slope options

Cool options for low-slope roofs include coatings and single-ply membranes, as well as cool surface layers that have been added to traditional roofing materials.

Cool coatings

Cool roof coatings are surface treatments that are best applied to low-slope roofs in good condition. Coatings have the consistency of thick paint (see Figure 5.4), although they have additives which make them far superior to paint in terms of their adhesion, durability, suppression of algae and fungus, and their ability to 'self-wash' or shed dirt under normal rainfall.

Cool coatings are not recommended for use over existing shingles on steep-slope roofs. The coating can inhibit normal shingle contraction and expansion, causing the shingles to curl up at the edges. The coatings can also block drainage channels between the shingles, potentially causing water to get caught under the roof.

There are two main types of cool roof coatings – cementitious and elastomeric. Cementitious coatings contain cement particles (see Figure 5.5); elastomeric coatings contain polymers that make the coatings less brittle and improve their adhesion. Either urethane, silicone or acrylic polymers can be used in elastomeric coatings, although acrylic polymers are most widely used. Some coatings contain both cement particles and polymers, making them both elastomeric and cementitious.

Figure 5.4 Application of an elastomeric cool roof coating

Both coating types are most commonly bright white in colour, and consequently have very high values of solar reflectance (usually 70 per cent or higher when new) and thermal emittance (over 80 per cent). More than two hundred coatings meeting these criteria can be found on the CRRC product list.

In addition to bright white coatings, there are also a handful of coloured coatings with high solar reflectance. As of the summer of 2007, there were about 15 tan or grey coatings on the CRRC list with solar reflectance values greater than 70 per cent. There were also 30 or so coatings of various colours, including tans, greys, greens and reds, with solar reflectance values greater than 40 per cent. All of these coatings are non-metallic and have high (greater than 80 per cent) thermal emittance.

Cementitious and elastomeric coatings are interchangeable in terms of their thermal performance. Coatings have no discernible effects on a roof's insulation or R-value, since they are applied in such thin layers. Coatings have no magic ingredient to insulate your roof against summer heat gain or winter heat loss, so watch out for incorrect claims to the contrary.

The best cool coating is one that stays on the roof. There are lots of horror stories about cool roof coatings that peeled or flaked off within a couple of years, or even months, of their application. Cementitious coatings, due to their brittle nature, tend to have more problems sticking to the roof than elastomeric coatings do. Coatings are formulated to adhere to a wide range of existing roof surfaces, including cap sheet or gravel over built-up roofing, modified bitumen, various single-ply materials, and metals. But any coating can have adhesion problems, either due to poor coating formulation or faulty application procedures.

There are many ways to steer clear of inferior

Figure 5.5 A cementitious cool roof coating

products and to guard against receiving a poor coating or installation. First, look for a product with at least a 10-year warranty against peeling, flaking or cracking of coating materials that is manufactured by a reliable, time-tested company to back up this warranty. Second, look for coatings that meet quality standards such as ASTM D 6083-97, the standard specification for liquid-applied acrylic coating used in roofing (ASTM, 1997a). This standard calls for an acrylic coating to meet specific values of viscosity, volume and weight of solids, elongation and tensile strength, permeability to water, water swelling, accelerated weathering, adhesion to a substrate, fungi and tear resistance, and low temperature flexibility. There is currently no similar standard in place to evaluate the quality of cementitious coatings.

Another way to ensure that a coating will stay on your roof is to do an adhesion test before applying the coating to the entire roof. This consists of applying a square of coating over a portion of the roof, with a tab of sturdy fabric embedded in the coating along one edge. Allow the coating to sit in place for a couple of weeks and then try to pull up the fabric tab. A well-adhered coating will not be easy to pull off the roof.

Before installation, realize that coatings are not meant to seal or repair leaks. It is important that all leaks, cracks or issues with poor drainage be repaired beforehand. The roof surface must also be cleaned, usually by pressure washing, before applying the coating. Coatings are generally sprayed or rolled onto the main roof area and are painted with a brush around roof penetrations and corners. They are generally applied in two separate coats, usually aiming for a total coverage of 0.8 to 1.2 litres per square metre, or about 500 to 750 micrometres of coating thickness. Coatings are best applied when weather conditions are dry and warm. For the best results, coatings should be applied according to the manufacturer's specifications for temperature and humidity.

There is some concern about coatings losing solar reflectance over time. A study by Lawrence Berkeley National Laboratory found that the solar reflectance of cool coatings does not decrease as much as feared. Reflectance was found to decrease by only about 20 per cent (Bretz and Akbari, 1994, 1997). Most of this decrease occurs in the first year after the coating's application, and no further degradation in reflectance takes place after three years. This means that a coating with an initial solar reflectance of 70 per cent can be expected to have its reflectance decrease to no less than 56 per cent. Both the Energy Star and CRRC lists report three-year weathered values, and Energy Star requires that solar reflectance does not deteriorate to below 50 per cent.

There are instances where a roof picks up more dirt than it can wash away during normal rainfall. If a building's roof tends to collect large amounts of particulate matter or debris, sweeping or washing the roof every year or so can help it stay reflective.

The application of a cool roof coating typically costs between $0.75 and $1.50 per square foot for materials and labour. This cost should include routine surface preparation such as pressure washing, but does not include the repair of any leaks, cracks or bubbling or any drain repairs on the existing roof surface. Installation costs vary depending on the size of the job, the number of roof penetrations or obstacles on the roof, the ease of access to the roof and market conditions.

Cool single-ply roofing

Single-ply roofing is the catch-all name for any roofing material that comes in a prefabricated sheet and is applied in one layer to a low-slope roof. These products are generally glued or fastened in place over the entire roof surface. Seams between the sheets must then be sealed by being heated and fused together (for thermoplastic materials that can melt and then re-solidify), or by being glued (for thermoset materials).

The majority of single-ply products on the market today are not cool, but an increasing number are being made with cool, bright white surfaces. These cool single-ply products come in a variety of materials, including thermoplastic polyolefin (TPO), polyvinyl chloride (PVC), ethylene propylene diene monomer (EPDM) or the copolymer alloy chlorosulphonated polyethylene (CSPE).

Single-ply roofing costs vary considerably from $1.50 to $3.00 per square foot, including materials, installation and reasonable preparation work. This cost does not include extensive repair work or removal and disposal of existing roof layers. As with any roofing job, costs vary depending on the size of the job, the number of roof penetrations or obstacles, and the ease of access to the roof.

PVC roofing

PVC used to be the most common cool single-ply material on the market. Its advantages are its relatively low cost, high initial solar reflectance and ease of installation. PVC is a thermoplastic material, so its seams can be heat-welded together for a very secure seal.

PVC's disadvantages became apparent rather quickly. PVC is not a naturally flexible material, so plasticizers must be added to make it more pliable. In some PVC formulations, the plasticizers tended to migrate towards the material's surface, forming a sticky layer that was attractive to dirt (see Figure 5.6). Especially in humid climates, the plasticizers fostered the growth of mould, mildew and bacteria. As the plasticizers leach out of the roof, the remaining PVC also becomes brittle.

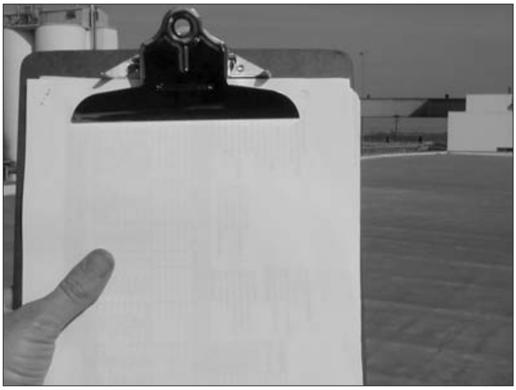


Figure 5.6 This PVC roof in the background was originally as white as the paper on the clipboard

One infamous PVC roof that suffered from a mould problem was at Minute Maid Park, home of the Houston Astros baseball team. The 45,000-square metre (480,000-square foot) retractable roof of the stadium was installed in 2000, but had become extremely discoloured by mould by the summer of 2003. The ballpark owners spent months in dispute with the roof manufacturers, finally forcing the manufacturer to pay for an extensive hand scrubbing of the roof just before the Super Bowl was held there in 2004. The long-term solution to the roof's problems has not been disclosed, but the roof will need frequent cleaning or a new acrylic coating to retain its bright white condition.

Another drawback to PVC is its chemical formulation. Due to the high chlorine content of PVC, dioxin, a known carcinogen, is produced during its manufacture. Chlorine does have the benefit of making PVC very flame retardant. But instead of burning, PVC smokes when it is heated, releasing not only dioxin but also highly toxic hydrogen chloride gas. Fire fighters are opposed to the use of PVC in building materials, since its smoke can seriously and fatally burn skin, eyes and lung tissue. Those choosing a PVC single-ply roof material should make sure it meets ASTM D 4434, the manufacturers' standard specification for PVC sheet roofing.

TPO roofing

TPO is a relatively new roof material that has rapidly become the leader in the cool single-ply market. Although TPO and PVC are comparable in price, TPO has outstripped PVC as the market leader for two reasons. First, TPO is flexible enough on its own to have no need for added plasticizers. Without plasticizers, TPO stays cleaner and more flexible and retains a higher solar reflectance over time. Second, the basic formulation of TPO contains no chlorine, so it is considered more environmentally friendly than PVC.

TPO is available in bright white versions with initial solar reflectance usually over 80 per cent, as well as in tans with initial solar reflectance greater than 70 per cent. As its name implies, TPO is a thermoplastic material, so its seams can be heat-welded together for a tougher, more reliable seal. However, heat-welding the material can be tricky, since it is not naturally fire resistant. TPO generally needs additives to improve its fire resistance. Halogenated TPO uses small amounts of chlorine or bromine as fire retardants. Halogens react in the atmosphere to reduce the ozone layer and increase the level of global warming. Non-halogenated TPO uses hydrated minerals or phosphate ions as fire retardants, and these materials are considered less environmentally harmful. TPO single-ply roof materials should meet ASTM D 6878, the manufacturers' standard specification for thermoplastic polyolefin-based sheet roofing.

Figure 5.7 A roll of standard black EPDM single-ply roofing

EPDM Roofing

EPDM is a synthetic rubber material that has been in use as a single-ply roofing material for many years, but has traditionally been black in colour with a solar reflectance of 10 per cent or lower (see Figure 5.7). Carbon black is usually added to the rubber mixture of EPDM to guard against damage by the sun's ultraviolet rays.

White EPDM usually comes in a double layer, with a bright, white top over a traditional black base. White EPDM is less durable than black EPDM, since it is not as well protected from the sun. Because of this, cool white versions of EPDM with high solar reflectance are not in common use. EPDM is a thermoset polymer, so it cannot be heat-sealed; instead, seams must be glued or taped together.

CSPE roofing

CSPE (also known by its trade name of Hypalon) is a bright, white single-ply roofing material in limited use. CSPE is durable, fire resistant and stands up to the weather and the sun's ultraviolet rays. But its formulation has varied over time, sometimes making it unreliable or vulnerable to microbial growth. CSPE is also more expensive than PVC or TPO roofing.

CSPE is a thermoplastic material when installed, so its seams can be heat-welded. It cures into a thermoset material within days, so later repairs must use glue or tape for sealing. All CSPE single-ply roofing should meet minimum standards set forth in the manufacturers' specification ASTM D 5019.

Traditional materials made cool

Manufacturers of some tried and tested layered roofing materials are now modifying their products to make them cool. Various manufacturers now make bright white cap sheets for the top layer of a built-up or modified bitumen roof.

These materials exceed 70 per cent solar reflectance and 80 per cent thermal emittance to make traditional roofs that are truly cool. You should expect to pay more for these materials since they are essentially two separate roofing systems: the same old materials with an extra cool coating or layer over the top.

Cool options for steep-slope roofs

The development of cool products for steep-slope roofs is at least ten years behind the low-slope market. Low-slope roofs are, for the most part, invisible to all but those in higher buildings or hills overlooking the roofs. Steep-slope roofing manufacturers must deal with the reality that their roofs are visible and contribute to the architectural statement of a building.

The easiest cool roof option, making the roof bright white, has not caught on as a design feature in most places throughout the world. Figure 5.8 shows a bright white roof in a home in Florida, one area where white roofs are sometimes used on residential buildings. While the wedding cake look might not be to everyone's taste, it seems to be more viable and desirable in hot and humid and hot and dry climates.

For many years, steep-slope roofing manufacturers could only lighten their colours using titanium dioxide to make their materials cool. With the advent of pigments that reflect infrared heat while keeping colours unchanged, steep-slope roofing manufacturers have more options. Currently, very few manufacturers are taking advantage of these opportunities. As of the summer of 2007, only small portions of the clay tile and metal roofing industries seem serious about developing and selling cool roofing products. Manufacturers of the largest segment of the steep-slope roofing market, composite shingles, have yet to develop or market any products with solar reflectance values higher than 29 per cent.

Figure 5.8 Bright white cool roof on a home in Florida

Cool tiles

MCA Clay Tile was the first steep-slope roofing manufacturer to use cool pigments in their products. They make clay tiles in a wide variety of colours, with solar reflectance values ranging from 30 per cent to upwards of 60 per cent, as shown in Figure 5.9 (Plate 13). They have been joined by a couple of other manufacturers who make cool coloured tiles, and are testing and registering them on the Cool Roof Rating Council product list. Clay tiles are extremely durable and long-lasting, but their high initial cost tends to keep their market share low.

Concrete tiles are somewhat more affordable, and they are fairly commonly used in new home construction. Concrete tile manufacturers have been reluctant, so far, to enter the cool coloured market. Manufacturers design tiles using different colour palates for different regions. They do not seem to place much importance on the solar reflectance or energy use of their products, or to see much demand for cool products. Some concrete tile products available today may already be cool, but their manufacturers have yet to test and register them on any cool roof product lists.

Cool metal roofing

Metal roofing manufacturers have so far produced the most widespread adoption of cool pigment technology. Metal roofing is usually coated during manufacturing, and the use of cool coatings was relatively simple to implement. By teaming up with forward-thinking coating

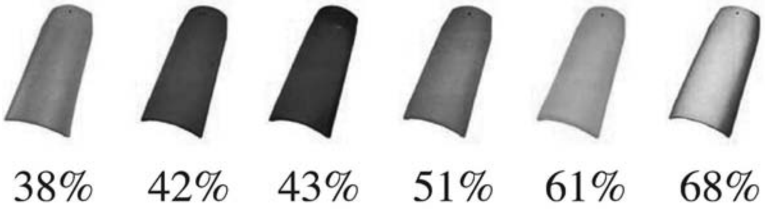


Figure 5.9 Cool coloured clay tiles and their solar reflectance values (see Plate 13 for a colour version)

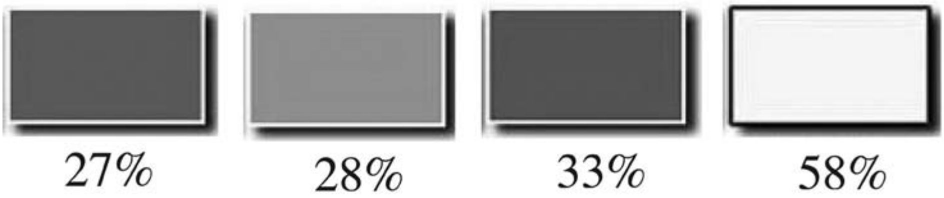


Figure 5.10 Cool metal roof coatings and their solar reflectance value (see Plate 14 for a colour version)

manufacturers, various progressive metal roofing manufacturers have developed a series of cool coloured products for steep-slope roofs. Coloured metal products, in shades of brown, grey, red, green and blue, are available with solar reflectance values as high as 56 per cent. Lighter grey and white coatings on metal roofing can have even higher reflectance. Figure 5.10 (Plate 14) shows a sample of cool metal coatings and their corresponding solar reflectance.

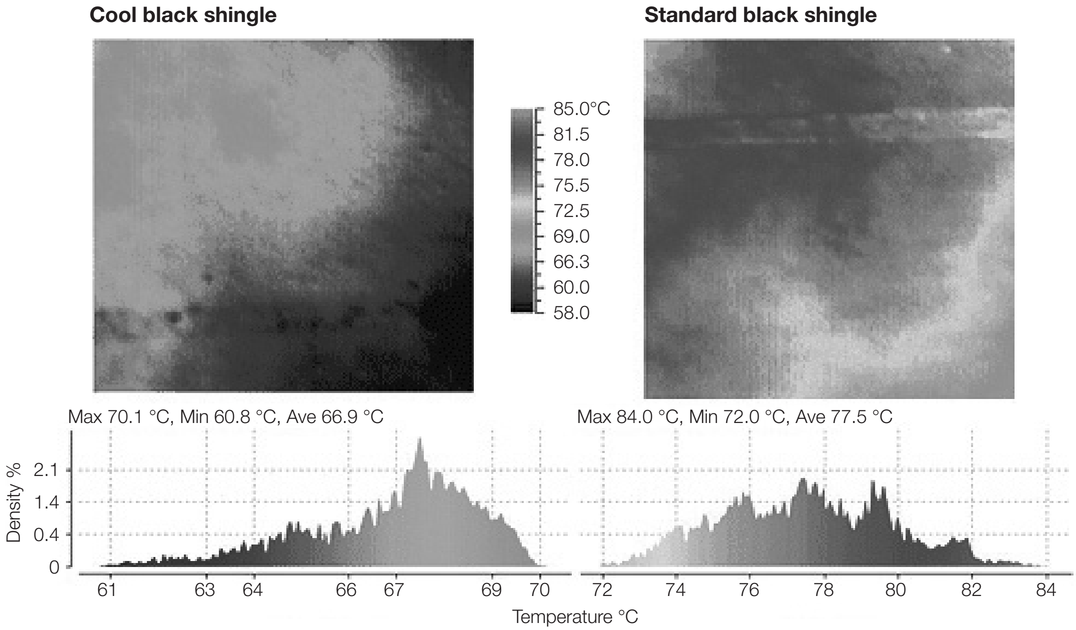
Cool shingles

Composite shingles are the least expensive and most commonly used material in the steep-slope roofing market. They make up more than 50 per cent of the steep-slope roofing market in the US (Hinojosa and Kane, 2002). Adoption of cool technologies by shingle manufacturers could have a big impact.

At present, only one manufacturer, GAF Materials Corporation, has registered any cool shingles, listing a series of shingles with a blanket 29 per cent solar reflectance on the Energy Star roof products list. 3M Corporation has no product listings on the Energy Star or CRRC roofing lists, but they do have a website describing their cool roofing granules. Here they compare a cool black shingle that reaches an average 66.9°C (152.4°F) to its traditional black counterpart at 77.5°C (171.5°F), for a difference of 10.6°C (19.1°F) (see Figure 5.11, Plate 15). This website states that 3M's cool granules have solar reflectance values up to three times those of comparable granules.

These efforts to cool composite shingles are somewhat disappointing for various reasons. First, it is not clear exactly what shingle GAF is referring to in the Energy Star list, since their 29 per cent reflectance shingle is not designated or named by colour. It is unlikely that all of their cool coloured shingles have the same 29 per cent reflectance. Second, 29 per cent is not an especially high value of solar reflectance for a cool coloured product, since values higher than 40 per cent are demonstrably achievable. 3M's efforts appear to be well meaning, and a temperature reduction of 10°C (20°F) is nice, but a 67°C (150°F) shingle is still pretty hot. 3M's website shows eight cool colours, but does not list their solar reflectance values. A solar reflectance that is 'three times higher' sounds impressive, but may only be referring to an increase from 5 per cent to 15 per cent. If any of these reflectance values were above 25 per cent, they would doubtless be listed with Energy Star.

Composite shingle manufacturers do face



Source: http://solutions.3m.com/wps/portal/3M/en_US/IMPD/Roofing-Solutions/Products/Cool-Roofing-Granules/#palette, accessed in August 2007.

Figure 5.11 Temperatures of 3M's cool black shingle versus a traditional, hotter, black shingle (see Plate 15 for a colour version)

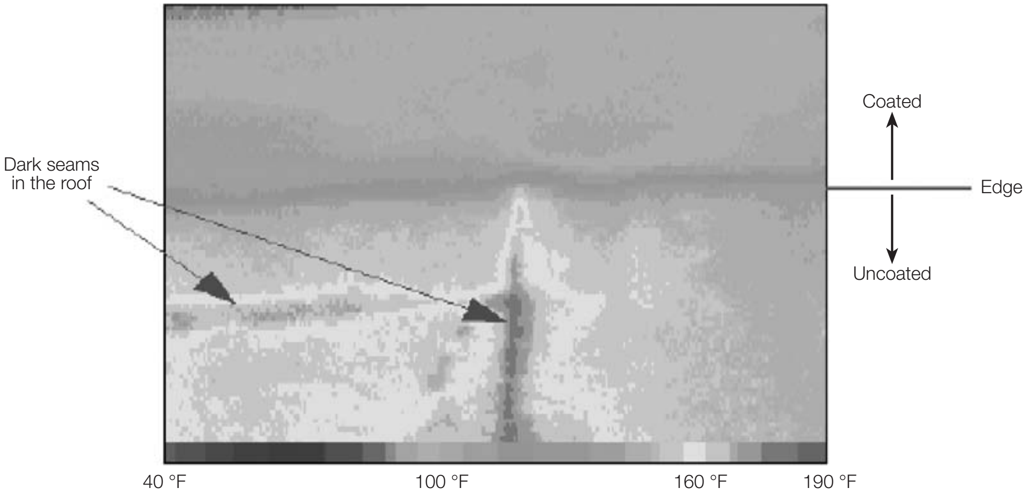
some unique difficulties in making their products cool. Shingles are made of a petroleum-based substrate covered with small granules. The granules are mineral particles covered with ceramic coatings and are essential to the shingle because they protect the substrate from rapid degradation by the sun's ultraviolet rays. Most shingle manufacturers buy their granules from a separate supplier, and the supplier decides what types and colours of ceramic coatings are used.

Granules also make a shingle's surface rougher, decreasing its solar reflectance. Sunlight reflected from a granule is more likely to bounce onto another granule, increasing the chance of its being absorbed into the shingle. Granulated surfaces can decrease solar reflectance by 5–10 per cent, making it harder to achieve high solar reflectance using cool coloured pigments. However, if coloured clay tiles and metal roofing can reach solar reflectance values above 50 per cent, composite shingles should be able to achieve values of 40 per cent or higher.

Tips on choosing and installing cool roofing

There are likely to be many different cool roof products that are suitable for any given roof. In general, a cool roof coating is a good choice if your existing roof needs only moderate repair, and a single-ply product is best if repair needs are extensive. The cut-off point is not always easily determined. It is best to get bids from various roofing contractors and sort through their prices and advice.

Quiz roofing contractors thoroughly about any proposed repairs and preparation work, as well as the expected durability and adhesion of proposed products over your existing roof. Ask to go up onto a nearby roof that uses the same product or system. Be aware that most roofing contractors specialize in certain products or techniques and tend to promote only methods they are familiar with. For more impartial advice, confer with a roof consultant experienced in cool roof technology.



Source: Konopacki et al, 1998.

Figure 5.12 Infrared photograph of a light grey asphalt roof in Gilroy, California, at the edge of a bright white cool coating (see Plate 16 for a colour version)

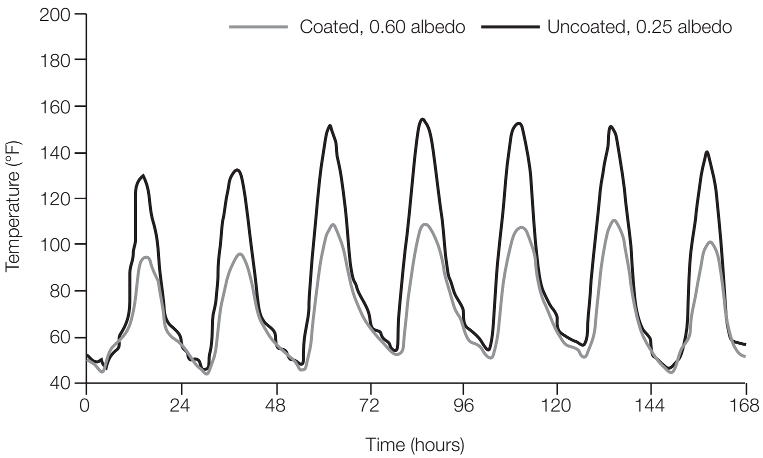
Many roofing contractors are unfamiliar with cool roofing and/or do not install it. Some contractors may have used inferior cool roofing products or have seen the negative effects of inferior products firsthand. Don't be surprised or dismayed if your regular roofing contractor does not recommend cool roofing technology. The roofing industry acquires expertise mainly through trial and error, so your regular contractor may not have had enough experience with cool roofing to judge its merits. Also be aware that the roofing industry is quite competitive – contractors working with more traditional roofing materials do not easily give up market share to new technologies.

Benefits of cool roofing

The benefits of cool roofing accrue to building occupants, building owners and the community at large. Benefits include improved building comfort, energy and utility bill savings, reduced roof maintenance, peak electricity demand reductions, reduced levels of air pollution and less roofing waste to landfills. The replacement of existing roofs with cool roofing can also diminish the heat island effect in our cities and suburbs.

The benefits of cool roofing all result from its ability to stay cooler in the summer sun. Figure 5.12 (Plate 16) shows an infrared photograph of a roof taken on a hot summer day at noon. A light grey asphalt cap sheet roof was being coated with a bright white cool coating. The temperature of the uncoated portion of the roof averaged about 70°C (160°F), with hot spots of up to 80°C (180°F) at darker coloured seams between roof sections. The coated portion of the roof was cooled to about 40°C (100°F), for a 30°C (60°F) temperature reduction.

Roofs do not stay at one temperature all day, but swing from a low temperature in the early morning to a high temperature at solar noon. Figure 5.13 shows a week of roof temperatures on the same Gilroy roof shown in Figure 5.12, both with and without a cool roof coating. The uncoated roof temperatures swing between lows of 10°C (50°F) and highs of 65°C (150°F), a 55°C (100°F) difference. Temperature swings for the coated roof are much smaller, between lows of 10°C (50°F) and highs of 45°C (110°F).



Note: Grey line = coated, 0.60 albedo; black line = uncoated, 0.25 albedo.

Source: Konopacki et al, 1998.

Figure 5.13 Temperature of an uncoated light grey asphalt roof versus a bright white cool roof coating on a Gilroy, California, rooftop during the week of 26 August to 1 September 1996

Improved building comfort

Besides reducing energy use, buildings with cool roofs tend to be cooler and more comfortable inside. There are two studies that illustrate potential comfort improvements.

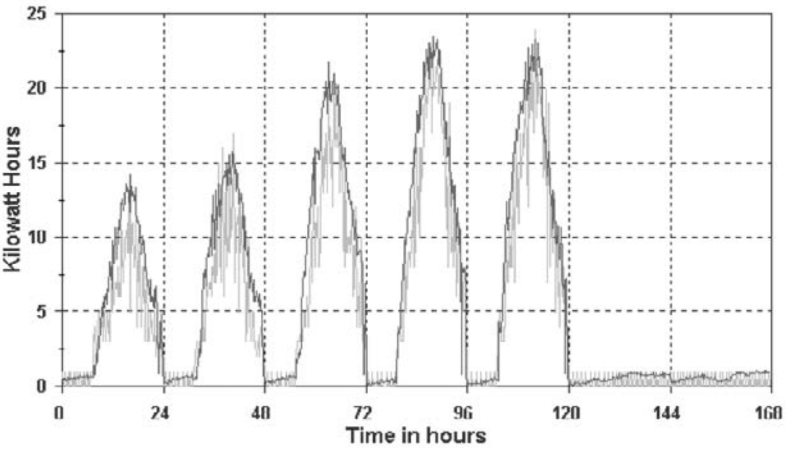
The Home Base store in Vacaville, California, (Gartland, 1998) was initially quite uncomfortable inside. This store used an undersized evaporative cooling system that was unable to meet the building's cooling loads. Indoor temperatures as high as 32°C (90°F) were recorded before the cool roof was added, with the coolers working constantly (even at night) to cool the building. After adding a cool roof coating, peak indoor temperatures were reduced to 29°C (85°F) or lower, and ten more hours a week were deemed comfortable (below 26°C (79°F) and 60 per cent humidity) inside the store. Although the evaporative coolers were still not powerful enough to cope with the hottest conditions, temperatures inside the store were significantly improved by the cool roof.

A Sacramento apartment complex (Vincent and Huang, 1996) also demonstrated the effects of cool roofing on building comfort. This complex's buildings had two storeys and an attic, with a substantial R-38 level of insulation above the second storey, and were not air-conditioned. Adding a cool roof lowered peak air temperatures in the attic by 16–22°C (30–40°F), cooled the second storey air temperatures by 2°C (4°F), and even cooled the first storey temperatures by 1°C (2°F). Whether or not a building uses air-conditioning, a cool roof can help it stay more comfortable during the summer months.

Reduced cooling energy use

A cooler roof transfers less heat to the building below, so the building stays cooler, more comfortable and uses less energy for cooling. Figure 5.14 shows the cooling energy used over one week in the Gilroy building for which the roof temperatures are shown in Figures 5.12 and 5.13. Note that the building is closed and the cooling system is turned off over the two weekend days. The cool roof causes daily energy use profiles to become shorter and narrower. The overall savings during the week added up to an impressive 860kWh, or 21 per cent of the cooling energy used.

Every building responds differently to the effects of a cool roof. Table 5.3 lists the general



Note: Grey line = coated, 0.60 albedo; black line = uncoated, 0.25 albedo.

Source: Konopacki et al, 1998

Figure 5.14 Effect of a bright white coating on the cooling energy use of a building in Gilroy, California, during the week of 26 August to 1 September 1997

characteristics and cooling energy savings of several different buildings monitored throughout the US, including the Gilroy, California, Kaiser Permanente building referred to above. Actual measured savings varied considerably from 0.04kWh/ft^2 annually up to 0.70kWh/ft^2, and from 2 to 69 per cent of the building's total cooling energy use.

Savings are influenced not only by the variables listed in Table 5.3, such as the number of storeys, the insulation level in the roof and whether the roof/ceiling assembly includes a plenum, but also by variables not listed, such as internal load levels, building configuration, solar gains through windows and cooling equipment sizing. For example, the San Jose drug store had very low cooling energy savings because its south wall was one big expanse of windows; the three remaining sides of the building contained uncooled storage and office space, and a very high ceiling caused hot air to stratify inside the store. Conversely, the private house in Sacramento had very high savings thanks to the owner raising the thermostat and often shutting off the air conditioner completely. The Vacaville Home Base store would have seen much greater savings, 30 per cent instead of only 10 per cent, if their cooling system were not so undersized. Although individual buildings vary, a cool roof is expected to save about 20 per cent of the cooling energy used by a building.

Reduced building maintenance expenses

The most compelling reason to use cool roofing is because over the long term the maintenance costs go down significantly. Table 5.4 shows a rough analysis of the costs of similar grades of cool roofing and traditional roofing over a 20-year span. This analysis assumes that a conventional 'hot' roof ordinarily adds a new top layer every ten years (for $1.50 per square foot) until the layers become too heavy and must be torn off and replaced with a single material layer (for $3.50 per square foot). In comparison, a cool roof is recoated with a cool coating every ten years (for $1.00 per square foot). Since this coating is much thinner and lighter than conventional roofing, the roof will not have to be torn off and replaced within the foreseeable life of the roof. Over 20 years, the cool roof will also save on energy bills (between $0.02 and $0.07 per square foot per year). Simply adding up these numbers, without correcting for present

Table 5.3 Cooling energy savings data for monitored buildings with cool roofing

Building	Location, reference	Use, size ft^2	No. of storeys	Roof insulation*	Plenum	Cooling saved
Long's Drugs	San Jose, CA (Konopacki et al, 1998)	Retail 32,900	1–2	Foil barrier	Yes	2%
CA Lottery	Sacramento, CA (Vincent, 2000)	Office 87,000	2	R-19	Yes	7%
Home Base	Vacaville, CA (Gartland, 1998)	Retail 110,000	1	None	No	10%
Private house	Merritt Island, FL (Parker and Barkaszi, 1994)	Residence 1800	1	R-25	Attic	10%
Retail store	Austin, TX (Konopacki and Akbari, 2001)	Store 100,000	1	R-12	Yes	11%
Kaiser Permanente	Gilroy, CA (Konopacki et al, 1998)	Medical 23,800	1	R-19	Yes	13%
Private house	Miami, FL (Parker et al, 1994a)	Residence 1341	1	R-11	None	15%
Kaiser Permanente	Davis, CA (Konopacki et al, 1998)	Medical 31,700	1	R-8	Yes	18%
Discovery Museum	Sacramento, CA (Vincent, 2000)	Exhibit 9000	1–2	None	None	20%
Private house	Merritt Island, FL (Parker et al, 1994a)	Residence 1700	1	R-7	None	20%
WEAVE Safehouse	Sacramento, CA (Vincent, 2000)	Residence 8000	1	R-11	Attic	21%
Private house	Cocoa Beach, FL (Parker et al, 1994b)	Residence 1795	1	R-11	Attic	25%
Private house	Nobleton, FL (Parker et al, 1994a)	Residence 900	1	R-3	Attic	25%
School trailer**	Volusia County, FL (Callahan et al, 2000)	School 1440	1	R-11	None	33%
School trailer	Sacramento, CA (Akbari et al, 1993)	School 960	1	R-19	None	34%
Our Savior's School	Cocoa Beach, FL (Parker et al, 1996)	School 10,000	1	R-19	Attic	35%
Private house	Cocoa Beach, FL (Parker et al, 1994b)	Residence 1809	1	R-0	Attic	43%
Private[C7] house	Sacramento, CA (Akbari et al, 1993)	Residence 1825	1	R-11	None	69%

Note: * The thermal resistance of insulation, or how well it resists heat flow, is indicated by its R-value, given here in imperial units of hour × square foot × °F/Btu. These insulation vales can be converted to SI units of square metre × °C/W by multiplying by 5.67.

** A school trailer is a portable, pre-manufactured, long rectangular building increasingly used in US schools for additional classroom space.

Table 5.4 Twenty-year cost comparison of a cool coating versus conventional roofing

	Cool coating (US$)	Conventional roofing (US$)
Recoat/relayer in year 0	+ $1.00/ft^2	+ $1.50/ft^2
Recoat/relayer in year 10	+ $1.00/ft^2	+ $1.50/ft^2
Recoat/tear off in year 20	+ $1.00/ft^2	+ $3.50/ft^2
Energy savings over 20 years	–$0.40 to –$1.40/ft^2	none
Total cost	$1.60 to $2.60/ft^2	$6.50/ft^2
Savings	$3.90 to $4.90/ ft^2	

value, shows a lifetime savings of $3.90 to $4.90 per square foot, depending on the level of energy savings.

If a cool roof coating is used, there may also be additional financial benefits. Roofing work is generally classified as a capital expense and must be depreciated over time when calculating annual taxes. If you are able to use a cool roof coating, this can often be classed as a building maintenance expense and be fully deducted during the year it is applied.

Besides saving on roof maintenance, a cool roof can save money on cooling equipment. Using less cooling because of a cool roof means that cooling equipment runs less often and lasts longer. When cooling equipment is eventually replaced, the new equipment's capacity can be downsized, since a cool roof significantly reduces the cooling loads on a building. Smaller equipment costs less and saves money on an expensive capital investment.

Reduced peak electricity demand

Another benefit of cool roofing is that it saves energy when it is most needed, during times of peak summertime electricity demand. Peak electricity demand occurs when buildings draw high amounts of electricity from the power grid, usually when cooling equipment and other appliances are being used on hot summer afternoons. A projection of energy savings in 11 cities in the US showed that widespread use of cool roofs could reduce peak power demand by more than 1300MW across the US (Konopacki et al, 1996). In Los Angeles alone, cool roofs have the potential to reduce summer peak electrical demand by over 250MW.

Individual buildings also stand to benefit from reduced electricity demand, and reduced demand charges, when using cool roofing. Unlike residential customers who pay for only the amount of electricity (kilowatt hours) they use, commercial and industrial electricity customers are usually charged for the largest amount of power they draw (kilowatts) during a billing period. Since cool roofing uses fewer kilowatt hours and draws fewer watts, commercial and industrial customers save money on both parts of their electricity bill.

Table 5.5 shows the estimated peak demand reductions for typical homes and office buildings throughout the US. Table 5.6 lists demand reductions found in buildings monitored for the effects of cool roofing. The numbers show that demand savings for individual buildings are significant and are likely to be greater in older, poorly insulated buildings and in hotter climates.

Reduce the heat island effect

A study by Lawrence Berkeley National Laboratory estimated the amount of tree shading and the percentages of different types of land surfaces in the Sacramento metropolitan area (Akbari and Rose, 1999). Figure 5.15 shows the breakdown of surface types. Grass or vegetation covers 21 per cent of the entire metropolitan area, paved surfaces cover 44 per cent (including 22 per cent roads, 12 per cent parking, 5 per cent sidewalks and 4 per cent driveways) and rooftops cover 20 per cent of Sacramento's surface area.

Table 5.5 Estimated peak electricity demand savings for cool roofing on typical old and new homes and office buildings

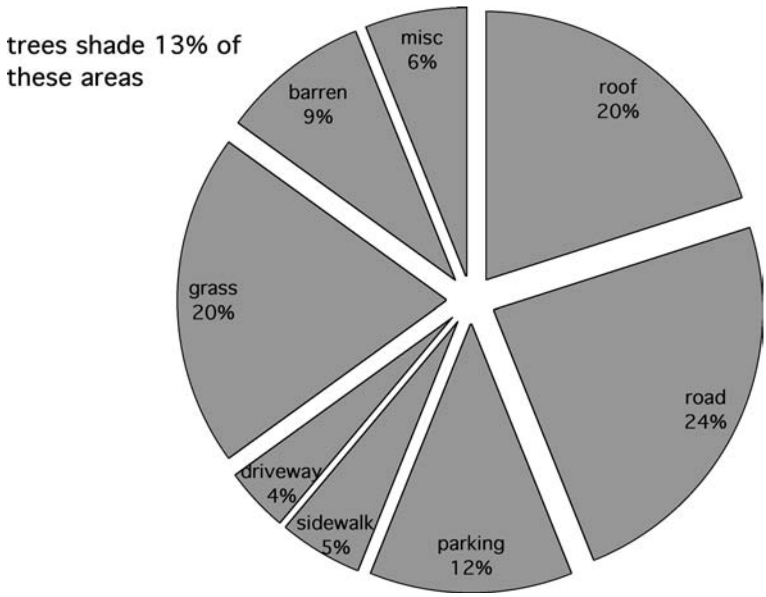
Location	Old house R-11* roof W/1000 ft²**	New house R-19* roof W/1000 ft²**	Old office R-11* roof W/1000 ft²**	New office R-19* roof W/1000 ft²**
Atlanta	143 (7%)	91 (6%)	247 (6%)	118 (4%)
Chicago	117 (5%)	52 (4%)	198 (5%)	129 (4%)
Los Angeles	247 (11%)	130 (9%)	292 (7%)	173 (6%)
Fort Worth	175 (5%)	97 (5%)	155 (3%)	100 (3%)
Houston	130 (4%)	110 (6%)	243 (5%)	141 (4%)
Miami	208 (9%)	84 (6%)	153 (3%)	57 (2%)
New Orleans	71 (3%)	84 (6%)	314 (7%)	143 (5%)
New York City	169 (7%)	84 (6%)	163 (4%)	63 (2%)
Philadelphia	201 (13%)	91 (10%)	247 (7%)	131 (6%)
Phoenix	162 (4%)	97 (4%)	196 (3%)	96 (2%)
Washington DC	162 (6%)	84 (5%)	233 (6%)	124 (4%)

Note: * The thermal resistance of insulation, or how well it resists heat flow, is indicated by its R-value, given here in imperial units of hour × square foot × °F/Btu.
These insulation values can be converted to SI units of square metre × °C/W by multiplying by 5.67.
To convert from W/1000ft² to W/km², multiply by 10.76. To convert from ft² to m², divide by 10.76.
Source: Konopacki et al, 1996.

Table 5.6 Peak electricity demand reductions due to cool roofing measured on monitored buildings

Building	Location, reference	Use, size ft²	Roof insulation	Plenum	Demand savings W/1000 ft²
Retail store	Austin, TX (Konopacki and Akbari, 2001)	Store 100,000	R-12	Plenum	350 14%
Private house	Miami, FL (Parker et al, 1994a)	Residence 1341	R-11	None	270 13%
Private house	Merritt Island, FL (Parker et al, 1994a)	Residence 1700	R-7	None	580 23%
Private house	Cocoa Beach, FL (Parker et al, 1994b)	Residence 1795	R-11	Attic	370 28%
Private house	Nobleton, FL (Parker et al, 1994a)	Residence 900	R-3	Attic	560 30%
School trailer	Volusia County, FL (Callahan et al, 2000)	School 1440	R-11	None	970 37%
School trailer	Sacramento, CA (Akbari et al, 1993)	School 960	R-19	None	625 17%
Our Savior's	Cocoa Beach, FL (Parker et al, 1996)	School 10,000	R-19	Attic	560 35%
Private house	Cocoa Beach, FL (Parker et al, 1994b)	Residence 1809	R-0	Attic	475 38%
Private house	Sacramento, CA (Akbari et al, 1993)	Residence 1825	R-11	None	330 32%

Note: * The thermal resistance of insulation, or how well it resists heat flow, is indicated by its R-value, given here in imperial units of hour × square foot × °F/Btu.
These insulation vales can be converted to SI units of square metre × °C/W by multiplying by 5.67.
To convert from W/1000ft² to W/km², multiply by 10.76. To convert from ft² to m², divide by 10.76.



Source: Akbari and Rose, 1999.

Figure 5.15 Land cover and tree shading in Sacramento, California

Taking into account all of these surfaces, trees shade 13 per cent of Sacramento.

The significance of the land cover pattern becomes clear when you look at the typical peak daily temperatures. Trees, grass and vegetation are the coolest, staying at temperatures of 15–38°C (60–100°F) or lower during peak summer conditions. Pavement temperatures are hotter, ranging from peaks of 49–60°C (120–140°F) for lighter off-white or grey pavements and up to 71°C (160°F) for darker pavements. Rooftops are easily recognizable as the hottest areas in cities and suburbs, with peak temperatures ranging between 66 ands 88°C (150 and 190°F). The average surface temperature of Sacramento under these conditions can be estimated as:

$$T_{vegetation} \times A_{vegetation} + T_{paving} \times A_{paving} + T_{roof} \times A_{roof} + T_{misc} \times A_{misc} =$$

$$27°C \times 0.21 + 54°C \times 0.44 + 71°C \times 0.20 + 52°C \times 0.15 = 52°C \quad (5.1)$$

where T is the temperature and A is the fraction of the total area. If rooftops were cooled by 50°F using cool materials, the average surface temperature of Sacramento could be reduced by 5.5°C (10°F), as shown below:

$$27°C \times 0.21 + 54°C \times 0.44 + 43°C \times 0.02 + 52°C \times 0.15 = 46°C \quad (5.2)$$

Heat islands form when urban air is warmed by hot surfaces, so cooling the average surface temperature by 5.5°C (10°F) can have a significant effect.

Reduced air pollution

The use of cool roofing reduces air pollution both directly and indirectly. Direct reductions come about because less cooling energy is needed, and lower energy use means lower power plant emissions. Indirect air pollution reductions can take place if cool roofing and other strategies are used widely enough to reduce the heat island effect and reduce a region's air temperature, thus further reducing the need for cooling.

Lawrence Berkeley National laboratory researchers have made estimates of direct and indirect reductions in carbon emissions due to the implementation of heat island mitigation strategies for five cities in the US. These reductions are summarized in Table 5.7. When the effects of tree shading and cool roofs are combined, their individual effects are somewhat diminished. Tree shade is less effective over a cool roof, and a cool roof is less effective under a shade tree. That is why the 'combined direct and indirect reductions' are not equal to the sum of the individual direct and indirect reductions.

Cooler urban air temperatures can also help reduce ground level ozone and smog. Smog does not come directly out of factory chimneys or car exhausts, but is instead formed in a chemical reaction between pollutants such as nitrogen oxides (NOx) and volatile organic compounds (VOCs) as they mix in the air. The reaction is dependent on the air temperature. The hotter it is, the more quickly the reaction occurs and the greater the amount of smog formed.

Studies of various cities in the US have shown that higher urban temperatures due to the heat island effect seem to be responsible for a surprising amount of ozone and smog formation. A simulation of the meteorology and air quality in Los Angeles found that cooling the city by 6°F with cool surfaces and trees reduced smog levels by 10 per cent (Akbari and Douglas, 1995; Akbari et al, 1996). A similar study for Sacramento found that adding tree cover and cool roofing and paving surfaces lowered peak air temperatures by about 3°F and reduced the smog concentration by 10 parts per billion, or 6.5 per cent (Taha et al, 2000). The effects of the heat island on air quality have also been modelled for Baton Rouge, Salt Lake City and the Northeast corridor (Douglas et al, 2000; Taha et al, 2000). The results revealed lesser impacts in Baton Rouge and Salt Lake City and very mixed impacts in the Northeast corridor.

The effects of heat island mitigation on ozone formation are extremely complex. Ozone reductions in one part of the metropolitan area appear to be accompanied by ozone increases in other areas. This type of air quality modelling is still subject to much scrutiny and refinement; such work is being done in Los Angeles (Emery et al, 2000) and elsewhere. Since the benefits of heat island mitigation are potentially very significant, work is ongoing to improve modelling techniques and to model new areas.

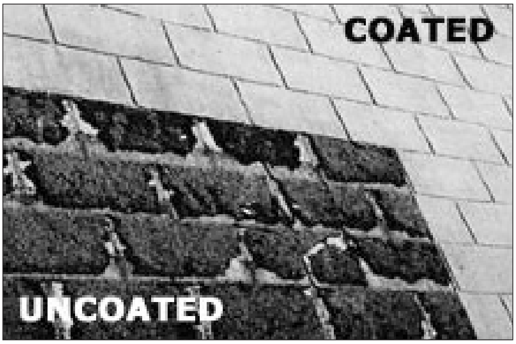
Reduce roofing waste to landfills

Cool roofing is likely to have a significantly longer life than traditional 'hot' roofing materials. A study by the Rohm and Haas Company (Antrim et al, 1994) investigated the effects of heat and sunlight on the weathering of asphalt-based roofing materials. It was found that both excess heat and ultraviolet rays from sunlight hasten chemical degradation processes in the roof. Side-by-side comparisons were made of uncoated asphalt shingles and shingles coated with a bright, white, cool roof coating. The tests found no degradation of the coated shingles after seven years, while the uncoated shingles were severely degraded (see Figure 5.16). This means

Table 5.7 Direct and indirect annual carbon emission reductions (thousand tons) due to the implementation of heat island mitigation strategies in five US cities

	Baton Rouge	Chicago	Houston	Sacramento	Salt Lake City
Base case carbon emissions	257	1749	1453	608	188
Direct reduction due to tree shading	12	26	58	18	3
Direct reduction due to cool roofs	19 (7%)	21 (1%)	80 (6%)	29 (5%)	5 (3%)
Indirect reduction due to air cooling	6	10	33	11	7
Combined direct and indirect reductions	35 (14%)	58 (3%)	170 (12%)	50 (8%)	9 (5%)

Source: Konopacki and Akbari, 2000, 2002.



Source: Antrim et al, 1994.

Figure 5.16 Coated and uncoated portions of an asphalt shingle roof in Pennsylvania

that periodic application of cool roof coatings can potentially preserve the underlying roof materials indefinitely, making roof tear-offs a thing of the past.

An estimated 11 million tons of asphalt roofing waste goes into US landfills every year, and over the past 40 years 7–10 per cent of the landfill space used has been filled with roofing waste from both commercial and residential buildings (RSI, 1993). Use of cool roof coatings and materials can greatly increase roofing life and reduce the amount of torn-off roofing waste going into landfills. The roofing waste that still remains could be recycled into road mixes using processes already operating, such as that in the RamCo recycling facility in Fort Myers, Florida (Roofer Magazine, 1996). These technologies can help turn the roofing industry towards a more 'green' or sustainable path.

Other cool roof considerations

Cool roof heating penalty

Cool roofs are very effective at reducing warm weather cooling needs, but buildings with cool roofs do have a wintertime heating penalty. Cool roofs reflect away useful heat that could warm the building in winter. In most urban climates this penalty is not large enough to cancel out the summertime savings. There are two reasons for this. First, in winter the sun is much weaker and there are fewer daylight hours. Therefore the amount of useful energy reflected away in the winter is much less than the undesirable energy reflected during the summer. Second, electricity is used to power cooling systems in most buildings, while natural gas is used for heating. Electricity has generally been more expensive than natural gas, so the net annual energy savings translate into overall annual utility bill savings. Natural gas prices have been volatile recently, but the price of electricity is fairly dependent on natural gas prices and is expected to keep pace over the longer term, keeping the economic advantage of cool roofs positive.

In a study by Lawrence Berkeley National Laboratory (Konopacki et al, 1996), researchers ran building energy simulations to look at the effects of cool roofing in 11 cities in the US. Table 5.8 shows the effect of the heating penalty on utility bills for older office buildings in each of these cities. The heating penalty is not high enough in any of these cities to cancel out even as much as half the monetary savings from installing a cool roof.

Insulation and cool roofing

Many researchers look at cool roofing and insulation as competing options for saving building energy. Numerous studies have evaluated the insulation levels needed to produce the same energy savings as a cool roof (Konopacki and Akbari, 1998; Akbari et al, 1999, 2000). These studies have been used to support building codes that allow reduced roof insulation if cool roofing is installed (Georgia Energy Code 1995; CEC 2001).

There are many reasons to avoid this type of trade-off comparison, both philosophical and technical. Philosophically, cool roofing has so many benefits that a comparison to insulation on an energy savings basis alone seems insufficient. Technically, cool roofing and insulation work in very different ways, and comparing them leads to confusion about seasonal performance. While insulation saves energy year-round, cool roofing saves energy in summer but produces a heating penalty during the winter.

Table 5.8 Effect of the heating penalty on old office buildings throughout the US with electrical cooling systems and gas furnaces

Location	Cooling savings kWh/1000 ft^2	Cooling savings \$/1000 ft^2	Heating penalty kBtu/1000 ft^2	Heating penalty \$/1000 ft^2	Overall savings \$/1000 ft^2
Atlanta	293	$22	776	$5	$17
Chicago	191	$16	1367	$7	$9
Los Angeles	377	$34	306	$2	$32
Fort Worth	305	$20	571	$3	$17
Houston	335	$25	327	$1	$24
Miami	424	$29	0	$0	$29
New Orleans	383	$32	367	$2	$30
New York City	168	$21	939	$6	$15
Philadelphia	221	$26	1796	$11	$15
Phoenix	562	$52	265	$2	$50
Washington DC	251	$18	1082	$6	$12

Note: To convert from units per 1000ft^2 to units per km^2, multiply by 10.76.

Source: Konopacki et al, 1996.

Another technical problem is that the energy model used to make these trade-off calculations does not reliably model cool roofs. The model generally used, DOE-2, does not account for radiative heat transfer in the attic or plenum space and does not allow for variation in insulation conductivity with temperature (Gartland et al, 1996). The model tends to under-predict cool roof energy savings, so cool roofing looks less effective than it actually is.

A decision to upgrade roof insulation levels should be made separately from a decision to install a cool roof. Adding roof or ceiling insulation should be considered if:

- there is substantially less roof insulation than called for in the latest local building codes
- the building is in a climate with significant cold weather and/or heating needs
- there is a large roof area compared to the rest of the building's surface area.

Cool roofing should be considered for all buildings, especially if:

- the building is in a climate with hot and sunny weather during at least part of the year
- significant cooling energy is used
- there are problems maintaining indoor comfort in the summer
- the roof area is large compared to the rest of the building's surface area
- the roof materials tend to crack and age prematurely from sun damage.

It is sometimes convenient to add insulation in conjunction with a cool roof project. Many people think that adding roof insulation means adding insulation under the roof or above the ceiling, which is difficult to do without disrupting the building's occupants. But various types of rigid insulation can be added to the roof deck, right under a cool roof coating or single-ply material. Expanded polystyrene (EPS) or spray polyurethane foam (SPF) are two rigid insulation materials commonly added during roofing projects. An inch of insulation can add an approximate R-6 (hr ft^2 °F/Btu) to the insulation rating of the roof assembly (see Figure 5.17). SPF is particularly attractive since it evenly covers joists and structural members. SPF leaves no gaps, it can seal leaks, and it can serve as a vapour and wind barrier.

Applying foam insulation can be tricky. Two separate compounds are mixed together during the spraying process. This must be done under

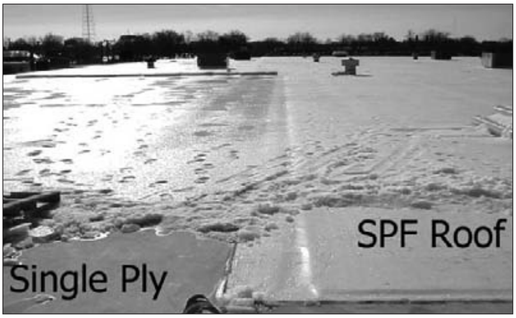


Figure 5.17 A cool roof in Connecticut shows less snowmelt on the right, where SPF insulation has reduced the heat transfer from the building

the correct weather conditions and in exact proportions. When done correctly, the foam hardens into a rigid and durable layer strong enough to take foot traffic. If not done correctly, the foam may not harden properly and may chip or crumble easily. As always, it is important to use reliable contractors with an experienced crew.

Cool roofing myths

Many advertisements for roofing materials make misleading, sometimes downright incorrect claims. Here are four of the most common false claims to watch out for:

> *This coating will keep your home cooler in summer and warmer in winter.*

No roof coating by itself can both cool a building in summer and warm it in winter. All cool coatings have a heating penalty during the winter, although this penalty is usually small enough to make using a cool coating worthwhile. Some advertisements that make this claim assume that the coating is applied inside the building on the walls and ceiling as well as on the building rooftop. Technically, it is not clear that this idea has merit. Increased reflectance of indoor surfaces may help offset some heating losses in the winter, but may also tend to trap heat inside a building during the summer. This is also not a good decorating idea. The most effective coatings are a very bright white, which is too harsh for interior spaces. Cool roof coatings are also formulated with agents to suppress algae and mildew growth and to promote self-washing capabilities, which are not needed on interior surfaces.

> *This coating adds an equivalent R-19 value of insulation to your roof.*

If it were that simple, wouldn't everyone just put a thin coating on their roofs to insulate them? Coatings do not provide any significant insulation because they are applied at thicknesses of only 508 or 762μm, which is much too thin to decrease a roof's heat conduction. The problematic word here is 'equivalent' (which is sometimes left out of a salesperson's argument). What this statement means is that the coating works as well as a layer of insulation for keeping heat out of a building – but only during peak hours in the summer. What this statement does not say is that at other times the coating will work completely differently, and not necessarily to the building's benefit. Don't expect any winter benefits from this 'equivalent R-19': in reality there are heating penalties instead.

> *This product's high emittance keeps your building cooler.*

A cool roof must definitely have a high emittance. But only bare metal roofs and metallic coatings have low emittance. All other types of roof products already have high emittance values, so this is nothing special.

> *This metallic product has high solar reflectance to keep your building cool.*

If a bare metal product or a metallic coating is being referred to, it may have high solar reflectance. But the low emittance of bare metals is what prevents them from being cool materials. If a colour-coated metal is being referred to, the added surface coating probably increases its emittance, but might have decreased its solar reflectance. To be cool, a coated metal roof must be bright white in colour with high solar reflectance, or have special infrared reflecting pigments with high solar reflectance. Without these high reflectance coatings, a coated metal roof has low solar reflectance and does not keep a building cool.

References

Akbari, H. and S. G. Douglas (1995) *Modelling the Ozone Air Quality Impacts of Increased Albedo and Urban Forest in the South Coast Air Basin*. Berkeley, CA, Lawrence Berkeley National Laboratory: 150

Akbari, H. and L. S. Rose (1999) *Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California*. Berkeley, CA, Lawrence Berkeley National Laboratory**:** 48

Akbari, H., S. Bretz, J. Hanford, D. Kurn, B. Fishman, H. Taha and W. Bos (1993) *Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations, and Results*. Berkeley, CA, Lawrence Berkeley National Laboratory**:** 146

Akbari, H., S. Konopacki, D. Parker, B. Wilcox, C. Eley and M. Van Geem (1999) *Calculations in Support of SSP 90.1 for Reflective Roofs*. Berkeley, CA, Lawrence Berkeley National Laboratory**:** 21

Akbari, H., S. Konopacki and D. Parker (2000) *Updates on Revision to ASHRAE Standard 90.2: Including Roof Reflectivity for Residential Buildings*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Akbari, H., A. Rosenfeld, H. Taha and L. Gartland (1996) *Mitigation of Summer Heat Islands to Save Electricity and Reduce Smog*. American Meteorological Society Annual Meeting, Atlanta, GA, American Meteorological Society

Antrim, R., C. Johnson, W. Kirn, W. Platek and K. Sabo (1994) *The Effects of Acrylic Maintenance Coatings on Reducing Weathering Deterioration of Asphaltic Roofing Materials*. ASTM Symposium on Roofing Research and Standards Development, Montreal, American Society for Testing of Materials

ASTM (1990) *Standard Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques*. West Conshohocken, PA, American Society for Testing of Materials

ASTM (1992) *Standard Test Method for Solar Absorptance, Reflectance and Transmittance of Materials Using Integrating Spheres*. West Conshohocken, PA, American Society for Testing of Materials

ASTM (1997a) *Standard Specification for Liquid-Applied Acrylic Coating Used in Roofing*. West Conshohocken, PA, American Society for Testing of Materials

ASTM (1997b) *Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field*. West Conshohocken, PA, American Society for Testing of Materials

ASTM (1998) *Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers*. West Conshohocken, PA, American Society for Testing of Materials, ASTM C 1371–98

ASTM (1999) *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces*. West Conshohocken, PA, American Society for Testing of Materials

Berdahl, P. and S. Bretz (1997) 'Preliminary survey of the solar reflectance of cool roofing materials'. *Energy and Buildings* **25**(2): 149–158

Bretz, S. and H. Akbari (1994) *Durability of High-Albedo Roof Coatings and Implications for Cooling Energy Savings*. Berkeley, CA, Lawrence Berkeley National Laboratory**:** 30

Bretz, S. and H. Akbari (1997) 'Long-term performance of high-albedo roof coatings'. *Energy and Buildings* **25**(2): 159–167

Callahan, M., D. Parker, J. Sherwin and M. Anelio (2000) *Demonstrated Energy Savings of Efficiency Improvements to a Portable Classroom*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

CEC (2001) *Energy Efficiency Standards for Residential and Nonresidential Buildings.* Title 24, California Energy Commission Publication No. P 400–01–024

Douglas, S. G., A. B. Hudischewskyj and V. Gorsevski (2000) *Use of the UAM-V Modelling System as an Air Quality Planning Tool for Examining Heat Island Reduction Strategies.* ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Emery, C., H. Taha and G. Gero (2000) *City of Los Angeles Cool Communities Program, Technical Review of Air Quality Modeling*. Technical Review of Air Quality Modeling, Los Angeles, CA, Environmental Affairs Department

EPA (2000) *ENERGY STAR Program Requirements for Roof Products, Partner Commitments*. Washington DC, US Environmental Protection Agency: 9

Gartland, L. (1998) *Roof Coating Evaluation for the Home Base Store in Vacaville, California*. Oakland, CA, PositivEnergy**:** 27

Gartland, L., S. Konopacki and H. Akbari (1996) *Modeling the Effects of Reflective Roofing*. Berkeley, CA, Lawrence Berkeley National Laboratory: 8

Georgia Energy Code (1995) *Georgia Amendment to the 1995 CABO Model Energy Code for Section 704*. Section 704

Hinojosa, O. and K. Kane (2002) 'A measure of the industry'. *Professional Roofing* April: 24–28

Konopacki, S. and H. Akbari (1998) *Trade-Off Between Cool Roofs and Attic Insulation in New Single-Family Residential Buildings*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Konopacki, S. and H. Akbari (2000) *Energy Savings Calculations for Heat Island Reduction Strategies in Baton Rouge, Sacramento and Salt Lake City*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Konopacki, S. and H. Akbari (2001) *Measured Energy Savings and Demand Reduction from a Reflective Roof Membrane on a Large Retail Store in Austin*. Berkeley, CA, Lawrence Berkeley National Laboratory**:** 26

Konopacki, S. and H. Akbari (2002) *Energy Savings for Heat Island Reduction Strategies in Chicago and Houston (Including Updates for Baton Rouge, Sacramento, and Salt Lake City)*. Berkeley, CA, Lawrence Berkeley National Laboratory: 48

Konopacki, S., H. Akbari, S. Gabersek, M. Pomerantz, L. Gartland and M. Moezzi (1996) *Energy and Cost Benefits from Light-Colored Roofs in 11 U.S. Cities*. Berkeley, CA, Lawrence Berkeley National Laboratory

Konopacki, S., L. Gartland, H. Akbari and L. Rainer (1998) *Demonstration of Energy Savings of Cool Roofs*. Berkeley, CA, Lawrence Berkeley National Laboratory**:** 116

Parker, D. and S. Barkaszi (1994) 'Saving energy with reflective roof coatings'. *Home Energy* May/June: 15–20

Parker, D., S. Barkaszi and J. Sonne (1994a) *Measured Cooling Energy Savings from Reflective Roof Coatings in Florida: Phase II Report*. Cape Canaveral, FL, Florida Solar Energy Center: 31 plus appendices

Parker, D., J. Cummings, J. Sherwin, T. Stedman and J. McIlvaine (1994b) 'Measured residential cooling energy savings from reflective roof coatings in Florida'. *ASHRAE Transactions* **100**(2): 36–49

Parker, D., J. Sherwin, J. Sonne and S. Barkaszi (1996) *Demonstration of Cooling Savings from Light-Colored Roof Surfacing in Florida Commercial Buildings: Our Savior's School*. Cocoa, FL, Florida Solar Energy Center**:** 18

Roofer Magazine (1996) 'Roofing debris recycling, ten years and counting'. *Roofer Magazine* July: 22–24

RSI (1993) 'Disposal costs go through the roof'. *Roofing, Siding, Insulation* October: 30–32

Schmeltz, R. and S. Bretz (1998) *Energy Star Label for Roof Products*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Taha, H., S. C. Chang and H. Akbari (2000) *Meteorological and Air Quality Impacts of Heat Island Mitigation Measures in Three U.S. Cities*. Berkeley, CA, Lawrence Berkeley National Laboratory

Vincent, B. (2000) Energy savings due to cool roofs for buildings monitored by SMUD, email communication to L. Gartland, August

Vincent, B. and J. Huang (1996) *Analysis of the Energy Performances of Cooling Retrofits in Sacramento Public Housing Using Monitored Data and Computer Simulations*. Sacramento, CA, for the California Energy Commission

6

All About Cool Paving

What is cool paving?

As was discussed in Chapter 4, paved surfaces cover large percentages of urban and suburban areas. Pavements contribute to the heat island effect by warming up in the sun and releasing this stored energy to their surroundings during the evening and overnight.

The hottest pavements tend to be impermeable and dark in colour, with solar reflectance values under 25 per cent. These pavements can heat to 65°C (150°F) or more in the summer sun. Conversely, cool paving temperatures are reduced by 15°C (30°F) or more (Asaeda et al, 1996; Pomerantz et al, 2000c; Gartland, 2001), keeping peak temperatures below 50°C (120°F).

There are two ways to make pavements cooler: (1) by increasing their solar reflectance, and/or (2) by increasing their ability to store and evaporate water.

Solar reflectance of a moderate 25 per cent or higher can be considered cool for pavements. Increasing solar reflectance means making pavements lighter in colour by using lighter-coloured ingredients in the pavement mix or by applying lighter coatings over the pavement surface. Since colour has the largest effect on solar reflectance, the lightest coloured pavements are usually the coolest, but cool pavements are generally lighter shades of grey, tan and other colours. Cool paving materials are not expected to mimic the bright white colour and high solar reflectance of their cool roof counterparts. In fact, if they were too bright they would cause a glare hazard.

Note that the thermal emittance of pavement is not usually an important factor in pavement temperature. All common paving materials generally have thermal emittance values of 80 per cent or higher.

Increasing the water storage capability of pavements means making them porous. Water then filters through the rigid top layer and is stored in the soil and supporting layers below. Porous pavements allow water to drain through during rainstorms and evaporate back out during hot, sunny weather. Evaporating water draws heat from the pavement, keeping the pavement cooler in the sun.

Types of cool paving

The most commonly used pavement types are asphalt cement concrete (ACC), usually referred to by laypeople simply as 'asphalt', and Portland cement concrete (PCC), usually just called 'concrete'. Both of these pavement types can be made cooler in various ways. There are also a couple of less commonly used types of pavement with great potential as cool pavements.

Asphalt pavements

Traditional asphalt pavements tend to be black or

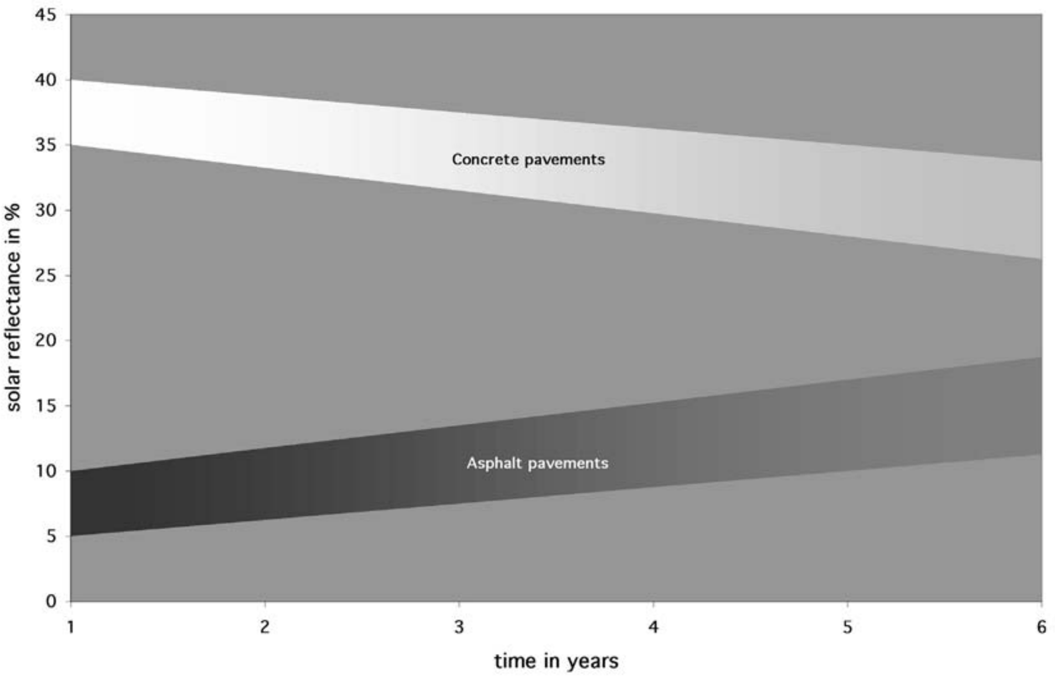


Figure 6.1 Variation of the solar reflectance of asphalt and concrete pavements over time

grey in colour, with solar reflectance values of 5–10 per cent when new. Asphalt pavements lighten and become more reflective as they age, as shown in Figure 6.1. However, their relatively dark colours tend to keep asphalt pavements at 65°C (150°F) or higher in the summer sun.

An older asphalt parking lot in Tucson, Arizona, is pictured in Figure 6.2, with pavement solar reflectance of around 15 per cent (Gartland, 2001). Figure 6.3 show how these pavement temperatures fluctuate daily, swinging between 25°C (80°F) at night and 65°C (150°F) at around noon, with dips when trees shade the pavement or when clouds cover the sun.

Figure 6.2 Tucson, Arizona, parking lot pavement with a solar reflectance of around 15 per cent

A Japanese study shows how heat is stored and released in asphalt pavements over the course of a day (Asaeda et al, 1996). Figures 6.4 and 6.5 plot surface temperatures and heat flows into and out of a dry asphalt pavement with solar reflectance of 10 per cent. Surface temperatures on this 34°C (93°F) day reached 57°C (135°F). As net radiation (radiation from the sun and the sky minus the reflected solar radiation and radiation emitted from the pavement's surface) to the pavement climbs, heat is released to the air through convection. In the morning and early afternoon, this convection is not enough to keep the pavement cool and heat is stored in the pavement. From mid-afternoon onward, as the sun's energy decreases, the asphalt is able to release stored heat and cool down. Without any water in the pavement, evaporation cannot help it stay cool.

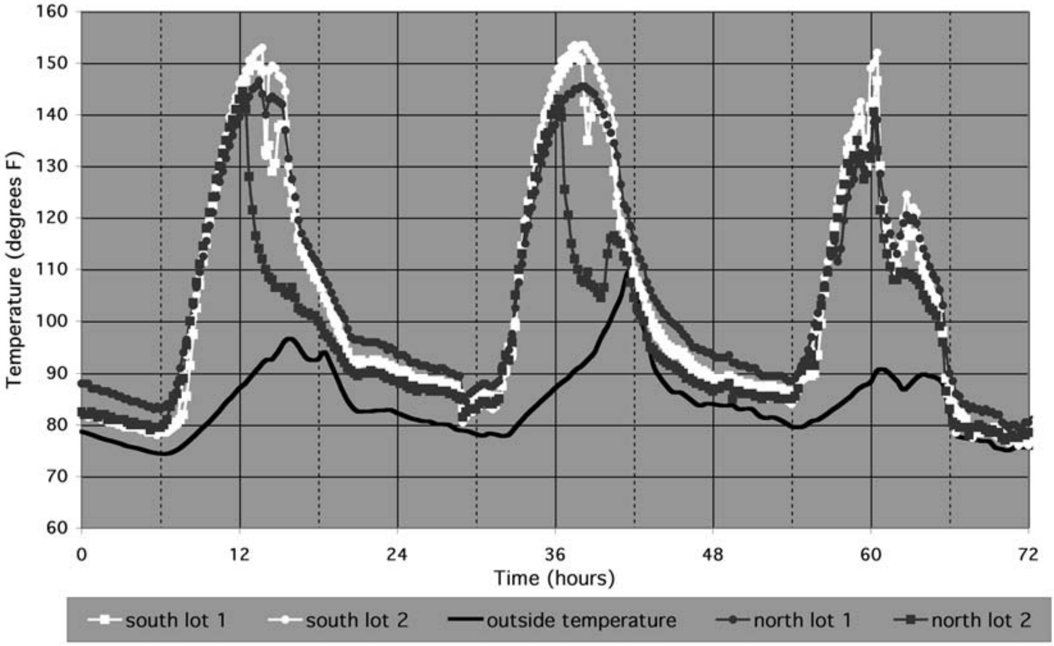
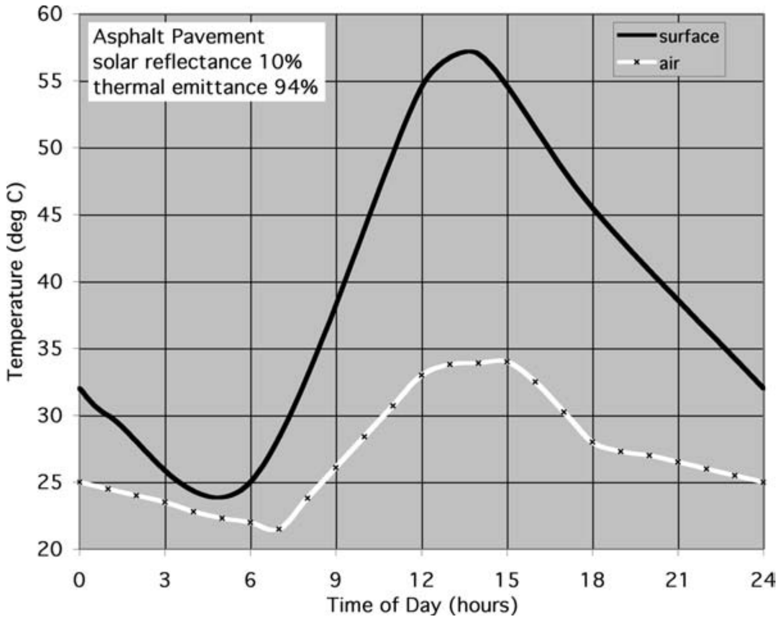
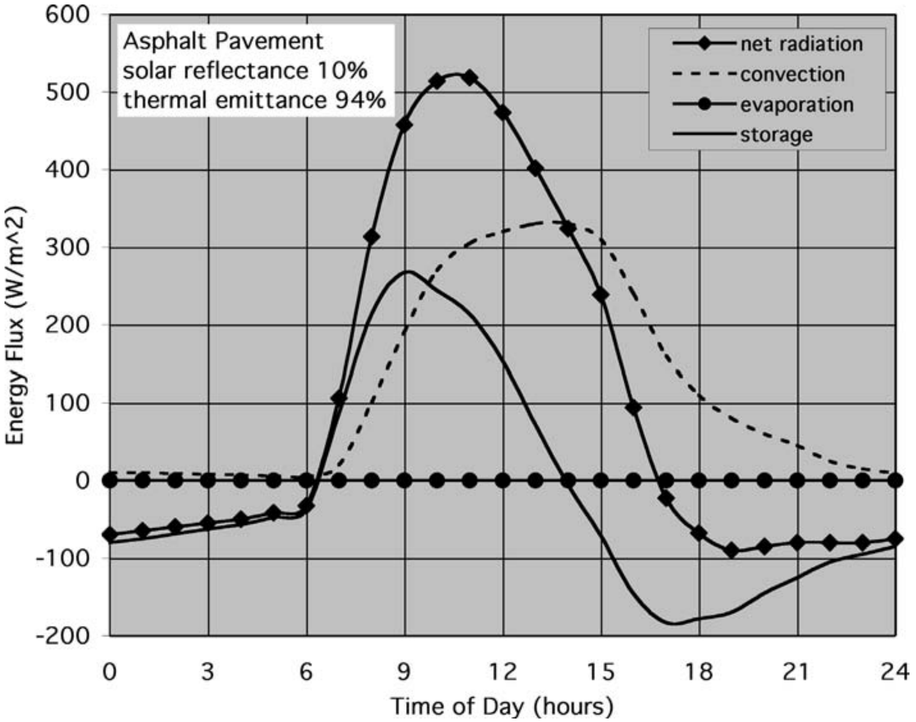


Figure 6.3 Tucson, Arizona, parking lot pavement temperature fluctuations



Source: Asaeda et al, 1996.

Figure 6.4 Asphalt pavement temperatures over one day



Source: Asaeda et al, 1996.

Figure 6.5 Asphalt pavement heat flow over one day

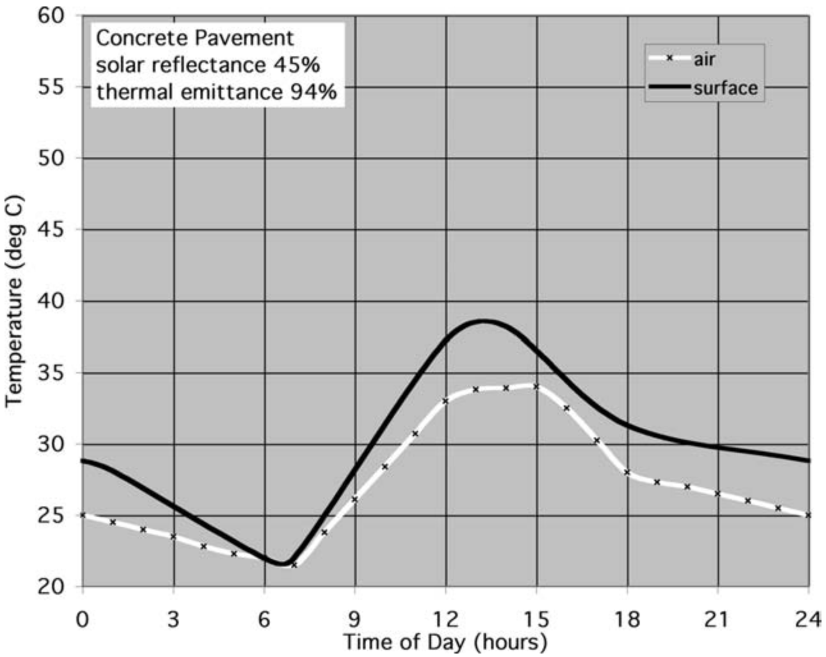
Concrete pavements

The second most prevalent type of pavement in use today is Portland cement concrete (PCC), often simply called concrete. Concrete pavements are light grey in colour, with solar reflectance values usually between 35 and 40 per cent when the pavements are new. Over time, concrete pavements become dirty, reducing their solar reflectance to 25–35 per cent. Figure 6.1 shows how the solar reflectance of asphalt and concrete pavements tends to vary over time. Due to their lighter colours and higher solar reflectance, concrete pavements tend to stay cooler in the sun than their asphalt counterparts, even when dirty.

A Japanese study of pavement heat flows and temperatures showed how concrete pavements stay cooler than less reflective pavements. Figure 6.6 plots the daily temperature of a concrete pavement with 45 per cent solar reflectance, and Figure 6.7 shows how heat flows in and out of the pavement over the same day. On this 34°C (93°F) day, the concrete heats up to only 38°C (100°F). This is mainly because the surface reflects more of the sun's radiation away, reducing net radiation to a peak of 350Wm^2, versus 520Wm^2 for the asphalt pavement (Figure 6.5). The cooler concrete pavement stores less heat in the morning and releases less heat back to the air in the afternoon than the asphalt pavement does. Once again, evaporative heat transfer is zero for this solid, dry pavement.

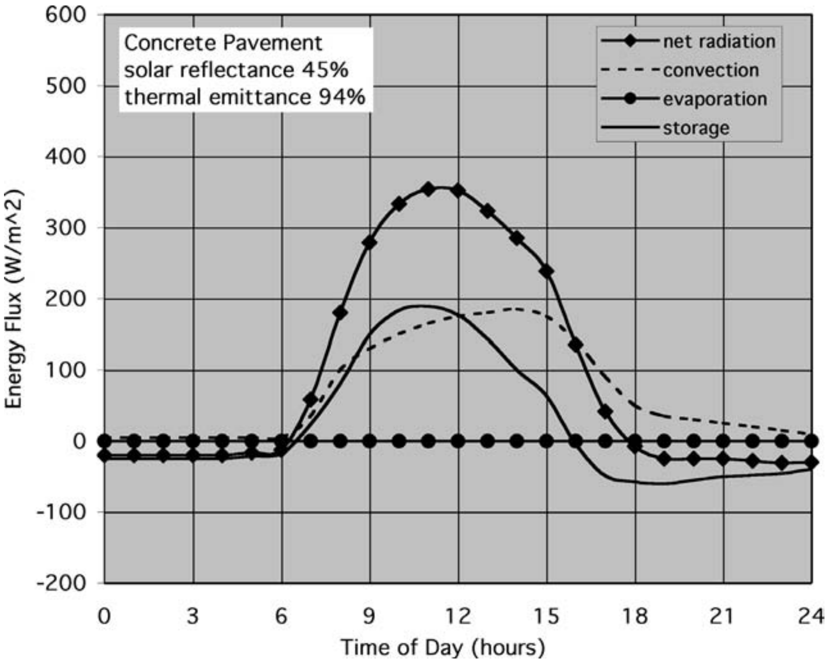
Lighter-coloured asphalt and concrete pavements

Asphalt pavements can be lightened and cooled in various ways. Light pigment can be added to the asphalt mix or lighter-coloured aggregates (rocks in the pavement mixture) or sand can be added. These measures can increase the solar reflectance of the pavement by up to 30 per cent.



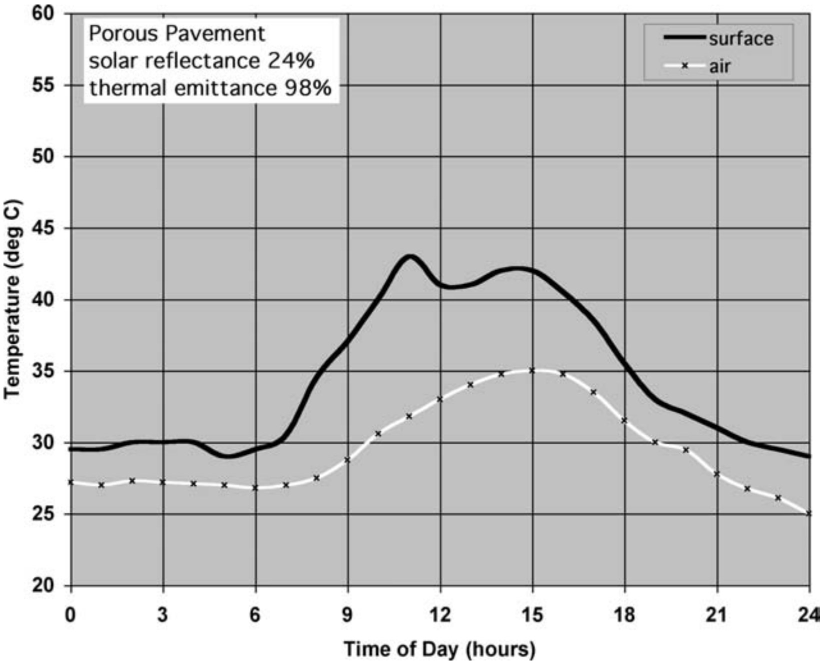
Source: Asaeda et al, 1996.

Figure 6.6 Concrete pavement temperatures over one day



Source: Asaeda et al, 1996.

Figure 6.7 Concrete pavement heat flow over one day



Source: Asaeda and Ca, 2000.

Figure 6.8 Porous pavement temperatures over one day

Pigment and lighter aggregates can also be added to emulsion seal coats and chip seals used to top existing pavements during routine asphalt maintenance (Cartwright, 1998; Ting et al, 2001). Asphalt pavements can also be finished in a variety of brick- or stone-like textures using light-coloured coatings to simulate the look of other materials.

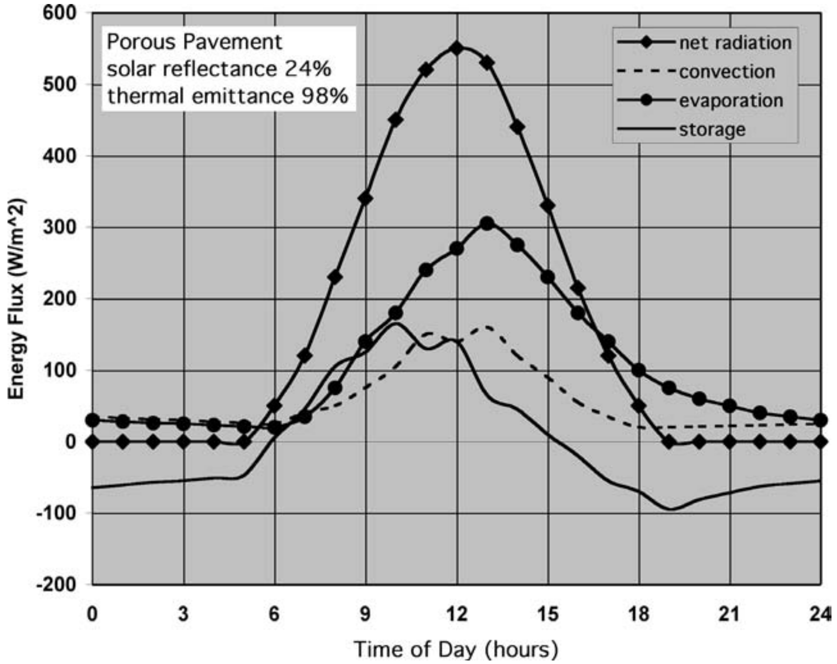
Concrete pavements can be cooled even further by the use of lighter-coloured aggregates and cement binders. Laboratory tests of specially lightened concretes measured solar reflectance values as high as 80 per cent (Levinson and Akbari, 2001). New layers of concrete can be applied over existing pavements through processes called white-topping. Ultra-thin white-topping uses fibre reinforcement to strengthen the pavement, keeping additional layers thinner and reducing the curing time (Hurd, 1997).

Porous asphalt and concrete pavements

Another way to cool an asphalt or concrete pavement is to make it porous or permeable. This allows rainwater to drain through the pavement and be stored in the layers and soil below. Water can then evaporate and cool the pavement during sunny weather.

Figures 6.8 and 6.9 show the temperature and heat flows of a porous pavement with solar reflectance of 25 per cent. This pavement reaches a maximum of 43°C (109°F) on a 35°C (95°F) day. The net radiation into the porous pavement reaches 550Wm^2, even higher than the 520Wm^2 of the asphalt pavement in Figure 6.5. But the porous pavement stays cool by using the sun's heat to evaporate water stored in the pavement and the soil below.

Asphalt and concrete pavements are made porous by leaving the smaller particles, or fines, of sand and rocks out of the pavement mix. These 'open-graded' pavements then have a void



Source: Asaeda and Ca, 2000.

Figure 6.9 Porous pavement heat flow over one day

space between the larger rocks that allows water to drain through the pavement. These void spaces must be carefully sized to avoid getting clogged by dirt and other materials. Both asphalt and concrete versions of porous pavements have been used on roads and parking lots (Smith, 1999; Maes and Youngs, 2002).

Non-traditional cool pavements

Block pavers are another type of cool pavement in use today. Block pavers are lattice blocks made of plastic, metal or concrete. These blocks are laid in place over a graded and prepared base. The blocks are then filled with rocks, or filled with soil and planted with grass, groundcover or wild flowers. The blocks provide structural support and allow water to drain, be stored and subsequently evaporate. Block pavers have been used successfully in low traffic areas such as alleyways, driveways, parking lots and fire lanes (Cote et al, 2000; Chicago, 2002). Block pavers are cooler by virtue of being porous and/or by the use of more reflective surfaces or vegetation.

Resin-based pavements use tree resins to bind the pavement together, instead of the asphalt or cement binders used in asphalt and concrete pavements. Unlike the black or grey binders used to hold traditional pavements together, the resin binder is clear. Resin-based pavements are free to assume the colour of the rocks and sand that make up the rest of the pavement mixture. Without the darker binders, resin pavements are generally lighter in colour than other pavements. Ingredients for the pavement mixture can often be taken straight from the site, allowing the pavements to blend in with the natural environment. Resin-based pavements have been used successfully as hiking and biking paths in parks and in other environmentally sensitive areas.

Catalogue of cool pavements

Details about the various types of cool

pavements available today are catalogued below. Information given for each type of pavement includes a description, construction information, typical applications, ranges of solar reflectance and an estimate of installation costs. PCC paving options are listed first (designated as concrete), followed by ACC (asphalt) options and then other pavement types (other). Some options are best for new pavement construction (new), while others are best for pavement maintenance or reconstruction (renew).

Note that material and installation costs for cool paving options are very difficult to pin down. Construction costs for any paving project vary greatly by region, contractor, time of year, materials chosen, site, underlying soils, size of the project, expected traffic and desired life of the pavement. On top of this variation, many cool paving options are quite new to the industry or are used only on specialty projects, so their costs are still unknown. Because of this, the initial cost figures quoted in the catalogue below cover a wide range.

Portland cement concrete (concrete, new)

Description: PCC is a mix of a binder (cement made from lime and clay), sand and aggregate. It is applied at depths of 8 inches (20 centimetres) or more for new construction of roads and parking lots. The thickness of the concrete depends on the underlying soil and expected traffic conditions.

Construction: Concrete is applied by first compacting the road bed and any base aggregate materials, spreading the concrete, allowing the concrete to cure and finally finishing the surface by cutting joints. Concrete can take up to a week to cure completely, and usually must be kept moist during this period to cure without cracking. Concrete mixes and construction methods have been developed to reduce the curing period to a day or less. Joints must be correctly spaced to allow the concrete to expand and contract with temperature without cracking due to its own brittleness. Concrete pavements can have service lives in excess of 35 years, with maintenance typically limited to joint and crack resealing. Periodic high-pressure washing can remove dirt and oil build-up to maintain reflectivity and appearance. All types of concrete tend to form a white haze called efflorescence on their surface in the early months of their installation. This haze is caused by calcium in the cement reacting with water, rising to the pavement surface and then reacting with carbon dioxide to form calcium carbonate. This haze may be beneficial from a heat island perspective, since it whitens the pavements and cools them further. It will most likely fade away over time, or it can be cleaned away with detergents.

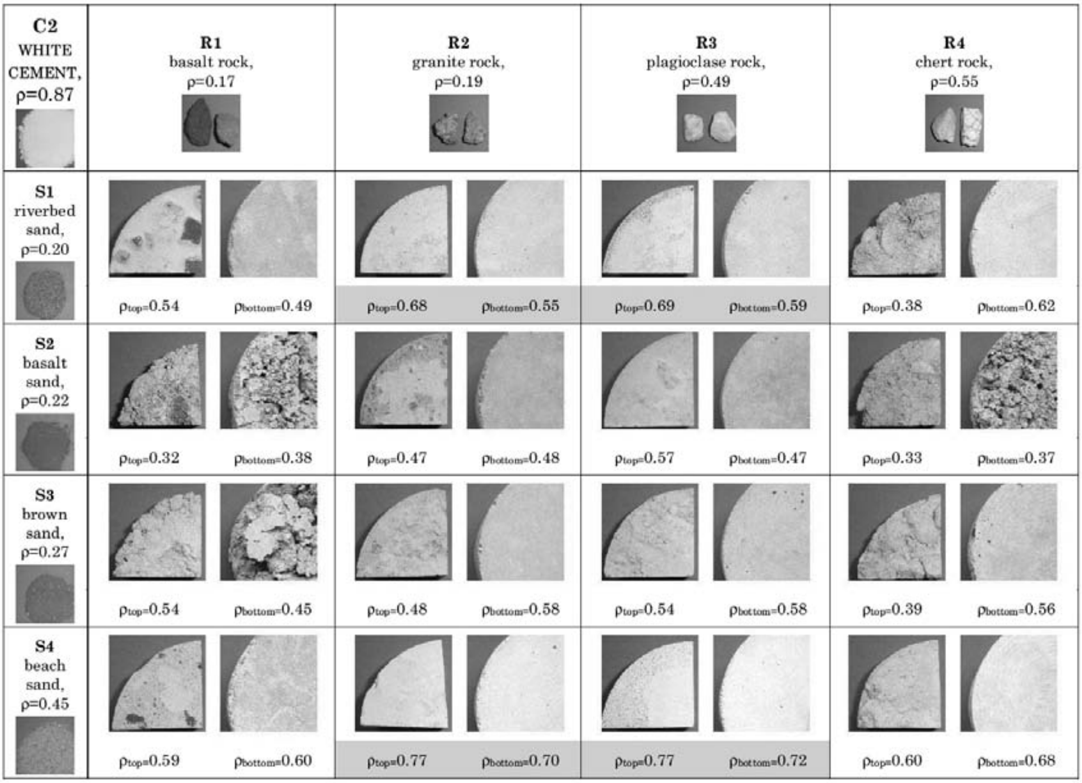
Applications: PCC is used for all types of roads, parking lots, sidewalks and other paved areas.

Solar reflectance: Traditional concretes have solar reflectance values ranging between 35 and 40 per cent when just installed, dropping to 25–35 per cent as the concrete ages and picks up dirt. With careful selection of lighter-coloured binder materials, sands and aggregates, cooler concretes can be made with solar reflectance of new installations ranging from 40 to 80 per cent. Figure 6.10 (Plate 17) shows various experimental concrete mixes with high solar reflectance.

Initial cost: \$2.00–\$6.00 per square foot for materials and installation. If highly reflective components are used the materials costs may double.

White-topping (concrete, renew)

Description: White-topping is a technique for covering existing pavements (usually asphalt concretes) with a layer of PCC. Traditional white-topping adds a layer of concrete 4–8 inches thick over an existing pavement. New concrete mixtures with fibre reinforcement, called ultra-thin white-topping, can be applied in layers 2–4 inches thick and still withstand normal residential and low-volume loads (Hurd, 1997). Special mixtures with higher cement content can also be used for surfaces that must be cured and ready for traffic within 24 hours.



Note: ρ, solar reflectance of each of the individual materials in the concret mix; ρ_{top}, solar reflectance of the naturally finished top surface of the concrete sample after 25 weeks of simulated weathering; ρ_{bottom}, solar reflectance of the smooth, diamond-cut bottom surface of the concrete sample with no weathering.
Source: Levinson and Akbari, 2001.

Figure 6.10 Cooler Portland cement concretes (see Plate 17 for a colour version)

Construction: The white-topping construction process consists of four steps: (1) coring the existing pavement to determine its depth, type and condition; (2) preparing the road surface by water or abrasive blasting, or milling and cleaning; (3) spreading the concrete; and (4) finishing and texturing the surface, and curing and sawing its joints. The proper joint spacing is critical to control cracking of the concrete surface.

Applications: White-topping is usually used to cover existing asphalt pavements on all types of roads, parking lots, sidewalks and other paved areas. Figure 6.11 shows ultra-thin white-topping being applied over an existing asphalt road surface.

Solar reflectance: Traditional concretes have solar reflectance ranging between 35 and 40 per cent when just installed, dropping to 25–30 per cent as the concrete ages and picks up dirt. With careful selection of lighter-coloured binder materials, sands and aggregates, cooler concretes can be made with solar reflectance of new installations ranging from 40 to 60 per cent.

Initial cost: \$1.50–\$3.00 per square foot for materials and installation. If highly reflective components are used the materials costs may double.

Figure 6.11 Ultra-thin white-topping being applied over an existing asphalt road

Interlocking concrete pavers (concrete, new or renew)

Description: Interlocking concrete pavers are blocks pre-cast into interlocking shapes. Segmented pavers are designed to withstand high load conditions, since the interlocking design helps to transfer stresses among the blocks. They come in many designs, patterns and colours.

Construction: The pavers are installed over a conventional aggregate base over which a thin layer of bedding sand has been placed. Machines can be used to mechanically lay and interlock the pavers at high speed. No sand or grout is usually needed to set the pavers since the joints are close fitting. Since the pavers are not generally grouted into place, they are easy to remove for repair or replacement. They can also be reused at other sites.

Applications: Interlocking pavers can be used in high load conditions such as industrial and warehouse operations, airplane taxiways and airport hubs, as well as in lower load applications such as sidewalks and driveways. Figure 6.12 shows the construction detail recommended for laying interlocking pavement on an airfield surface.

Solar reflectance: They are often tinted with pigment, so interlocking pavers can have a wide range of reflectance values. Choose the lightest colours for the coolest pavements.

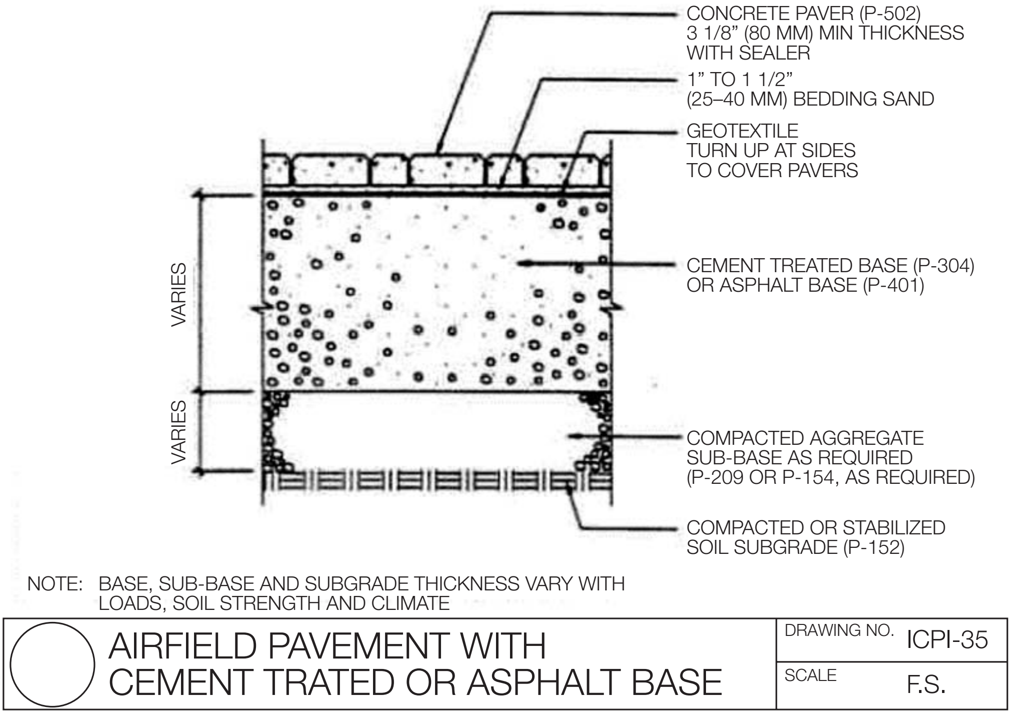


Figure 6.12 Interlocking concrete paver construction detail for an airfield

Initial cost: \$1.50–\$3.00 per square foot for materials and installation. If highly reflective components are used the materials costs may double.

Porous PCC (concrete, new)

Description: Porous or permeable PCC is exactly like its impermeable counterpart except the 'fines' – small particles such as sand and smaller aggregates – are left out of the mix. This leaves void spaces between the larger aggregate materials that allow water to drain through the concrete surface. Void spaces can take up 10–25 per cent of a pavement's volume. These void spaces do not generally get clogged when they are sized appropriately. Traffic over the pavement also helps to remove debris from the surfaces.

Construction: Porous concrete is constructed and maintained in the same manner as regular PCCs.

Applications: Roads, parking lots and other applications. Appropriate for most surface types as long as the base is properly composed and the concrete is the right thickness. Figure 6.13 shows a porous concrete pavement used in the parking lot of Bannister Park in Fair Oaks, California.

Solar reflectance: Permeable concretes come in the same range of colours as all other types of concrete pavements, but its slightly rougher surface may lower the solar reflectance by as much as 5 per cent. However, its ability to hold moisture keeps permeable pavements cooler than impermeable surfaces.

Initial cost: \$2.00–\$6.00 per square foot for materials and installation. If highly reflective components are used the materials costs may double. There is the potential to eliminate the expense of drainage system installation and maintenance.

Source: Youngs, 2005.

Figure 6.13 Porous concrete parking lot at Bannister Park in Fair Oaks, California

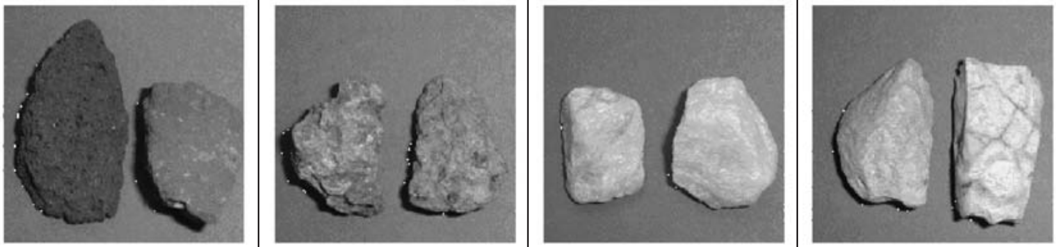
Cool ACC pavements (asphalt, new)

Description: Asphalt pavements are typically composed of aggregate or rock held together by an asphalt binder. The asphalt binder is very dark in colour, so to achieve a cool pavement, lighter-coloured aggregate materials must be used. Cool asphalts start out only slightly lighter in colour and cooler than their traditional counterparts. But as the binder ages and lightens in colour, the aggregate material is revealed and the solar reflectance of the pavement increases.

Construction: Cool asphalt pavements are constructed just like their traditional alternative, except that a lighter-coloured aggregate is added to the concrete mix. Check with material suppliers to encourage them to find lighter-coloured aggregate sources. Asphalt pavements typically require maintenance every 3–10 years, depending on their application. This maintenance depends on local custom, and can include coating with emulsion seal coats, slurry seals or chip seals, or complete resurfacing of the asphalt. Preliminary research indicates that cooler asphalt pavements will require less maintenance and have longer life cycles.

Applications: Asphalt pavements are used successfully in every paving application. Lighter-coloured asphalts can also be used everywhere.

Solar reflectance: Measurements of the solar reflectance of asphalt pavements with lighter-coloured aggregates have not yet been made, but measurements of PCC using lighter-coloured aggregates have found that reflectance increases by 10–30 per cent when aggregates with 30–40 per cent more reflectance are used (Levinson and Akbari, 2001). Figure 6.14 (Plate 18) shows various aggregates and their solar reflectance.



R1 (ρ = 0.17)	R2 (ρ = 0.19)	R3 (ρ = 0.49)	R4 (ρ = 0.55)
dark red volcanic rock (basalt)	black and red rock (granite)	white rock (plagioclase)	gold and white rock (chert, iron impurities)
d_{50} = 18 mm	d_{50} = 16 mm	d_{50} = 14 mm	d_{50} = 16 mm

Note: d_{50} is the mass-mean diameter, a measure of the average rock size.

Figure 6.14 Solar reflectance of various types of aggregate used in pavements (see Plate 18 for a colour version)

Initial cost: $1.00–$2.00 per square foot for materials and installation. The price of using lighter-coloured aggregates varies depending on the material availability and cost.

Chip seals (asphalt, renew)

Description: The application of chip seals over asphalt pavements is a maintenance technique that has been used for decades throughout the US. Chip seals are less costly than complete pavement resurfacing and can be applied very quickly, so roads are ready for use in less than a day. Since very little of the binder shows through, the pavement surface takes on the appearance of the aggregate used.

Construction: Chip seals are applied in a four-step process. An asphalt emulsion binder is first sprayed onto the pavement. This is followed immediately by an application of rock chips. Next the rocks are pressed into the asphalt binder using a heavy roller. Finally excess aggregate is swept off the road surface. The service life of chip seals is usually 5–7 years.

Applications: This process is more appropriate for use on roads than on parking lots, since the chips do not adhere well under the lateral stresses of almost stationary tyres turning left and right to park and steer.

Solar reflectance: The road takes on more of the colour of the rock used in the chip layer since it is not mixed together with the asphalt binder, so the use of lighter-coloured aggregate here can make more of a difference in cooling the road surface. Solar reflectance values of 40–50 per cent can be realized if the lightest-coloured aggregates are used.

Initial cost: $0.50–$1.00 per square foot for materials and installation. The price of using lighter-coloured aggregates varies depending on the material availability and cost.

Coloured asphalt seals and seal coats (asphalt, renew)

Description: Black asphalt seals and seal coats are familiar pre-mixed products often seen on shopping centre parking lots or on driveways.

They consist of a fine aggregate (rocks of small size) in emulsion (suspended in water) with a black asphalt binder. Seal coats can be prepared in different colours by mixing in special pigment additives.

Construction: Seal coats are applied over existing pavements to seal small cracks and protect the surface. Seal coats need to be applied over a clean, dry surface. Seal coats come in different varieties, from the lightest fog seals that use very little aggregate, to heavier emulsion seal coats, sand seals and slurry seals. When applied properly, they are expected to last 3–10 years, depending on the weight of the seal coat.

Applications: Wide application over all types of pavements. Coloured seal coats are also used to designate different traffic areas (bike lanes versus car lanes) and for decorative design purposes. Pigment additives can also be used to colour ACC mixes, as was done at Los Angeles' Union Station (Cartwright, 1998).

Solar reflectance: Standard seal coats are specified to be black, and in fact are often made to stay blacker for a longer period of time by the addition of the pigment carbon black. These black coatings are extremely undesirable in terms of heat island mitigation. Alternative pigment additives can be used instead to turn the seal coats to various shades of grey, tan, red and green. Figure 6.15 (Plate 19) shows a road surfaced with a brick-red seal coat. Lighter colours can be custom-mixed by adding zinc oxide, titanium dioxide or other lightening pigments.

Initial cost: \$0.50–\$1.00 per square foot for materials and installation. Addition of pigment for colouring and lightening may cost more, although the removal of carbon black may cost less.

Open-graded asphalt pavements (asphalt, new)

Description: Like its porous PCC counterpart, open-graded asphalt leaves out the 'fines' or small aggregate particles in order to leave void spaces in the pavement. This allows water to drain through the pavement surface. These void spaces do not generally get clogged when they are sized appropriately. Traffic over the pavement also helps to remove debris from the surfaces.

Construction: Open-graded asphalt is constructed and maintained in the same way as impermeable asphalt.

Applications: Roads, parking lots and other applications. Appropriate for most surface types

Source: Asphacolor Corporation, www.asphacolor.com.

Figure 6.15 Roadway outside of Union Station in Los Angeles surfaced with a coloured asphalt emulsion sealcoat (see Plate 19 for a colour version) as long as the base is properly composed and the pavement has the right thickness. This pavement was used on a stretch of California Highway 49 running through Sutter's Mill State Park, helping to reduce water run-off and keep traffic noise levels down (Smith, 1999).

Solar reflectance: Open-graded concretes can be made up to 30 per cent more reflective by using lighter-coloured aggregates. However, its ability to hold moisture is what keeps open-graded asphalt pavements cooler than impermeable pavements.

Initial cost: \$1.00–\$2.00 per square foot for materials and installation. The price of using lighter-coloured aggregates varies depending on the material availability and cost.

Pavement texturing (asphalt, new or renew)

Description: Pavement texturing is a process that uses standard asphalt to produce a decorative pavement in a variety of colours and patterns. These pavements are less expensive and labour-intensive to install than real paving stones or blocks, with the additional advantage of having no joints where water can infiltrate and weeds can grow.

Construction: The construction process consists of first laying the asphalt, compacting it into a patterned form and then finishing it with a polymerized cement coating. The resulting pavement can withstand extreme weather and traffic loading by combining the strength of cement with the flexibility of asphalt. Textured pavements can be patched fairly easily.

Applications: Textured pavements are used in street paving, traffic calming, pedestrian areas, medians and boulevards, parking lots, playgrounds and other applications. Figure 6.16 (Plate 20) shows textured pavement in a shopping centre.

Solar reflectance: The choice of a lighter-coloured coating is needed to make the surface more reflective and keep it cooler.

Initial cost: \$2.00–\$6.00 per square foot for materials and installation.

Source: Integrated Paving Concepts, www.integratedpaving.com.

Figure 6.16 Asphalt pavement in a Hialeah, Florida, furniture store's parking lot, textured to resemble paving stones (see Plate 20 for a colour version)

Resin-based pavements (other, new or renew)

Description: Instead of using the petroleum-based binders of typical asphalt pavements, resin-modified emulsion pavements use a binder made primarily from tree resins. This binder is mixed with aggregate materials to produce compacted pavement of higher strength and resistance to fuel spills than traditional asphalt.

Construction: The construction/installation process for resin-based pavements is similar to that for asphalt pavements. The resin binder is first applied alone to the prepared area as a base coat. The binder and aggregate are mixed on site and then applied and compacted to a smooth finish. A final coat of resin is used to seal the pavement. Unlike asphalt pavements, the resin emulsion does not need to be heated for application.

Applications: This product is useful for environmentally sensitive sites. Figure 6.17 (Plate 21) shows a resin-based pavement path at Crissy Field along the San Francisco Bay.

Solar reflectance: The resin binder is clear, so the pavement retains the colour of whatever aggregate is used. Use of lighter-coloured aggregates allows for a more reflective, cooler pavement.

Source: Soil Stabilization Products Company Inc., www.sspco.com.

Figure 6.17 Resin-based pavement used in the Land's End Coastal Trail alongside the San Francisco Bay (see Plate 21 for a colour version)

Initial cost: About $3.00 per square foot for materials and installation.

Porous block pavement systems (concrete or other, new or renew)

Description: Porous pavements are specifically designed to let water drain through them to the soil below while allowing pedestrian or light traffic loads to be supported. These prefabricated paving systems are usually lattice structures made of concrete, plastic or metal. Lattice blocks are filled with aggregate materials or with soil and grass or groundcover. Figure 6.18 shows the underlying lattice structure of two types of commercially available porous block pavers.

Construction: Construction of porous pavement systems consists of grading and fertilizing an underlying bed of soil, placing the pavers and securing them with spikes and/or against a stationary edge, then filling the pavers with soil and seed or with aggregate. Once grass has grown or enough aggregate has been put in place, the underlying pavers are invisible. If grass is used, it will require normal watering and mowing maintenance.

Applications: Porous pavers are useful for pedestrian walkways, driveways, parking lots, overflow parking, fire lanes or any other less frequently travelled surfaces. The lattice pavers can also be used to control soil erosion on hillsides. Figure 6.19 shows a grass paver system used for overflow parking at a Connecticut shopping mall.

Solar reflectance: If the blocks are filled with aggregate, a lighter-coloured aggregate should be chosen for cooler temperatures. Light-coloured aggregates could deliver solar reflectance values of between 30 and 50 per cent. The solar reflectance of grass is about 20 per cent, but grass also stays cooler and cools the air above it by evapotranspiring water through its leaf blades.

Initial cost: $1.50–$5.00 per square foot for materials and installation.

Source: Soil Stabilization Products Company Inc., www.sspco.com.

Figure 6.18 Porous pavers being filled with aggregate for use in a parking lot at the University of California Merced Campus

Benefits of cool paving

The main reason this book promotes the use of cool paving materials is to cool the air in urban and suburban areas. But there are other significant benefits of cool paving that may be reaped, including better management of water run-off, increased pavement durability, less need for night-time lighting, less traffic noise and the potential for more creative urban design. More detailed information about these benefits is discussed below.

Cooler urban and suburban air temperatures

Hot pavements transfer heat to the air that flows above them, and the hotter the pavement, the hotter the air will become. A study in Japan

Source: Soil Stabilization Products Company Inc., www.sspco.com.

Figure 6.19 Porous pavers filled with soil and grass used as emergency fire lanes around buildings at the Microsoft campus in Washington state measured the heat flux from traditional asphalts and concretes (Asaeda et al, 1996). The pavement heat was absorbed into the lower atmosphere and increased air temperatures near the ground. An asphalt pavement with 10 per cent solar reflectance reached 66°C (150°F) at 1:00pm and convected about 350Wm^2 to the air (see Figures 6.4 and 6.5). A concrete pavement with 45 per cent solar reflectance (a bit higher than the typical 35–40 per cent value for concrete in the US) reached 49°C (120°F) at 1:00pm and emitted only about 200Wm^2 to the air (see Figures 6.6 and 6.7).

The Japan study (Asaeda et al, 1996) also looked at bare soils and found that the heat flux from soil is greatly dependent on its water content. Moist soils stayed cooler and transferred less heat to the air, despite their low solar reflectance of around 15 per cent. Instead of heating up in the sun, the sun's energy evaporates moisture in the soil. This indicates that porous or permeable pavements, with channels to the water-retentive soils underneath, are also effective as cool paving materials.

One other important finding from Japan (Asaeda et al, 1996) is that pavement heat flux is a significant factor in urban heating. Pavement heat flux in Tokyo was found to equal about half the energy consumption rate of the city.

Researchers at Lawrence Berkeley National Laboratory have also investigated the effect of hot paving materials on air temperatures (Pomerantz et al, 2000c). Models of Los Angeles and other cities predict that an air temperature decrease of 1.5°C (2.7°F) is possible when rooftops and pavements are cooled and trees and vegetation are added to the landscape. Interpolating from these results, it is estimated that making pavement changes alone could reduce air temperature by 0.5°C (1.0°F).

Better management of water run-off

Most pavements in use today are impermeable, and most of the rainwater falling on them must be channelled into storm drains and sewers. In contrast, porous pavements allow water to drain through the paved surface to the soil below. Segmented concrete pavers and porous block pavers are permeable, allowing water to run off between segments or through the blocks. Both ACC and PCC can also be constructed as porous pavements. Omitting sand and small aggregates from the concrete mix leaves small spaces through which water can permeate without sacrificing structural integrity. The void space left in porous pavements usually ranges between 10 and 25 per cent, and these voids are capable of absorbing between 120 and 325 litres per minute over every square metre of pavement surface (Youngs, 2005).

Not only does the moisture collected in the pavement keep it cooler, as discussed earlier in this chapter, but porous pavements help disperse stormwater instead of channelling it all through drains. This has many beneficial environmental effects. Porous pavements reduce the potential for flooding during heavy storms and keep groundwater well distributed for healthier vegetation around pavements. Filtering rainwater through soils also helps to remove pollutants such as oil and gasoline from the water system.

Porous pavements can be safer for driving. Pavements that absorb water reduce hydroplaning of car tyres, water spray and accidents associated with driving in wet weather.

Porous pavements also bring financial benefits. If designed correctly, streets and parking lots using porous pavements can reduce or eliminate drainage systems. Porous pavements are a relatively new development, so the cost savings are still unclear, but significant amounts of money can potentially be saved on the construction and long-term maintenance of drainage systems and sewer systems.

Increased pavement durability

Asphalt pavement has various modes of failure that are intensified or hastened by higher pavement temperatures, including:

- rutting – channels caused by car tyres form in the pavement
- shoving – asphalt is pushed in the direction of motion when heavy braking occurs

- ageing – asphalt becomes brittle and stiff with age
- fatigue – gradual pavement cracking
- bleeding – asphalt binder material accumulates at the pavement surface.

The effect of cooling asphalt pavements on rutting, shoving and ageing have been investigated by researchers from Lawrence Berkeley National Laboratory and the Institute for Transportation Studies at the University of California, Berkeley (Harvey and Popescu, 2000; Pomerantz et al, 2000a; Ongel and Harvey, 2004). At 53°C (127°F) rutting reached the failure depth after less than 20,000 test repetitions, but at 42°C (108°F) it took 270,000 repetitions to reach failure. At 60°C (140°F) it took 10 cycles of the repeated simple shear test (RSST at 12 pounds per square inch) for shoving to reach a permanent 0.01 shear strain; at 40°C (104°F) about 1000 cycles were required to reach the same strain level.

Chemical and physical reactions occur in asphalt over time due to oxidation, exposure to the sun's ultraviolet rays and heat. The brittleness associated with this ageing can be gauged from a pavement's viscosity (resistance to flow). Asphalt pavements in California were studied to see how brittle they became over time (Kemp and Predoehl, 1980). Climates with similar dry and sunny conditions but with different average air temperatures were chosen for the study. The viscosity of 4-year-old pavements was found to be about ten times higher at an average air temperature of 23°C (73°F) than it was at 17°C (63°F). It was also shown that pavements at higher air temperatures became brittle more quickly. This suggests that protecting asphalt from heat can reduce its brittleness and enhance its durability significantly.

Less is known about the effects of temperature on PCC durability. It is clear that concrete pavements last longer than asphalt pavements. A review of testing by various state and federal agencies found that concrete's service life spans 13–35 years, whereas asphalt pavements last 6–20 years (Packard, 1994), indicating that concrete can last one and a half to two times longer than asphalt in similar situations when it is properly constructed. It is also clear that concrete pavements stay cooler than asphalt pavements, since concretes have higher solar reflectance values. Another study of concrete pavements showed that this type of rigid pavement does not rut, shove or age in the same way that flexible asphalt pavements do, and so concrete pavements are relatively insensitive to changes in their solar reflectance (Ongel and Harvey, 2004). But it is not clear whether the lower temperature of a concrete pavement keeps it from fatigue cracking, or whether concrete pavements would last even longer if they were made from lighter-coloured and cooler materials.

Better night-time illumination and lower lighting energy use

Pavements with higher solar reflectance also reflect artificial light more efficiently at night. Researchers at Lawrence Berkeley National Laboratory have found that light reflected from a horizontal pavement helps to illuminate a vertical object (Pomerantz et al, 2000b). Pavements with a 10 per cent solar reflectance bounce an additional 10 per cent of the street illumination back to a sign or pedestrian; pavements with a 30 per cent solar reflectance bounce 30 per cent more of this light back. Higher levels of illumination can help make streets and parking lots safer with fewer accidents and less crime.

Another study found that money and energy can be saved when pavements with higher reflectance are used and lighting designs are modified accordingly (Stark, 1986). A major commercial road with an asphalt pavement was found to need 39 light fixtures per mile to meet recommended night-time lighting levels. The same road paved with a more reflective concrete pavement would need only 27 light fixtures per mile – 31 per cent fewer fixtures. The costs of initial construction, maintenance and energy are all expected to decrease, with projected monetary savings of $24,000 per mile on construction, $576 per mile per year on maintenance costs, and $600 per mile per year in energy bills.

Less road noise

Surprisingly, various researchers have found that the slightly rougher texture of porous road surfaces decreases tyre noise. The Australian Road Research Board found that traffic noise on open-graded ACC is 2–8 decibels quieter than on the dense-graded version (Glazier and Samuels, 1991). Tests of porous asphalt and cement concrete surfaces carried out in France found both surfaces kept roadside noise levels below 75 decibels (Hughes and Heritier, 1995; Pipien, 1995). Instead of increasing road noise, the crevices in these pavement surfaces absorb the noise of tyres rolling along the pavement.

Greater flexibility and beauty in urban design

As declared by Peter Olin in the introduction to the proceedings of the *Parked Art* parking lot conference (Minnesota Landscape Arboretum, 1993):

> *Though an integral part of our daily lives, parking lots (and streets) can have a troubling impact. All too often they are constructed as massive black-topped surfaces, devoid of life and style.*

Pavement options exist beyond the standard black asphalts and grey concretes. By introducing a variety of lighter colours, vegetation and porous pavements, colour and texture can be used to enhance urban and suburban areas.

Other cool paving considerations

Solar reflectance of cool paving

Many of the cool paving options catalogued depend on being able to use components with high solar reflectance. This calls for lighter-coloured ingredients, including aggregate, sand and binders. In some regions of the world, lighter-coloured components may already be in use and incur no extra cost. Fewer quarries supply light-coloured materials, so it is likely that these components will be more expensive or harder to find. One study estimates that white sand for use in a PCC mix costs twice as much as the more commonly used grey sand (Levinson and Akbari, 2001).

The cool paving options listed in this chapter leave the colour choice up to the consumer. At this time the paving industry is mostly unfamiliar with the concept of solar reflectance. Very few paving materials have had solar reflectance measurements made, and there are no common standards for collecting and validating any measurements that might have been made. In general, the lightest colours of each component or finish material should be chosen to get the highest solar reflectance and hence the coolest pavements.

Since cool paving is a relatively new phenomenon for the construction industry, it is not well recognized or understood by industry professionals. Cool or porous pavements are not currently listed or rated by any agencies. No standards or standard tests have been designated for solar reflectance, thermal emittance, porosity, drainage, water storage or any other characteristics pertinent to cool pavements.

Test methods for measuring the solar reflectance of roofing materials can certainly be applied to paving materials, and work is being done to evaluate the drainage properties of porous pavements. Until universal standards are adopted by the pavement industry or an influential agency, the evaluation of lighter-coloured or porous materials is left to the consumer.

Measurements of the temperature and solar reflectance of existing pavements can be made fairly easily. A portable infrared thermometer can measure pavement temperatures at various times of day and at various intervals after a rainstorm to determine the effects of moisture, sun and air temperature. Solar reflectance can be measured using a portable albedometer according to (ASTM, 1997). This method flips a solar energy sensor up and down to measure the incoming sunlight and the sunlight reflected from the surface. The solar reflectance is the ratio of these measured values:

$$\text{Solar reflectance, percentage} = (\text{sunlight reflected from a surface} / \text{incoming sunlight}) \times 100 \quad (6.1)$$

Initial costs of cool paving

Concrete pavements are naturally cooler than their asphalt counterparts, but concrete is generally about 33 per cent more expensive to install than asphalt (Packard, 1994). Concrete installation costs more for a couple of reasons. First, concrete materials tend to cost more than asphalt. Second, more care must go into laying concrete because it is more brittle and less forgiving than asphalt. The subsurface must be more carefully graded and prepared, and a layer of concrete tends to be much thicker than a layer of asphalt under similar conditions. In addition, unlike asphalt, which is ready for use as soon as it has cooled, concrete may need a couple of days to cure before it is ready to handle traffic loads.

The cost of using lighter-coloured aggregates to make cooler pavements is largely unknown and depends greatly on their availability in any particular region. Using lightening pigment in pavement generally adds to the overall cost. Some asphalt mixes and seal coats already include a pigment, such as carbon black, to darken pavements. Removing this pigment, or replacing it with a lightening pigment, may even reduce the cost.

Porous versions of asphalt and concrete may also cost less than impermeable versions. The basic construction methods are the same for porous and impermeable pavements, but fewer materials are needed to construct porous pavements. Porous block pavers generally do cost more to install than other pavements; however, as with all porous pavements, money can potentially be saved on the construction and maintenance of storm drain systems.

Resin-based pavements can also cost more than traditional pavements. If, however, aggregate materials can be taken from the construction site, the overall project cost may be reduced.

Life-cycle costs of cool paving

The life-cycle cost of any pavement depends on its initial installation cost plus the maintenance expense over the expected life of the pavement. The costs of removal and disposal must also be factored into life-cycle costs.

Numerous studies have confirmed that concrete pavements last much longer than asphalt pavements. Concrete is estimated to last between 13 and 35 years, versus a life of 6–20 years for asphalt. Concrete also has lower maintenance costs, with asphalt maintenance costing 13 times more than concrete maintenance. However, concrete pavements are more expensive to install, costing as much as 33 per cent more than asphalt pavements. Adding it all up, concrete pavements generally have equal or lower life-cycle costs than asphalt pavements (Packard, 1994). Yet the higher initial cost of concrete pavements still keeps them from being installed in many applications.

As reviewed earlier in this chapter, it appears that making asphalt pavements cooler can prolong their life. Reducing pavement temperatures reduces significantly the tendency of asphalt to rut, shove and become brittle. It is not clear how many years of pavement life can be bought by cooling asphalt. At a current expected life of 6–20 years, even one extra year of life can considerably reduce life-cycle costs and offset any extra expenses incurred making the pavement cool.

For cool pavements to be adopted widely, spending must shift to pavements with lower life-cycle costs. Both cool asphalt and concrete pavements are expected have life-cycle costs equal to or less than those of standard hot paving materials. Specifications that emphasize long-term maintenance and replacement costs as well as initial installation costs are likely to foster further development and implementation of cool pavements.

Concrete environmental considerations

The production of concrete pavements has two problems associated with it: high energy use and the generation of a lot of carbon dioxide. It is the cement used in concrete that is responsible for its high environmental price.

A typical mixture of PCC is composed of cement (12 per cent), sand (34 per cent), crushed stone (48 per cent) and water (6 per cent) (Wilson, 1993). Cement is the binder that holds the other ingredients together. In 2004, 2159 million tons of cement were produced worldwide. China alone produced about 44 per cent of this cement, followed by India at 6 per cent, the US at 5 per cent, and Japan at 3 per cent, and numerous other countries that each produced 2 per cent or less of the total cement. Each ton of cement uses an average of 5GJ of energy and generates 0.87 tons of carbon dioxide (Price and Worrell, 2006). To put this in context, cement production consumes 7.6 per cent of all industrial energy use and generates 22 per cent of all industrial carbon dioxide emissions (Price and Worrell, 2006).

Why does cement production use so much energy and generate so much carbon dioxide? The answer is in the chemical process of cement formation. To make cement, limestone is heated to high temperatures in a kiln, together with clay or sand. A chemical reaction during heating, called calcining, breaks the limestone down into lime and carbon dioxide. The lime then bonds with the clay or sand in a process called sintering and then cools and solidifies into 'clinker' pellets. The pellets are finally ground into cement powder for use in concrete mixes.

The calcining process itself is very energy intensive, although the amount of energy used varies greatly depending on the type of kiln used. A traditional wet kiln uses as much as 6.2–7.3GJ/ton of cement produced, while a state-of-the-art dry kiln using a preheater and pre-calciner can reduce energy use to only 3.2–3.5GJ/ton (Price and Worrell, 2006).

Burning fossil fuels to provide this energy generates a significant amount of pollution. Pollution in the form of nitrogen oxides, sulphur oxides, particulate matter and carbon monoxide is released during the combustion of fuel. 'Dirtier' fuels, such as coal, are responsible for greater emissions of nitrogen and sulphur oxides. Table 6.1 lists the pollutants released per tonne (or ton) of cement produced in the US. Emissions are also calculated for each tonne (or ton) of concrete production, assuming that concrete is composed of 12 per cent Portland cement by weight. Emissions from the production of asphalt pavement are given for comparison. The construction of PCC pavements produces far greater amounts of nitrogen oxides and sulphur dioxide than ACC pavements do, mainly due to the use of highly polluting fuels to power the energy-intensive cement making process.

Carbon in fuel is also converted into carbon dioxide during combustion. Carbon dioxide is a

Table 6.1 Emissions of criteria air pollutants from the US cement and asphalt manufacturing industries

Pollutant	Portland cement production		Portland cement concrete production[a]		Asphalt cement concrete production	
	kg/tonne	(lbs/ton)	kg/tonne	(lbs/ton)	kg/tonne	(lbs/ton)
Particulate matter, ⩽10μm	0.230	(0.470)	0.028	(0.056)	0.032	(0.066)
Nitrogen oxides	1.220	(2.450)	0.147	(0.294)	0.010	(0.021)
Sulphur dioxide	1.170	(2.350)	0.140	(0.280)	0.003	(0.006)
Carbon monoxide	0.390	(0.780)	0.047	(0.093)	0.065	(0.135)
Volatile organic compounds	0.070	(0.150)	0.009	(0.018)	0.008	(0.017)

Note: [a] Assuming that cement is 12 per cent by weight of the concrete mixture.

Source: EPA, 2000; Jacott et al, 2003.

greenhouse gas that contributes to global warming. The amount of carbon dioxide created depends on the type of fuel used. Fuels with a high carbon content, such as coal, release more carbon dioxide during combustion, while low-carbon fuels such as methane release less carbon dioxide yet provide more energy. In the US, where coal fuels over 60 per cent of cement production (Wilson, 1993) and wet kilns are still used for 27 per cent of production, the energy used for cement production is responsible for about half a ton of carbon dioxide for every ton of cement produced (Malin, 1999).

The chemical reactions in the calcining process also produce a lot of carbon dioxide. Another half ton of carbon dioxide is released during calcining for every ton of cement produced (Malin, 1999). When cement is mixed into concrete, some carbon dioxide is reabsorbed during the curing process. Under typical conditions, only about 10 per cent of the original calcining emissions are reabsorbed (Malin, 1999), but a research laboratory was able to increase this absorption to 80 per cent by increasing the levels of humidity and carbon dioxide around the concrete while it was curing (EBN, 1995).

There are many ways to reduce the environmental hazards of concrete production. First and foremost is to increase the energy efficiency of cement production. As stated before, switching to dry kilns that use preheaters and pre-calciners can reduce energy use and carbon dioxide release from fuels by about half.

The second way to improve cement production is to use better fuels. Fuels with lower carbon to fuel ratios, such as natural gas or methane, produce more energy with less carbon dioxide emissions. Using solid waste as a fuel is also attractive for cement production, since the high temperatures required in the process result in clean combustion with low emissions (Wilson, 1993). Wastes from tyres, motor oil, ink and other residues also have higher fuel contents than coal, and generate less carbon dioxide. Agricultural waste, such as peanut shells or rice straw, can also be used as fuel. The renewable nature of agricultural waste means that the carbon dioxide released when it is burned can be offset during the next season of growth and carbon storage.

Another way to make concrete more environmentally friendly is to use less cement. Various industrial by-products with cementitious properties, called pozzolans, can be used in place of cement (Malin, 1999). Like cement, these materials have the ability to react with water to harden and bind concrete aggregates together. Unlike cement, the production of these materials does not generate large amounts of carbon dioxide. Fly ash, a by-product of coal-powered plants and steel mills, and blast furnace slag, an iron and steel by-product, are the most common pozzolans used as substitutes for cement. As a bonus, fly ash and slag also tend to create a stronger and longer-lasting concrete than cement. If all the available pozzolans were used in this way, up to 50 per cent of the cement in concrete could be replaced, and another quarter ton of carbon dioxide emissions per ton of cement production could be avoided (Malin, 1999).

The concrete curing process can also be controlled to increase the amount of carbon dioxide reabsorbed into the concrete. Blowing moist air around the concrete helps it absorb more carbon dioxide and also helps the concrete to strengthen more quickly (EBN, 1995).

The cement and concrete industries are making fairly rapid improvements to their energy efficiency and environmental sustainability. The reasons behind this are mainly economic, since energy prices continue to increase and Portland cement is becoming harder to obtain (Malin, 1999). Consumer awareness and the demand for more sustainable concrete are also pushing the industry to make improvements. When specifying concrete pavements, always make sure to specify that your contractors follow more sustainable manufacturing practices as well.

Promoting cool paving research, development and implementation

The use of cool paving materials looks to be quite beneficial. Yet at this time very few cool pavements are being installed. Research and development of cool paving lags behind the progress made with cool roofing materials. There are steps we can take to encourage the implementation of cool paving.

Foremost, research and testing of cool pavements must continue, especially in the area of ACC pavements. The potentially longer life of cool asphalt pavements is extremely promising and should be confirmed with modelling, laboratory work and field tests. Asphalt pavements are the predominant pavements being used in the US, as well as being the hottest pavements, so more effort must go towards cooling them. Cooler asphalt mixtures must be developed and their benefits promoted to contractors, transportation departments and municipalities.

Standard PCC and other concrete products are already quite cool and are ready to be installed today. But the market share of concrete pavements lags far behind that of asphalt pavements. Numerous studies have confirmed that concrete pavements last much longer (13–35 years, versus 6–20 years for asphalt), have lower maintenance costs (13:1 for asphalt maintenance:concrete maintenance) and have equal or lower life-cycle costs than asphalt pavements (Packard, 1994). Yet the higher initial cost of concrete pavements – as much as 33 per cent higher than asphalt pavements – prevents them from being installed in many applications.

For cool pavements to be adopted widely, spending must shift to pavements with lower life-cycle costs. Both cool asphalt and cool concrete pavements are expected have life-cycle costs equal to or below those of standard hot paving materials. Specifications for pavement projects must emphasize long-term maintenance costs as well as initial installation costs.

Work must also be done to educate the pavement industry and its customers about heat islands and the benefits of cool paving. Black is still perceived to be beautiful when it comes to pavement. In fact, the standard specification for an asphalt emulsion seal coat still calls for it to be black in colour. The link between dark paving colours and unnecessarily hot pavements has not been consciously understood as a problem with a fairly simple solution. A good place to start the education process would be to propose that the pavement industry voluntarily adopt testing for solar reflectance, as has been done in the roofing industry.

There are also exciting new paving options – porous pavements, grass pavers and resin-based pavements – that are unfamiliar to most pavement customers. As well as being cooler, these pavements are a significant advancement from the current mainstream of paving technology. Their adoption can go a long way towards making our communities more sustainable and environmentally sensitive.

References

Asaeda, T. and V. T. Ca (2000) 'Characteristics of permeable pavement during hot summer weather and impact on the thermal environment'. *Building and Environment* **35**(4): 363–375

Asaeda, T., V. T. Ca and A. Wake (1996) 'Heat storage of pavement and its effect on the lower atmosphere'. *Atmospheric Environment* **30**(3): 413–427

ASTM (1997) *Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field*. West Conshohocken, PA, American Society for Testing of Materials

Cartwright, P. (1998) 'Blue diamond materials and excel paving provide colored asphalt for union station project'. *California Asphalt* November/December: 8–9

Chicago (2002) *Urban Heat Island Initiative: Alley Reconstruction*. Chicago, IL, City of Chicago**:** 1

Cote, M. P., J. Clausen, B. Morton, P. Stacey and S. Zaremba (2000) *Jordan Cove Urban Watershed National Monitoring Project*. Boston, MA, US Environmental Protection Agency, Office of Ecosystem Protection: 8

EBN (1995) 'Concrete as a CO_2 sink?' *Environmental Building News* **4**(5): 3

EPA (2000) *Hot Mix Asphalt Plants Emission Assessment Report*. Research Triangle Park, NC, US Environmental Protection Agency

Gartland, L. (2001) *Cool Roof Energy Savings Evaluation for City of Tucson Thomas O. Price Service Center Administration Building One*. Tucson, AZ, City of Tucson

Glazier, G. and S. Samuels (1991) 'Effects of road surface texture on traffic and vehicle noise'.

Transportation Research Record **1312** (Energy and Environmental Issues): 141–144

Harvey, J. T. and L. Popescu (2000) *Rutting of Caltrans Asphalt Concrete and Asphalt–Rubber Hot Mix under Different Wheels, Tires and Temperatures – Accelerated Pavement Testing Evaluation*. Berkeley, CA, Pavement Research Center, Institute of Transportation Studies, University of California

Hughes, J. and B. Héritier (1995) 'Tapiphone, a technique for reducing noise in towns'. *Revue Générale des Routes et Aérodromes* **735**: 37–40

Hurd, M. K. (1997) 'Ultra-thin whitetopping'. *Concrete Construction* February

Jacott, M., C. Reed, A. Taylor and M. Winfield (2003) *Energy Use in the Cement Industry in North America: Emissions, Waste Generation and Pollution Control, 1990–2001*. 2nd North American Symposium on Assessing the Environmental Effects of Trade, Mexico City, Commission for Environmental Cooperation

Kemp, G. R. and N. H. Predoehl (1980) *An Investigation of the Effectiveness of Asphalt Durability Tests – Final Report*, FHWA/CA/TL/-80/14, Office of Transportation Laboratory, California Department of Transportation, Sacramento, CA

Levinson, R. and H. Akbari (2001) *Effects of Composition and Exposure on the Solar Reflectance of Portland Cement Concrete*. Berkeley, CA, Lawrence Berkeley National Laboratory: 51

Maes, L. and A. Youngs (2002) *Pervious Concrete Parking Lot Offers Cost-Saving and Environmental Benefits to City of Cerritos*. Cerritos, CA, Southern California Ready Mixed Concrete Association, California Cement Promotion Council: 2

Malin, N. (1999) 'Checklist for making more climate-friendly concrete'. *Environmental Building News* **8**(6): 4–5

Minnesota Landscape Arboretum (1993) *Third Annual Parking Lot Conference. Parked Art, Beyond Asphalt and Plants, the Parking Lot as a Piece of Art!* Chaska, MN, Minnesota Landscape Arboretum, University of Minnesota, 19 March

Ongel, A. and J. T. Harvey (2004) *Analysis of 30 Years of Pavement Temperatures using the Enhanced Integrated Climate Model (EICM)*. Berkeley, CA, Pavement Research Center, Institute of Transportation Studies, University of California

Packard, R. G. (1994) 'Pavement costs and quality: A consumer's report'. *Concrete International* **16**(8)

Pipien, G. (1995) 'Pervious cement concrete wearing course offering less than 75 dB(A) noise level'. *Revue Générale des Routes et Aérodromes* **735**: 33–36

Pomerantz, M., H. Akbari and J. T. Harvey (2000a) *Cooler Reflective Pavements Give Benefits Beyond Energy Savings: Durability and Illumination*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Pomerantz, M., H. Akbari and J. T. Harvey (2000b) *Durability and Visibility Benefits of Cooler Reflective Pavements*. Berkeley, CA, Lawrence Berkeley National Laboratory: 23

Pomerantz, M., B. Pon, H. Akbari and S. C. Chang (2000c) *The Effect of Pavements' Temperatures on Air Temperatures in Large Cities*. Berkeley, CA, Lawrence Berkeley National Laboratory: 20

Price, L. and E. Worrell (2006) *Global Energy Use, CO_2 Emissions and the Potential for Reduction in the Cement Industry*. Cement Energy Efficiency Workshop, Paris, France, International Energy Agency

Smith, R. (1999) 'All's finally quiet at Sutter's mill'. *California Asphalt* January/February: 22

Stark, R. A. (1986) 'Road surface's reflectance influences lighting design'. *Lighting Design and Application* April

Ting, M., J. Koomey and M. Pomerantz (2001) *Preliminary Evaluation of the Lifecycle Costs and Market Barriers of Reflective Pavements*. Berkeley, CA, Lawrence Berkeley National Laboratory: 67

Wilson, A. (1993) 'Using concrete wisely: A checklist for builders and designers'. Environmental Building News **2**(2)

Youngs, A. (2005) 'Pervious concrete maintenance.' Available at www.cncpc.org, California Nevada Cement Promotion Council

7

Cooling with Trees and Vegetation

Introduction

Trees and vegetation are vital, working components of a healthy city or suburb. Healthy trees and vegetation bring numerous benefits, including more comfortable communities, lower energy use, reduced air pollution, decreased stormwater run-off and an improved ecosystem, all while increasing property values. Although often viewed as an added expense, trees actually produce net monetary benefits over their lifetime.

Trees and vegetation reduce heat islands in two ways. First, they shade buildings, pavement and people from the sun. This keeps surfaces cooler, reducing the amount of heat transferred to the air above them and reducing the energy use of buildings below. Shade from trees also keeps people cooler and more comfortable, reduces their risk of heat stroke and protects them from the sun's ultraviolet rays

Second, during the process of photosynthesis, trees and vegetation use a process called evapotranspiration to keep themselves cool. Plants use the sun's energy to evaporate water, preventing that energy from heating up the city. Air temperatures are cooler within and downwind of well-vegetated areas due to evapotranspiration.

Trees and vegetation can also be positioned to shield buildings and spaces from the wind. This effect is most beneficial during the winter. Slower wind speeds around buildings reduce heat loss through the walls and roof, and decrease the amount of cold air that infiltrates through cracks around windows, doors and joints. Slower winds also make public spaces more comfortable in cold weather.

Effective landscaping to reduce the heat island includes the use of shade trees and smaller plants such as bushes, shrubs, vines, grasses and groundcovers. This chapter presents various ways plants can be used to reduce heat islands, lists the benefits of trees and vegetation, and looks at the costs and other considerations of landscaping urban areas.

Also included in this chapter is a review of green or garden roofing. Green roofing is an effective way to both cool a roof and introduce vegetation into urban areas. Information is presented about green roof technology, benefits, considerations and policies.

Benefits and costs of trees and vegetation

Trees and vegetation bring many positive benefits to communities, including improving comfort, reducing energy use, removing carbon dioxide (CO_2) from the air, decreasing air pollution and decreasing stormwater run-off. Information on these benefits is compiled below.

Reduced heat islands and more comfortable communities

Trees and vegetation moderate heat islands and improve community comfort in three ways: through shading, evapotranspiration and wind shielding (Huang et al, 1990).

Leaves and branches on trees and vegetation shade the areas below them by reducing the amount of solar radiation that is transmitted through their canopy. The amount of radiation transmitted varies with the type of tree but generally ranges between 6 and 30 per cent in the summer and 10 and 80 per cent in the winter (Huang et al, 1990).

The shade from trees has been found to lower the temperatures of the surfaces below them. Table 7.1 lists various experiments in which trees and vegetation were planted around buildings. Shaded walls were found to have peak temperatures 5–20°C (9–36°F) cooler than unshaded walls (Meier, 1990). The cooler a surface is, the less heat it will transmit to the air surrounding it, reducing the heat island effect.

Another study found that temperatures inside parked cars were reduced by about 25°C (45°F) when the car is shaded by trees (Scott et al, 1999).

Trees and vegetation absorb water through their roots and emit it as vapour through their leaves. This process, called evapotranspiration, removes heat from the air to evaporate the water. A large, well-watered tree can process up to 400 litres of water and remove 960MJ (910kBTU) of heat a day during the summer. Evapotranspiration alone can bring about reductions in peak summer air temperatures. Various studies (Huang et al, 1990; Kurn et al, 1994) have found that:

- Peak temperatures in tree groves were 5°C (9°F) cooler than those above open terrain.
- Air above irrigated agricultural fields was 3°C (6°F) cooler than air above bare ground.
- Suburban areas with mature trees were 2–3°C (4–6°F) cooler than new suburbs without trees.
- Temperatures above grass sports fields were 1–2°C (2–4°F) cooler than air above parking lots.

As the process of evapotranspiration cools the air, it also adds moisture and raises the air's humidity. In dry and desert climates, higher humidity may be welcome, but in moister climates more humidity may not be beneficial. Very little work has been done to date to evaluate the trade-off between temperature reduction and humidity increase due to evapotranspiration. When trees and vegetation are used prudently to shade buildings and pavement, it can be assumed that the benefits of lower temperatures outweigh any negative effects of higher humidity.

Measurements have found that trees reduce wind speeds by 20–80 per cent, depending on the density of the canopy (Huang et al, 1990). Tree shielding is most useful when blocking cold

Table 7.1 Measured peak-period effects of vegetation planted within a yard of the west wall of a building

Researcher	Location	Plant type	West wall temperature reduction	Peak cooling energy savings (W/m^2) or heat gain reduction (W)
Halvorson	Pullman, WA	Vine	20ºC (36ºF)	Not measured
Hoyano	Tokyo	Vine	18ºC (32ºF)	175W/m^2 75%
Hoyano	Tokyo	Evergreen trees	5–20ºC (9–36ºF)	60W/m^2 50%
Makzoumi	Baghdad	Vine	17ºC (31ºF)	Not measured
McPherson	Tucson	Shrubs	17ºC (31ºF)	104W 27%
McPherson	Tucson	Turf	6ºC (11ºF)	100W 25%
Parker	Miami	Shrubs and trees	16ºC (29ºF)	5000W 58%

Source: Meier, 1990.

north winds in the winter, but is less advantageous if cool summer breezes are obstructed. Slower wind speeds mean less heat is convected away from buildings and less air infiltrates windows, doors and walls.

Energy savings in buildings

Many studies have investigated the effects of trees and vegetation on the energy use of buildings. In addition to the studies listed in Table 7.1 (Meier, 1990), more recent studies have measured or modelled the effects of trees on building energy use.

A joint study by Lawrence Berkeley National Laboratory (LBNL) and the Sacramento Municipal Utility District (SMUD) placed varying numbers of trees in containers around houses to shade windows, and then measured the energy use of the houses (Akbari et al, 1992, 1993). The results are summarized in Table 7.2. Cooling energy savings ranged between 7 and 40 per cent and was greatest when trees were planted to the west and southwest of buildings.

Another study investigated the energy savings resulting from SMUD's residential tree planting program. Researchers studied a sample of 254 program participants in the Sacramento area, then modelled the effect of new shade trees planted around houses (Simpson and McPherson, 1998). An average of 3.1 new trees were planted within 10 feet of each house. Annual cooling energy savings were 153kWh (0.52MBtu, or 7.1 per cent) per tree, peak demand reduction was 0.08kW (273Btu per hour, or 2.3 per cent) per tree and the annual heating energy use decreased by 230kWh (0.79MBtu) or 1.9 per cent per tree. Note that the net wintertime effect of trees is to decrease heating energy use, since the positive wind shielding effect outweighs the negative effect of added shade.

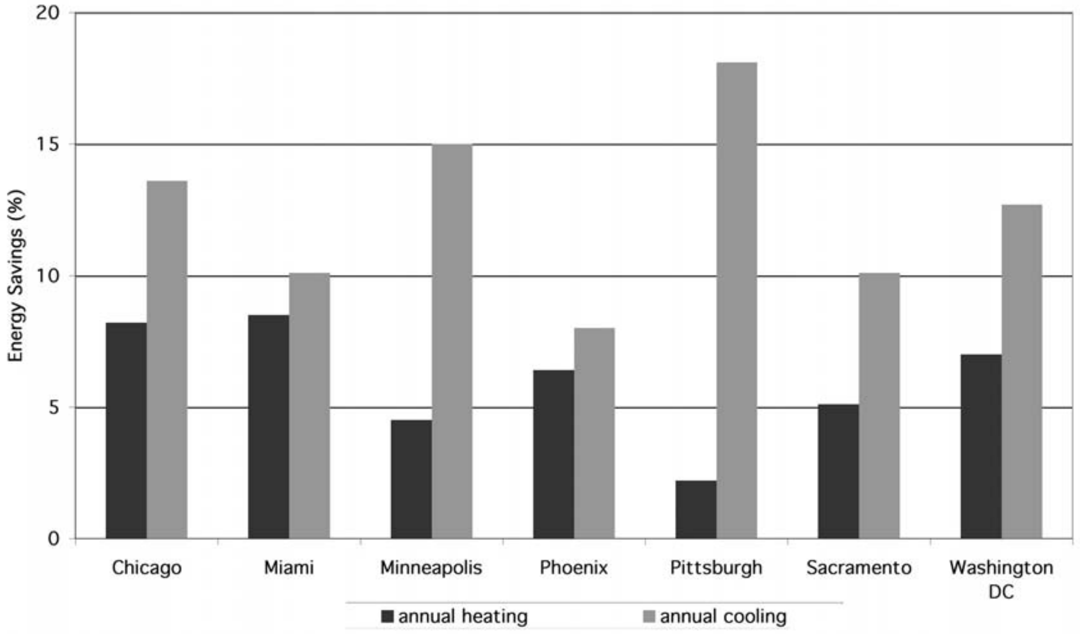
Yet another Sacramento area study evaluated how much energy was being saved by existing trees in Sacramento County (Simpson, 1998). This study modelled the effects of shading and wind speed reduction on both residential and commercial buildings. An average of seven trees were planted within 10 feet of each building. These trees saved a total of 157GWh annually (11 per cent of the total air conditioning energy), decreased peak electricity demand by 124MW (6 per cent of air conditioning demand) and reduce heating energy use by 40GWh (137GBtu) annually (0.7 per cent of heating energy).

A study by Lawrence Berkeley National Laboratory modelled the effects of trees on homes in various cities throughout the US. Assuming that one tree is planted to the west and another to the south of the house, the results were annual cooling savings of 8–18 per cent and annual heating savings of 2–8 per cent, as shown in Figure 7.1.

Table 7.2 Energy savings from trees around six buildings in the Sacramento area

Tree locations around buildings	Cooling energy savings	Peak demand reduction
Two 8ft (2.5m) trees, east	7%	Not measured
Two 8ft (2.5m) trees, west; one 8ft (2.5m) tree, south	40%	Not measured
Two 8ft (2.5m) trees, southwest	32%	Not measured
One 20ft (6m) tree, southwest; five 8ft (2.5m) trees, south	12%	Not measured
Eight 20ft (6m) trees and eight 8ft (2.5m) trees, southwest	29%	22%
Eight 20ft (6m) trees and eight 8ft (2.5m) trees, southeast, south and southwest	29%	23%

Source: Akbari et al, 1992, 1993.



Source: Huang et al, 1990

Figure 7.1 Predicted energy savings in typical homes in seven US cities due to tree shading and wind shielding effects, assuming one tree is planted to the south and one to the west

Carbon dioxide reduction

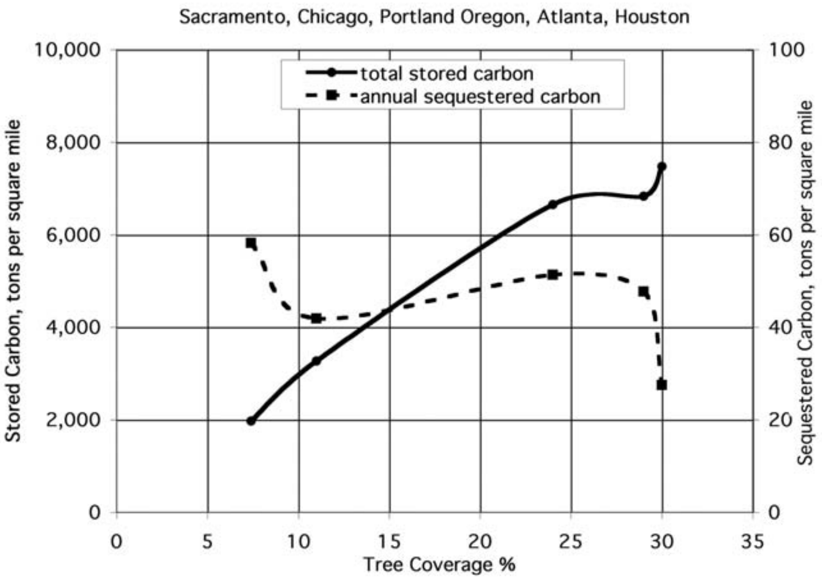
Plants absorb CO_2 from the atmosphere during the process of photosynthesis, storing carbon for growth and emitting oxygen back to the atmosphere. Due to oxygen production alone, trees and vegetation are a vital part of our ecosystem. According to the American Forestry Association, an average sized tree releases enough oxygen for a family of four, and an acre of trees can produce enough oxygen for eighteen people.

The removal of atmospheric CO_2 is also an important function of trees and vegetation. CO_2 is a 'greenhouse gas' thought to contribute to global climate change. Trees and vegetation annually remove or sequester significant amounts of CO_2 from the air, storing its carbon and releasing its oxygen. Rates of sequestration range from 35lb (16kg) of CO_2 per year for smaller, slower-growing tree species to 800lb (360kg) per year for larger trees growing at their maximum rate (McPherson and Simpson, 1999a).[1]

The total amount of carbon stored in mature trees can be 1000 times more than the carbon stored in small, young trees. Figure 7.2 plots carbon storage and sequestration per square mile versus the percentage of tree coverage in five metropolitan areas. The fairly straight solid line of Figure 7.2 shows that larger forests with more trees per square mile tend to store more carbon. The tree mix and growth rate in each metro area varies, so the dashed line of Figure 7.2 does not show a clear relationship between tree coverage and carbon sequestration.

In addition to sequestering carbon, trees have other influences on CO_2. Table 7.3 lists a complete accounting of the CO_2 budget for trees in Sacramento County, California. The shading and wind shielding effects of trees reduce the energy use of buildings, and this in turn reduces CO_2 emissions from power plants. Trees also emit CO_2 when they die, and their stored carbon is released back into the atmosphere during decomposition or burning.

Figure 7.3 shows how effective trees around buildings are at reducing CO_2 production.



Source: McPherson et al, 1994; McPherson, 1998a; American Forests 2000, 2001a, 2001b, 2002b.

Figure 7.2 Total stored carbon and annual carbon sequestration in metric tons per square mile as a function of tree coverage percentage in five US metropolitan areas

Planting trees around buildings has three effects, which are summed to find their net annual energy use and CO_2 reduction:

1. Trees shade windows and walls from the sun, which tends to reduce cooling energy use during the summer but increases wintertime heating energy use.
2. Trees block winds, which tends to reduce wintertime heating use and potentially increases summertime cooling needs.
3. Trees reduce air temperatures around buildings, which is most beneficial during the summertime.

Figure 7.3 shows how the net reductions vary, depending on climate and the location of the tree relative to the building. Five US climate

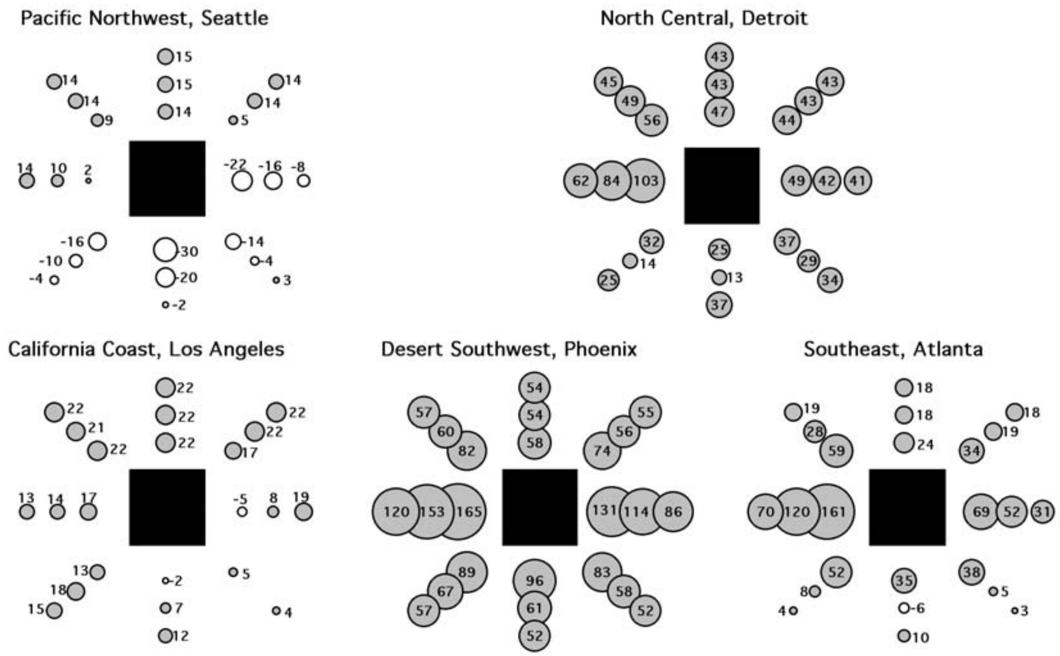
Table 7.3 Breakdown of the effects of trees on annual atmospheric CO_2 levels in Sacramento County, CA

Number of trees	6,000,000
Tree coverage	7%
Annual CO_2 sequestration	238,000 tons[a]
Annual CO_2 avoided emissions due to electricity use reductions[b]	75,600 tons
Annual CO_2 emissions due to tree mortality	–9400 tons
Net annual CO_2 removal	*304,200 tons*
Annual regional CO_2 emissions from transportation, energy use, etc.	17,000,000 tons
Offset of regional CO_2 emissions	1.8%

Note: [a] in metric tons.

[b] Avoided emissions for Sacramento County tend to be lower than for other regions because the local Sacramento Municipal Utility District generates much of its power from hydroelectric sources.

Source: McPherson, 1998a.



Source: Simpson and McPherson, 2001.

Figure 7.3 Net reduction in CO_2 production (kg per tree) in five climate regions when a medium-sized, 40-foot-high, deciduous tree is planted in various positions around a residence built after 1980

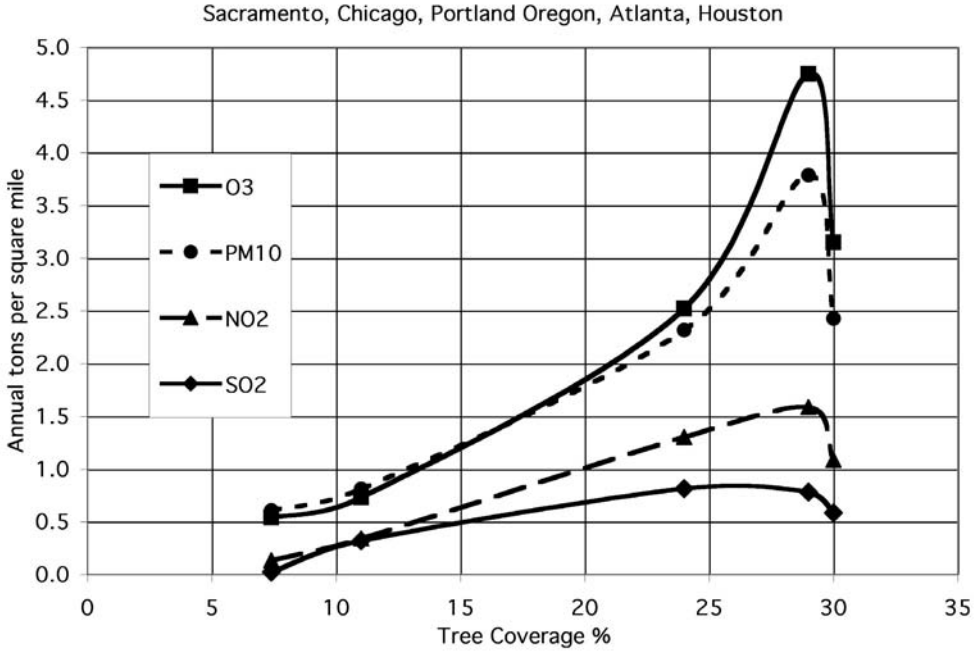
regions were studied, with trees theoretically planted in each of 24 different locations around a house. The effect of trees is most pronounced in the Desert Southwest and least pronounced in the Pacific Northwest. Net reductions are greatest for trees planted to the west and east of a building, where they block the sun at its lowest angle in the morning and evening hours. Trees to the south are most effective when planted close to a building, where they will block summer sun but allow winter sun below their crown. Trees planted to the north have negligible effects during the summer, but tend to block cold winter winds.

Reduced air pollution

Trees remove pollutants from the air by absorbing gases or collecting particles via their leaves. This type of pollutant removal is called dry deposition, since it takes place without the aid of precipitation. Dry deposition can remove the following pollutants from the air:

- Nitrogen oxides (NOx or NO_2) – emitted as by-products of combustion from cars and power plants, for example
- Sulphur oxides (SOx or SO_2) – produced when burning fuels containing sulphur, such as coal or oil, mostly from power plants or other large fuel burners
- Particulate matter (PM10, or particles less than 10μm in diameter) – from processes that release dust into the air such as farming, demolition or combustion
- Ozone (O_3) – formed in the air through photochemical and heat-sensitive reactions of oxygen with volatile organic compounds and nitrogen oxides.

Figure 7.4 plots values of pollutant removal per square mile versus the percentage of tree coverage in five US metropolitan areas. Areas with



Source: McPherson et al, 1994; Scott et al, 1998; American Forests, 2000, 2001a, 2001b, 2002b.

Figure 7.4 Annual pollutant reduction in metric tons per square mile due to deposition on trees in five US metropolitan areas as a function of tree coverage

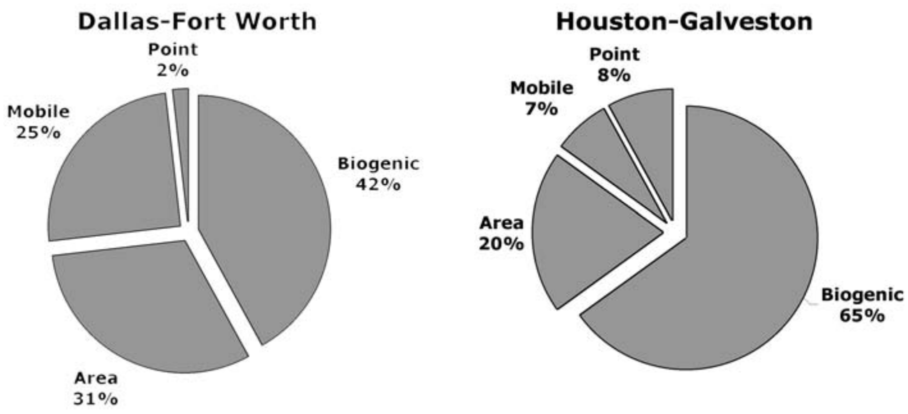
more large trees have higher rates of pollutant removal. As expected, pollution removal does tend to increase with higher tree coverage percentages, and areas with greater numbers of larger trees usually have even higher rates of pollutant removal.

One other documented effect of trees is to reduce emissions from parked cars. By cooling streets and parking areas, fewer hydrocarbons evaporate from the gas tanks of cars while parked, as well as when the engine is started. Evaporative emissions throughout Sacramento County could be reduced by 0.75 metric tons per day, and start emissions by 0.09 metric tons per day, if the tree canopy in parking lots were increased from 10 to 50 per cent (Scott et al, 1999).

Trees and plants usually emit a sizable portion of any area's various volatile organic compound (VOC) emissions. Figure 7.5 shows that biogenic emissions from trees and vegetation represent 42 per cent of the total VOCs emitted in the Dallas-Fort Worth area and 65 per cent of the total in the Houston-Galveston area (Neece, 1998).

VOC emissions from trees contribute to ozone formation not just because of the amount of their emissions but also because of the type of emissions and the timing of their release. The most reactive VOCs from plants are isoprene and monoterpene (Carman et al, 1999). Odourless isoprene is emitted from oaks and other species during the day, with peak emissions in the afternoon. Monoterpene, which gives plants in the pine family their distinctive smell, is emitted continuously at low levels, day and night.

An index called the ozone-forming potential (OFP) is used to rate the effect a tree species can have on ozone formation, depending on the environmental levels of sunlight, temperature and humidity. The emission rates and OFP of different species of trees vary tremendously. Even trees in the same family and genus show wide variations in VOC emissions (Benjamin et al, 1996; Benjamin and Winer, 1998). Table 7.4 lists a selection of oaks, pines and citruses, from a



Note: Point sources of pollution include stationary objects like smokestacks; mobile sources include cars and other transportation equipment; area sources include vegetative emissions or dust from construction or agriculture.

Source: Neece, 1998.

Figure 7.5 VOC emission sources in the Dallas–Fort Worth and Houston–Galveston areas

much more complete list of trees and shrubs (Benjamin and Winer, 1998), to show how their emissions and OFP vary in Los Angeles.

When planting trees, it is important to choose a species from the low OFP category, or choose a species within a genus with a lower OFP, if at all possible. By choosing trees wisely, their benefits can outweigh their detriments.

Decreased stormwater run-off

During a rainstorm, the soil can soak up only so much water. If the rain falls too fast or if the ground becomes saturated, the remaining rainfall becomes run-off. Run-off problems are exacerbated by the large amounts of impervious surfaces in our communities. The remaining exposed soil must also absorb the rain falling on the adjacent paved parking lots, streets and driveways.

Run-off becomes a problem when drains cannot handle the flow or when flash flooding occurs, causing streets, parking lots and other paved areas to flood. Some cities have older water management systems where the drains are combined with the sewers. When these systems overflow, sewage can back up into the street. Run-off also picks up oil and other pollutants from pavements and transports them through drains to the local waterways.

Trees and vegetation help reduce the run-off problem by catching rainfall on their leaves, branches and trunks. This reduces the amount and rate of water hitting the ground, and ultimately reduces the volume of water that becomes run-off. This interception works best during the smaller rainstorms that account for most precipitation. During the summer, with trees in full leaf, evergreens and conifers in Sacramento were found to intercept up to 36 per cent of the rainfall that hit them (Xiao et al, 1998).

Figure 7.6 shows the estimated stormwater retention due to urban forest in four US metropolitan areas. These estimates were all made using CITYgreen software's stormwater event model (American Forests, 2002a). Results depend on storm patterns as well as the amount and type of tree coverage.

Miscellaneous other benefits

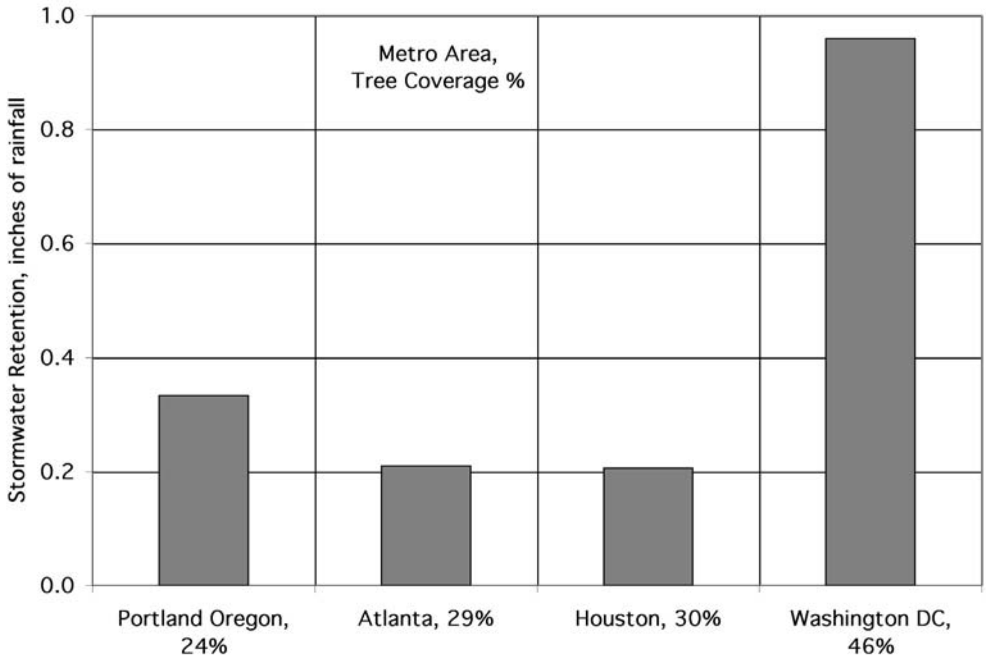
Trees and vegetation bring numerous other benefits to a community, including those listed below:

Table 7.4 Examples of tree emissions and their ozone-forming potentials in the Los Angeles climate

Common name	Genus and species	Emissions (µg/g dry leaf weight per day) Isoprene	Emissions (µg/g dry leaf weight per day) Monoterpene	Biomass (kg of leaf per tree)	Ozone-forming potential Low	Ozone-forming potential Medium	Ozone-forming potential High
Oaks							
White oak	*Quercus alba*	59.7	13.5	7.7		X	
Blue oak	*Quercus douglasii*	66.6	0	7.7		X	
California Scrub oak	*Quercus dumosa*	228.1	0	2.4			X
Oregon White oak	*Quercus garryana*	453.0	5.4	7.7			X
Bluejack oak	*Quercus incana*	349.0	1.8	7.7			X
Scrub oak	*Quercus laevis*	186.0	7.2	2.4			X
Valley oak	*Quercus lobata*	26.0	0	7.7		X	
Myrtle oak	*Quercus myrtifolia*	116.3	1.8	7.7		X	
Water oak	*Quercus nigra*	188.3	0	7.7			X
Willow oak	*Quercus phellos*	246.4	0	7.7			X
Chestnut oak	*Quercus prinus*	49.7	13.5	7.7		X	
Black oak	*Quercus velutina*	144.6	9.0	7.7			X
Virginia Live oak	*Quercus virginiana*	154.6	2.7	7.7			X
Pines							
Sand pine	*Pinus clausa*	0	103.8	29.6			X
Red pine	*Pinus densiflora*	0	1.8	29.6	X		
Slash pine	*Pinus ellotii*	0	47.9	29.6		X	
Aleppo pine	*Pinus halepensis*	0	2.7	29.6	X		
Longleaf pine	*Pinus palustris*	0	53.3	29.6		X	
Italian Stone pine	*Pinus pinea*	0	1.8	29.6	X		
Monterey pine	*Pinus radiata*	0	7.2	14.4	X		
Foothill pine	*Pinus sabiniana*	0	5.4	29.6	X		
Scots pine	*Pinus sylvestris*	0	57.8	29.6		X	
Loblolly pine	*Pinus taeda*	0	46.0	29.6		X	
Citruses							
Lisbon lemon	*Citrus limon*	0	28.9	16.7		X	
Meyer lemon	*Citrus limon* 'Meyer'	0	13.5	16.7	X		
Navel orange	*Citrus sinensis*	0	16.3	16.7		X	
Valencia orange	*Citrus sinensis* 'Valencia'	0	16.3	16.7	X		

Source: Benjamin and Winer, 1998.

- *Noise reduction.* Various studies have found that trees reduce urban noise by as much as 15 decibels, about as well as a typical masonry sound barrier (Nowak and Dwyer, 2000). Noise reduction is an especially useful benefit for urban areas.
- *Ecosystem improvement.* Adding trees and vegetation to urban areas gives birds, animals and insects a home. The quality of this home is even better if a selection of native plant species is reintroduced to the urban landscape.
- *Protection from ultraviolet light.* Skin cancer has become epidemic in our population due in part to the cumulative effects of everyday, involuntary exposure to the sun's ultraviolet



Note: 1 inch = 25mm.

Source: American Forests, 2000, 2001a, 2001b, 2002b.

Figure 7.6 Stormwater retention for urban forests in four US metropolitan areas

rays. With the thinning of the Earth's ozone layer, ultraviolet exposure is becoming even more problematic (Weatherhead, 2000). Trees and other vegetation that shade playgrounds, school yards, sports fields, picnic areas and other places where people, and especially children, congregate, can reduce exposure to ultraviolet light by about half (Grant et al, 2002).

- *Reduced pavement maintenance.* Asphalt pavements protected by extensive tree canopy have been found to last longer. In Modesto, California, it was found that well-shaded asphalt streets needed to be resealed every 20–25 years, compared to every 10 years for unshaded streets (McPherson et al, 1999b).
- *Aesthetic improvements.* Numerous studies show that property values are higher on tree-lined streets (Wolf, 1998d; Thompson et al, 1999). Shopping centres with landscaping are more prosperous than those without, since shoppers linger longer and are willing to spend more (Wolf, 1998a, 1998b, 1998c). Community gardens and neighbourhood parks are popular features in most metropolitan areas and help to reduce physiological stress, improve well-being, reduce domestic conflict and decrease school aggression (Wolf, 1998e).

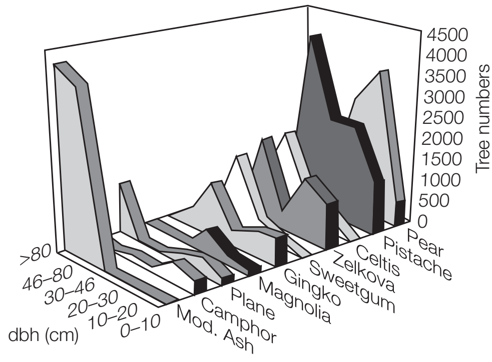
Cost–benefit analysis of trees

The planting and maintenance of trees and vegetation costs money, and increasingly communities are being asked to justify these expenditures. Procedures and tools have been developed to help quantify and weigh the costs and benefits of trees in communities. Monetary values can be found for the following:

- costs of trees – planting, pruning, tree stump removal, pest and disease control, irrigation and miscellaneous other costs including repairing root damage, lawsuits and liability, and tree program administration

- benefits of trees – building energy savings, CO_2 reduction, air quality improvements, stormwater retention, property value increases and the value of mulch or hardwood recovered during tree pruning and removal.

The majority of a tree's costs arise during planting, pruning and maintenance in the first years of its life. Trees grow slowly, so it may take as long as 5 years for a tree's benefits to take effect. After 15 years, an average tree has matured and can make a significant difference to its environment (McPherson, 2002). Mature trees are true workhorses, and are worth more in terms of energy savings, pollution reduction and stormwater retention than newly planted trees.



Source: McPherson, 2003.

Figure 7.7 Size distribution of ten different species of street trees in Modesto, California, in terms of diameter at breast height (dbh)

Table 7.5 Costs and benefits of nine different species of street trees in Modesto, California, in annual US dollars per tree

COSTS (US$)	Prune	Remove	Plant	Root-related	Storm/ liability	IPM/ other	Total
Pear	18.55	1.27	0.20	0.53	0.26	0.12	20.94
Pistache	25.06	1.54	0.39	0.44	0.19	0.16	27.78
Camphor	8.34	1.78	1.05	0.14	–	0.09	11.40
Southern magnolia	17.38	1.13	0.03	0.95	0.70	0.19	20.38
Sweetgum	49.70	0.90	0.03	2.14	0.62	0.92	54.31
Ginkgo	6.56	3.42	2.18	0.75	0.24	0.14	13.28
Zelkova	16.01	2.60	0.78	1.09	0.42	0.24	21.14
Modesto ash	45.22	0.83	0.01	1.43	0.37	0.93	48.80
Plane	6.14	0.59	0.51	0.27	0.02	0.13	7.66

BENEFITS (US$)	Energy	Air quality	CO_2	Stormwater	Aesthetics	Total	Net benefit
Pear	34.00	2.98	1.95	1.47	14.19	54.59	33.65
Pistache	65.31	10.27	2.82	3.34	11.03	92.76	64.98
Camphor	54.29	7.62	2.85	6.71	11.29	82.75	71.36
Southern magnolia	79.44	2.42	2.81	2.79	6.15	93.61	73.23
Sweetgum	79.88	10.16	6.29	5.24	31.38	132.95	78.64
Ginkgo	51.51	2.79	5.43	3.27	35.18	98.18	84.90
Zelkova	89.25	8.26	4.69	3.37	18.47	124.05	102.91
Modesto ash	97.83	52.61	7.67	11.19	5.67	174.96	126.16
Plane	136.76	25.76	4.80	7.59	11.33	186.24	178.57

Note: IPM, integrated pest management.

Source: McPherson, 2003.

Table 7.6 Average annual costs and benefits of urban trees over a 40-year lifespan in three regions of California

	Annual benefits (per tree) (US$)	Annual costs (per tree) (US$)	Annual net value[a] (per tree) (US$)
San Joaquin Valley			
Small tree	$9–$12	$4 – $9	$1–$8
Medium tree	$37–$44	$7 – $15	$26–$37
Large tree	$63–$73	$11–$21	$48–$63
Inland Empire (east of LA)			
Small tree	$15–$22	$ 8–$17	–$2 to $14
Medium tree	$60–$75	$18–$27	$33–$57
Large tree	$97–$109	$24–$31	$66–$85
Southern California			
Small tree	$17–$22	$13–$21	$1–$7
Medium tree	$42–$48	$16–$23	$25–$28
Large tree	$78–$93	$17–$28	$60–$68

Note: [a] The range of net values cannot necessarily be added up from the benefits and costs, since these values represent four sets of trees, those to the east, south and west of buildings plus public trees.

Source: McPherson et al, 1999b, 2000, 2001.

Costs and benefits of trees also vary from species to species. The distribution of ten different species of street trees in Modesto, California, is shown in Figure 7.7 and a comparison of the costs and benefits of these trees is shown in Table 7.5 (McPherson, 2003).

The greatest cost for all of Modesto's trees was associated with pruning, and larger trees tended to have higher pruning expenditures. The plane tree was an exception, perhaps because most of these very large trees had reached maturity and were growing very slowly. The greatest benefit of trees was their ability to reduce the energy expenditures of nearby buildings. This depended on the size of the tree as well as its location. For instance, many magnolias shaded commercial buildings that used a lot of air conditioning, so they had greater energy impacts. All nine of the Modesto tree species studied yielded more benefits than costs. The largest and most mature trees generally yielded the highest net benefits.

In other regions of California, the net monetary benefits of most trees have also been found to outweigh their costs. Table 7.6 lists the estimated costs and benefits for urban trees in the San Joaquin Valley, Inland Empire and Southern California regions. A handful of smaller, younger trees had yet to show net benefits, but they are expected to more than pay for themselves as they grow.

The lifetime costs and benefits of trees have been evaluated for many other communities, and a reference list of studies is given in Table 7.7 overleaf. Also see the description of tools for evaluating urban forest costs and benefits included below.

There are various tools available for calculating the costs and benefits of trees in communities. First, the report 'A practical approach to assessing structure, function and value of street tree populations in small communities' (Maco and McPherson, 2003) is useful background reading for understanding the steps required for estimating costs and benefits of trees in your own community.

A collection of USDA Forest Service urban forestry tools can be found at http://www.itreetools.org, including the STRATUM program (USDA Forest Service, 2002) for tree cost–benefit analysis.

Another tool, the Community and Urban Forest Inventory and Management Program (Pillsbury and Gill, 2003), produced by the

Table 7.7 Cost–benefit studies of urban trees in various communities

Study	Communities
Akbari, 1997	Atlanta, Chicago, Dallas, Houston, Los Angeles, Miami, New York, Philadelphia, Phoenix and Washington DC
McPherson, 1998b	Sacramento, CA
McPherson et al, 1999b	San Joaquin Valley, CA
McPherson et al, 1999a	Modesto, CA
McPherson et al, 2000	Coastal Southern California
McPherson et al, 2001	Inland Empire, CA
McPherson et al, 2002	Western Oregon and Washington
Maco and McPherson, 2003	Davis, CA

Urban Forest Ecosystems Institute of California Polytechnic State University, helps to inventory urban forests and estimate an economic value of wood recovery. Program documentation is available at http://www.ufei.org/files/ufeipubs/CUFIM_Report.pdf and program files are available at http://www.ufei.org/files/ufeipubs/CUFIM.zip.

CITYgreen, from American Forests, is a geographical information system (GIS)-based program for calculating benefits from urban trees, including energy savings, air quality, stormwater improvements, carbon storage and the growth of forests (American Forests, 2002a). For more information go to http://www.americanforests.org/productsandpubs/citygreen/.

Effective landscaping for cooling

Presented below are the most effective places to add landscaping: around buildings, along streets, in parking lots and in areas where people congregate. Advice is then given about how to select, plant and maintain trees and other types of vegetation.

Landscaping around buildings

The relative benefits of planting deciduous trees around buildings were shown in Figure 7.3 for five US climate regions. The reduction in CO_2 emissions results from the net effects of trees on a building's annual heating and cooling energy use. The largest CO_2 reductions, i.e. the greatest energy benefits, tend to occur when trees are planted to the west and east of buildings. Trees in these locations block the sun in the morning and afternoon when the sun is at its lowest angle. Trees to the north tend to save energy by blocking cold winter winds. Trees to the south tend to be least beneficial. Shade from trees to the south tends to be very shallow since the sun is directly overhead during the middle of the day. Trees to the south also tend to block useful sun during the winter.

Guidelines for planting trees around houses and office buildings are shown in Figures 7.8 and 7.9.

Ideally, trees planted for summer shade should shelter western and eastern windows and walls, but be tall enough not to block views or breezes. Trees should be at least 1.5–3.0 metres (5–10 feet) away from the building making sure to allow enough room for growth of the limbs above ground and the roofs below, but less than 10–15 metres (30–50 feet) away. Before planting, make sure the building's insurance policy allows vegetation close to the building. Some policies will not cover damage from excessive root growth or from fire, if the fire was exacerbated by vegetation close to the building. For the best shade, plant shorter trees closer to buildings, and taller trees further away.

It also helps to shade air conditioner condenser units or other building cooling equip-

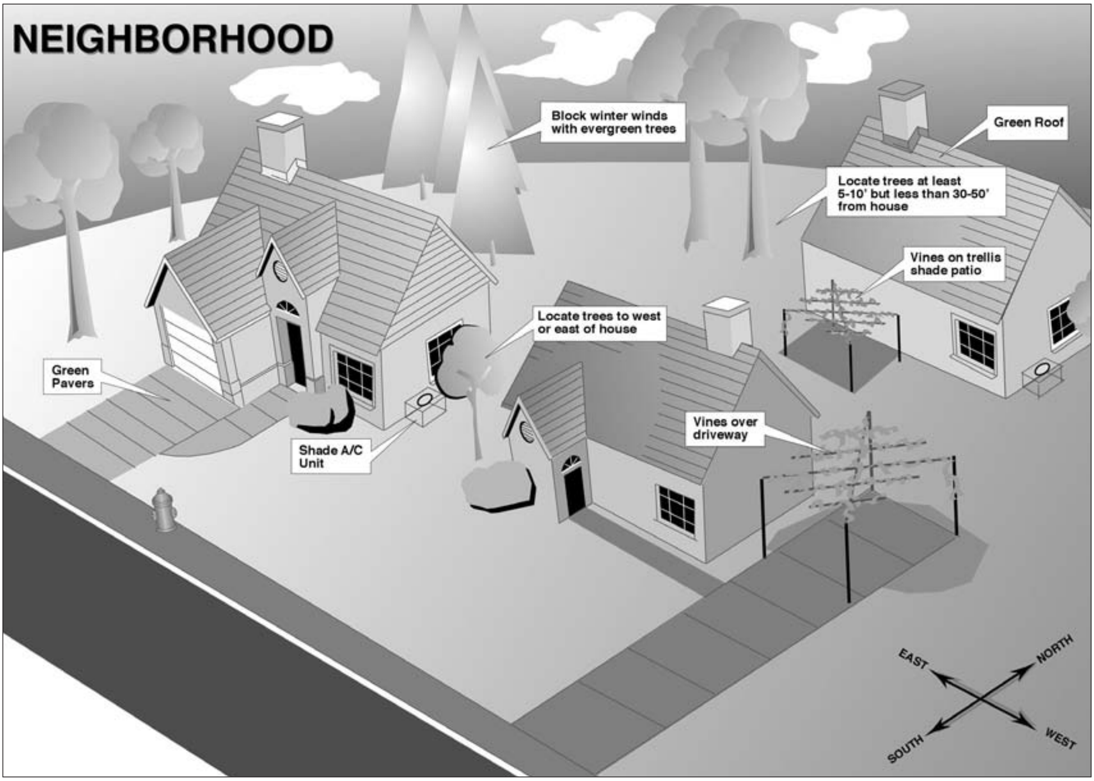


Figure 7.8 Effective landscaping to reduce heat islands in residential neighbourhoods

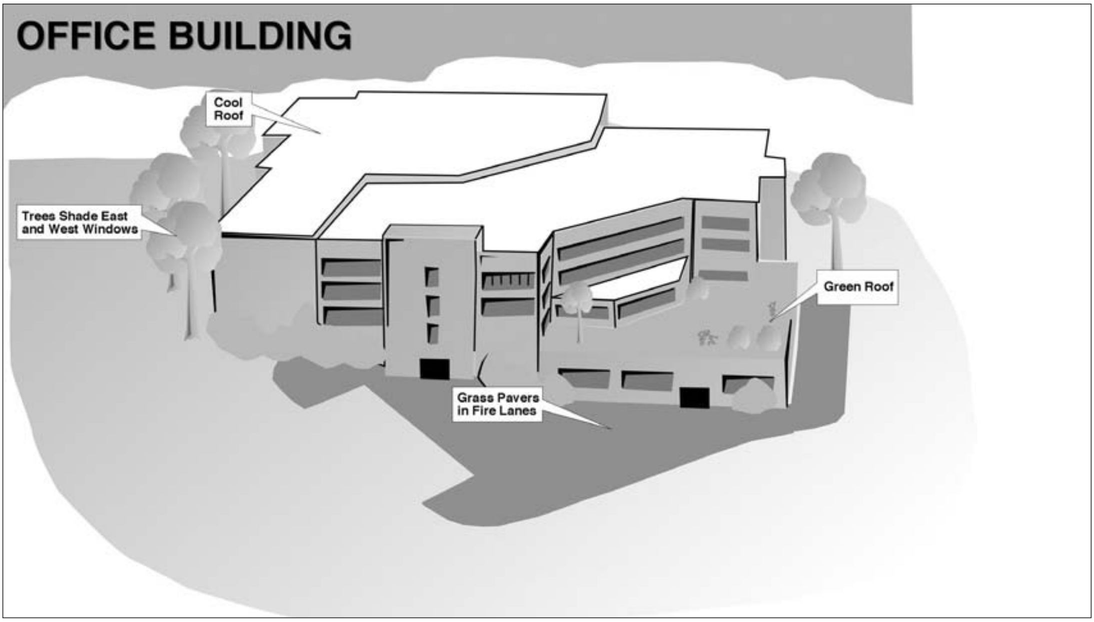


Figure 7.9 Effective landscaping to reduce heat islands around office buildings

ment. This equipment works less efficiently when it is hot. Shade them with trees, vines or shrubbery, making sure to leave clearance around the unit for airflow.

To block winter wind, a row of evergreens should be planted perpendicular to the main wind direction, usually to the north or northwest of a home. Ideally the row should be about 15 metres (50 feet) away from the building, be longer than the width of the building and grow to twice the height of the building.

In the real world, neighbouring buildings, driveways, fences and other urban features tend to interfere with the most effective landscape designs. There are ways to make the best of these limitations. First, shade from trees planted in less favourable locations can be optimized by pruning tree branches to a height that blocks the summer sun, yet lets winter sun through. Second, more compact vegetation such as bushes, shrubs or vines can shade windows and walls in places where trees will not fit.

Patios, driveways and walkways also benefit from shading. Pavements store heat when exposed to the sun and warm the air above them. Trees, trellises and large bushes or awnings or umbrellas are recommended to shade pavement, cars and people.

Permeable grass pavers can also replace traditional pavements in parking areas, patios, fire lanes and other paved areas. Grass pavers are specifically designed to let water drain through to the soil below, while allowing pedestrian or light traffic to be supported. Pavers are usually prefabricated lattices made of concrete, plastic or metal. Lattice blocks are first filled with soil and then planted with grass or groundcover plants.

Finally, consider installing a green roof, or garden roof. All types of green roofs work well on low-slope, essentially flat, roofs. Simpler and lighter so-called 'extensive' green roofs, such as turf or grass roofs, can be used on roofs with slopes of up to 30°. More information about green roofs is given later in this chapter.

Landscaping streets and parking lots

Figure 7.10 shows the best locations for planting trees along streets. Trees can be planted at regular intervals of 6–12 metres (20–40 feet) along both sides of a street, as well as along medians in the centre of the street. Placing trees close to the curb allows them to shade the street and sidewalk, benefiting any parked cars.

Trees can provide useful shade around the perimeter and in the interior of parking lots, as shown in Figure 7.11. Many cities have ordinances that require trees to shade 50 per cent of the parking area within 15 years of a parking lot's construction (Davis, 1998; Sacramento,

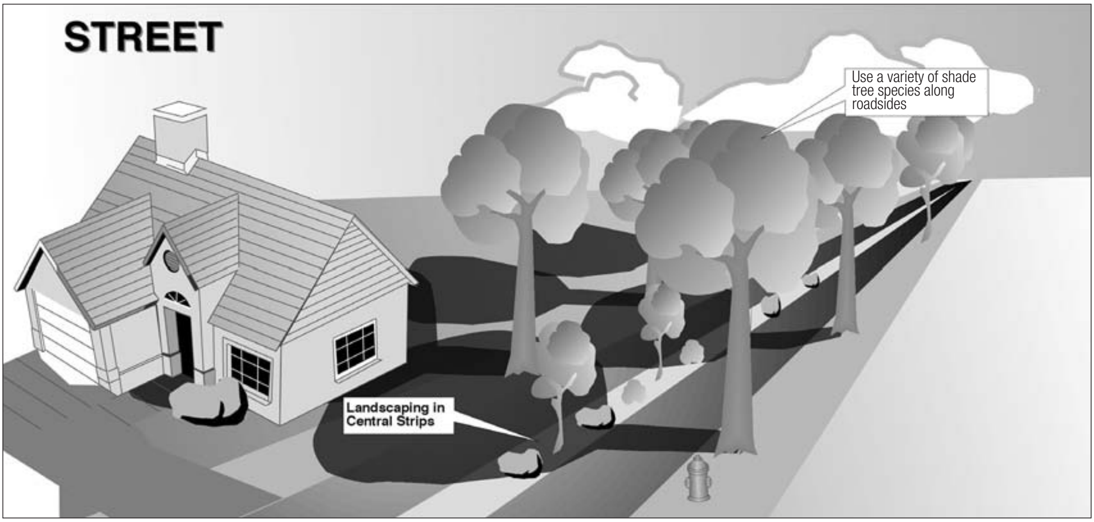


Figure 7.10 Reduce the heat island by planting trees at regular intervals along streets

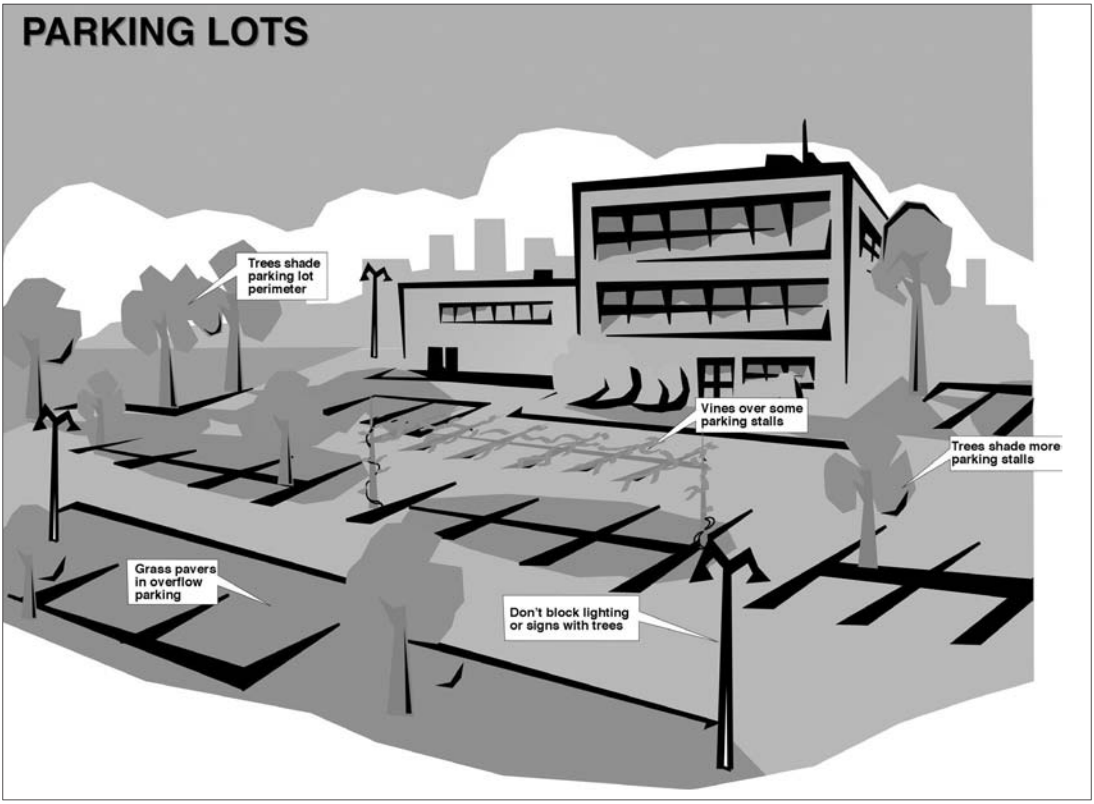


Figure 7.11 Effective landscaping in parking lots can reduce heat islands

2003). Depending on the size of the chosen tree's canopy, this means planting 0.5–2 trees per hundred square metres (0.5–2 trees per thousand square feet) of the parking lot.

It is sensible to use a variety of tree species along a street or in a parking lot. This is more visually interesting and helps protect against losing everything to pests or disease.

There are many useful alternatives to trees. If space is tight or soil is scarce, plant vines to grow on trellises. Use solar collectors as combination shade devices and charging stations. Permeable grass pavers can be also be used over low-traffic areas of the parking lot, such as pedestrian walkways or overflow parking used once or twice a week.

When landscaping streets and parking lots, be mindful of lighting, signage, wires and other important safety and visibility concerns. Landscaping should not interfere with these features as the plants grow. Thoughtful placement of correctly sized plants will reduce maintenance for years to come.

Playgrounds / school yards / sports fields

Playgrounds, school yards and sports fields often lack adequate vegetation. Some playgrounds are completely paved and barren, with no vegetation at all. While an unvegetated yard is easy to maintain, it is not especially appealing or healthy. Trees and other types of cooling are needed to protect people, especially more vulnerable children, from the sun's heat and ultraviolet rays.

Figure 7.12 shows how to use vegetation around playgrounds and other areas. Shade trees are useful in areas where people are likely to congregate, such as over team seating, spectator stands, jungle gyms, sand boxes, swings and picnic tables. Trees take time to grow, so grow

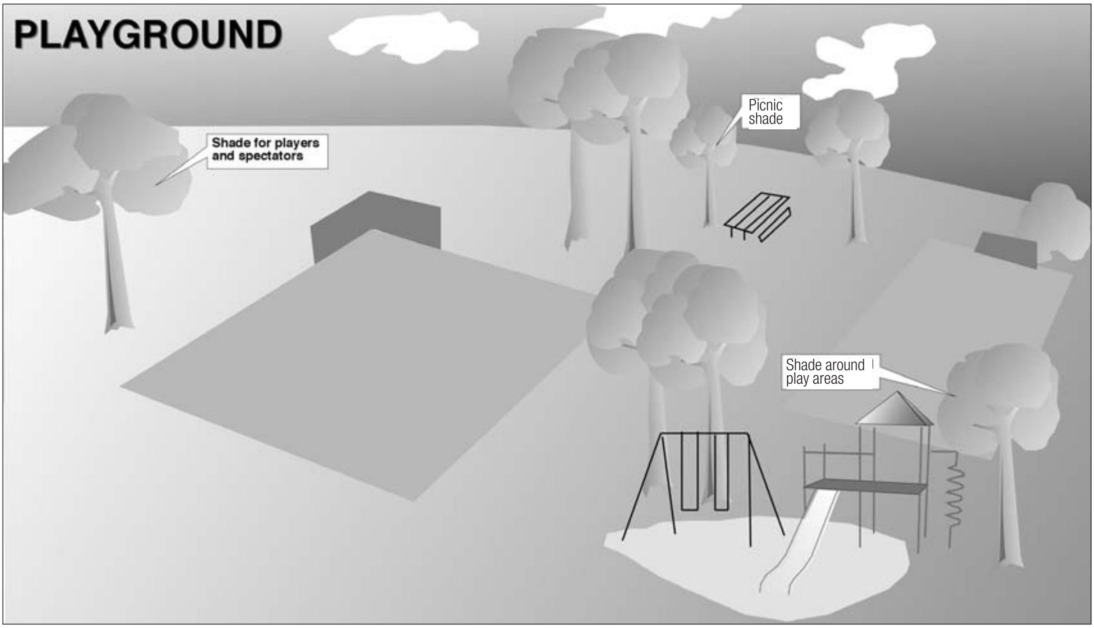


Figure 7.12 Landscaping to shade and cool a playground

vines on trellises to get useful shade more quickly.

Tools for plant selection

Various plant selection guides available on the internet are listed in Table 7.8.

It may also be helpful to evaluate the ozone-forming potential (OFP) of the trees of interest. A list of many trees and their OFPs is found in 'Estimating the ozone-forming potential of urban trees and shrubs' (Benjamin and Winer, 1998).

For more local information on tree selection, contact local tree planting organizations, community arbourists, horticultural organizations or landscape design agencies.

Tips for planting and maintaining trees

Planting and maintaining urban landscapes takes education, skill, experience and hard work. Many common problems can be avoided by adhering to good landscape design and maintenance practices. Planning ahead can minimize any potential damage to buildings, electrical wires and sidewalks; preserve views of traffic and signs; and preclude the need for excessive water use.

Below are a few important steps to take when planting a tree in an urban area (McPherson and Simpson, 1999b; Tree City, 2001). Following these practices can help a tree grow faster and live a longer, healthier and more productive life.

- Choose the right plant.
  - Select a plant that won't grow too wide or tall, has a non-invasive root structure and has watering needs that can be met by normal rainfall or existing irrigation.
  - Also consider other factors in tree selection that may impact long-term maintenance, such as the production of pollen, flowers or fruit; the rate of growth; resistance to disease; and the expected hardiness of the tree in given conditions. Refer to the tree selection tools listed below for more guidance.
  - Make sure the plant hasn't spent too much time in its container. Roots should not grow around the edge of the

Table 7.8 Tree selection guides on the internet

Organization	website	Description
International Society of Arboriculture Tree Selection	http://www.isa-arbor.com/consumer/select.htm	Tips on matching trees to your site characteristics and requirements
Plants Database	http://plants.usda.gov	Lists, tools and information about plants of the US and its territories
Tree Link	http://www.treelink.org	Information, research, and an urban and community forestry network
SelecTree for California	http://selectree.cagr.calpoly.edu	Searchable database of trees that thrive in various California climates
Allergy-Free Gardening	http://www.allergyfree-gardening.com	How to select plants with low pollen counts that won't aggravate allergies
Urban Trees: site assessment, selection for stress tolerance, planting	http://www.hort.cornell.edu/department/faculty/bassuk/uhi/urbantrees1.html	Information on site assessment, plus a list of trees for USDA Zone 6 and below
CABI Forestry Compendium	http://www.cabicompendium.org/fc (fee-based)	Complete technical information on over 1200 tree species

container, through drain holes or around the root ball.
  - Conversely, make sure the plant has enough healthy roots by wiggling the tree in its container. It should remain firmly rooted without loosening the container soil.
- Choose a good spot.
  - Keep the plant at least 1.5–3 metres (5–10 feet) from wires, buildings or other structures to avoid potential damage and allow roots and branches to grow.
  - Try to stay at least 1 metre (3 feet) away from sidewalks or pavement to avoid damage to the pavement from the roots. If this is not possible, try to maximize the soil volume as much as possible and use a root barrier to contain the roots.
  - Keep trees about 10 metres (30 feet) away from traffic intersections to make sure there is adequate visibility.
  - Try to keep trees away from power lines, street lights, traffic signs or buildings. If this is impossible, choose species that do not grow large enough to interfere with their surroundings. In general, choose trees that grow taller than 7 metres (20 feet) only where there is plenty of space.
  - Check with local utilities before digging to locate water, sewer, gas and telecommunication lines. This keeps them from being cut while digging and ensures that the tree has enough space to grow healthy roots.
- Dig and plant.
  - Provide as large a soil volume for the tree as possible. Excavate the soil to a depth of at least 1 metre (3 feet) and make sure that the soil in the tree well or within at least 2 metres (6 feet) of the tree is free of rocks and debris.
  - Install root barriers if needed. These can reduce the incidence of roots growing into unwanted areas and tearing up sidewalks and pavement. Installing root barriers as a regular practice can prevent a lot of expensive pavement maintenance in the future and may even reduce future legal liability for tripping hazards.
  - Dig a planting hole as deep as the root ball and two to three times as wide. Place the tree so that the top of the root ball is slightly above ground level, then fill around the ball with native soil. Do not compact the soil. Build a 15cm (6 inch)-high berm, or narrow shelf, of soil around

  the tree about half a metre (1 or 2 feet) from the trunk. This berm helps to hold water around the tree and allows it to percolate down to the roots.
  - Water the tree until the ground is soaked, then gently rock the trunk to settle the soil and the roots into place. Again, do not compact the soil.
  - Cover the area inside the berm with a 10cm (4 inch) layer of coarse, organic mulch, but keep the mulch out of contact with the tree trunk.
  - Optionally, apply a moderate amount of slow-release fertilizer.
  - Do not prune a newly planted tree, except to remove dead or damaged branches.
- Water and maintain.
  - Water the new tree twice a week for the first month, then once a week during the next two or three growing seasons. Newly planted trees need an extra 400–800 litres of water per year for the first couple of years, in addition to normal rainfall. After they have become established, properly chosen trees should not need much extra water. Mature trees use at least 3000 litres of water per year, but this comes mainly from natural rainfall (McPherson, 2002).
  - Add more mulch around the tree as needed.
  - If the tree initially needed a stake to stand upright, remove the stake as soon as the tree can stand by itself.
  - As the tree grows, prune it to keep the branches equally spaced, removing any branches that cross or rub. Consider having the tree professionally pruned by a certified arbourist.

Planting other types of vegetation

Trees do not fit into every space, but in most cases there are other types of vegetation that can provide similar benefits. Grasses or groundcovers can be used in place of pavement to provide cooling benefits. Shrubs and bushes can shade windows or walls without growing too large or tall. Vines grow very quickly on vertical or overhead trellises and can be used in locations with little available space or soil.

The procedures for planting trees, listed above, also apply to other types of plants, but there are a few more guidelines to consider:

- Choose low-maintenance plants.
  - To avoid excessive pruning in the future, choose plants that will grow naturally into the correct size and shape to cover the designated space.
  - Select grasses and groundcovers that do not need regular mowing. Choose among many varieties of low-growing groundcovers, or pick ornamental grasses and allow them to grow to their full height.
  - Choose plants that need little or no extra water. Native plants are often well suited to the typical rainfall of their particular climate.
  - Select plants that will grow well in the space's conditions. Consider carefully the amount of sunlight, the type of soil and any potential interactions with other nearby plants.
  - Consult the plant selection tools listed below for more guidance.
- Keep the proper spacing between plants.
  - Know the mature size of the plants and space them accordingly. This keeps the plants from crowding each other as they grow, and eliminates the need for excessive pruning or removal of overcrowded plants later on. It also saves money when buying plants.
- Give vines the right type of support.
  - Vines climb by various means: by entwining tendrils or roots around supports, by attaching suction-cup-like mechanisms or by using thorns to catch onto supports. Some vines need to be fastened manually to supports with string or wire. Match the type of vine to the existing or planned support. Avoid the use of suction-cup or tendril-producing vines near walls or other building materials that may be damaged.

  - Vines can climb on trellises, along fences, over rock walls or even along a simple string or wire.
  - Plan ahead to train the vines as necessary. Vines often need to be directed to their supports and encouraged to grow in the right direction. Some vines can be invasive, so be prepared to prune them often to keep them contained.
- Maintain plants regularly.
  - Remove weeds, since they can crowd out new plants. It is much easier to remove a small, young weed than an older, stronger one. With frequent attention, the growth of weeds is suppressed over time as more of the weed's root structure is removed and the maturing plant blocks sunlight.
  - Prune new plants after they flower and/or fruit. Bushes, shrubs and especially vines tend to need more pruning than trees. Keep the plant growing into the desired shape and direction by removing unwanted shoots.

Green roofing, or garden roofing

Green roofing, or garden roofing, straddles the categories of landscaping and cool roofing, bringing benefits from both technologies to communities. Green roofing represents a unique opportunity for adding vegetation back into the urban landscape. Information about green roof construction, benefits and other considerations is given below.

Green roof description

A green roof is essentially a garden grown on a rooftop. It can be as simple as a turf roof, generally termed an 'extensive' rooftop garden system, or as complex as a fully accessible park complete with trees, called an 'intensive' system.

No matter what type of system is chosen, the components of a green roof remain essentially the same (Peck and Kuhn, 2001). From the top down, as shown in Figure 7.13, green roofs include the following layers:

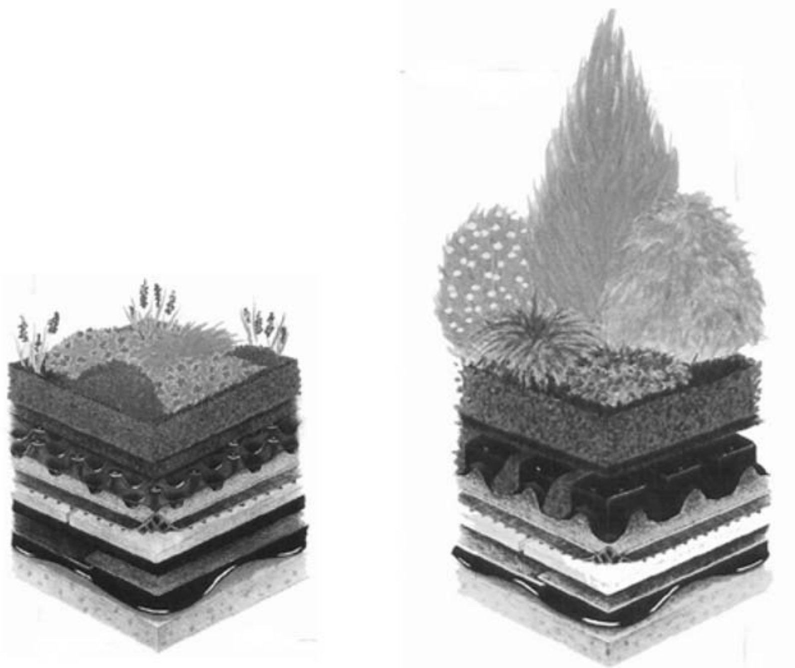
- plants, often specially selected for particular applications
- a lightweight, engineered planting medium, which may or may not include soil
- a root barrier or filter cloth to contain the roots and the growing medium
- a specialized drainage layer, sometimes with built-in water reservoirs
- a waterproofing / roofing membrane, with an integral root repellent
- the roof structure, with traditional insulation either above or below
- the building, with structure to support the garden even when fully saturated.

The simpler, lighter-weight, extensive roof system on the left of Figure 7.13 is usually planted with grasses, mosses or wild flowers. The concept is to design a rugged green roof that needs very little maintenance or human intervention. Locally native species are good plant choices and may allow a system to forgo installation of irrigation and drainage systems.

Extensive gardens use less soil, up to about 10cm (4 inches), and generally weigh between 25 and 150kg/m^2 (5–30lb/ft^2), excluding water weight. The lightest systems may not require any additional structural support, and therefore might be used to retrofit existing roofs. Roofs need not be flat for extensive gardens, which can be grown on roofs on slopes of up to 30º.

One of the most famous examples of an extensive roof in the US is on the GAP Company headquarters building in San Bruno, California, near San Francisco, as shown in Figure 7.14. This building was designed by William McDonough and Partners and includes many other sustainable features.

An intensive green roof is very much like a traditional garden, with almost no limit on the type of plants that can be used. Intensive gardens are often designed for access by the public or by building occupants. These systems are more expensive than extensive systems for a number of reasons. They use more soil, as much



Source: American Hydrotech, 2000

Figure 7.13 Layers of an extensive (left) and an intensive (right) garden roofing system

as 25cm (10 inches) or more, and therefore weigh more, from 100–200kg/m^2 (20–40lb/ft^2) when dry. Sub-sequently, they need stronger structural support in the building below. Intensive systems generally require irrigation and drainage systems. The more diverse gardens also require a higher initial investment and more maintenance over the long term than an extensive roof system. Figure 7.15 shows an intensive rooftop garden on the City Hall of Chicago, Illinois.

Green roof components

The components of a green roof are generally more robust than those of a traditional roof. The roof deck must be stronger, since it must support the weight of plants, wet soil, and perhaps even people (see the section below on green roof weight). The waterproofing membrane on a traditional roof is usually only 0.08cm (30 thousandths of an inch) thick, while on a green roof this membrane can be over 0.25cm (100 thousandths of an inch) thick.

Insulation is an optional, but highly recommended, component of a green roof. Soil in a green roof loses most of its insulation value when it is wet, so an added layer of insulation helps the roof conserve energy during wet weather or after watering.

Green roof systems also incorporate a more robust drain system than traditional roof systems. A drainage layer prevents plant roots from suffocating and filters out soil particles from drain water. Some drain systems take the form of egg-crates, which allow for some water to be stored. Roots from some plants can penetrate roof drains and other materials, so a specialized root barrier must be installed below the soil and above the drainage layer.

Soils used in green roof systems are usually engineered to provide the best support for plants with the lightest weight. Typical soil mixes are composed of 75–80 per cent lightweight inorganic materials such as vermiculite, and

Source: Business Week, 1998.

Figure 7.14 Gap Inc. corporate headquarters in San Bruno, California, complete with extensive rooftop garden planted with grass

Source: Thompson, 2002.

Figure 7.15 The intensive green roof on City Hall in the City of Chicago

20–25 per cent organic materials such as topsoil (Wilson and Pelletier, 2001).

The choice of plants for a green roof is endless. Extensive green roofs tend to be covered with grasses or groundcovers. Sedums, hardy succulents that come in a wide variety of sizes, shapes and colours, are a popular groundcover for green roofs, since their high water content makes them fire resistant. Intensive roof gardens can also incorporate shrubs, bushes and trees in their design. It is useful to choose native plants or other plants well suited to the local climate, since these plants are likely to require less care and watering.

Green roof benefits

Green roofs combine the benefits of cool roofing and urban landscaping, such as urban cooling, stormwater reduction and air pollution removal. They can also beautify a community and provide a more hospitable environment for insects, animals and people.

Reducing the heat island

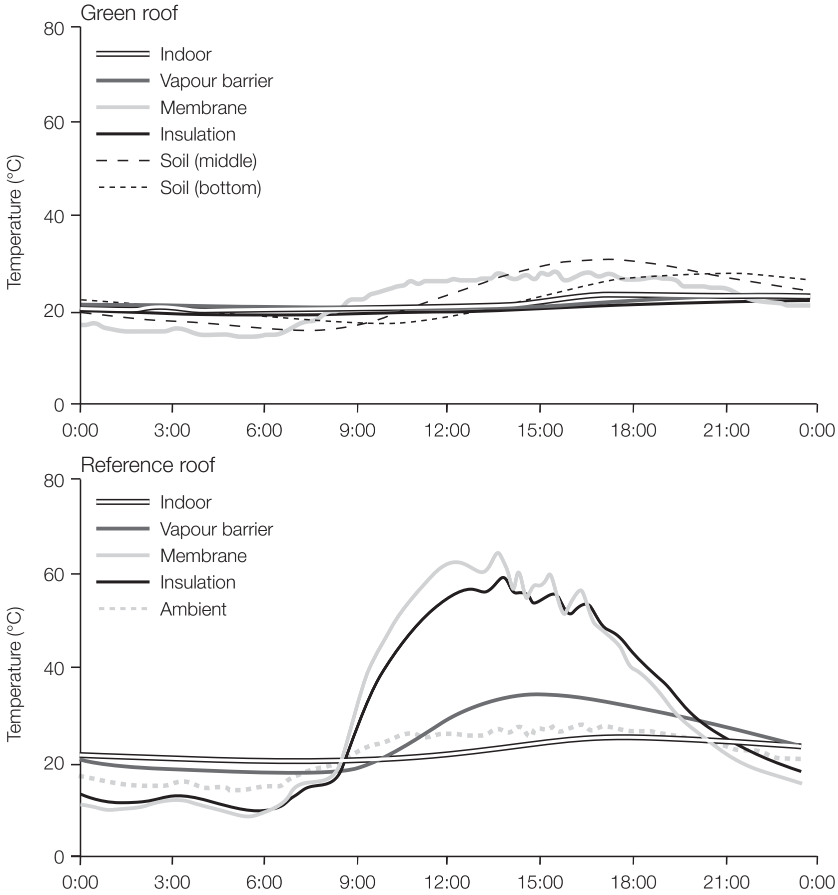
Using green roofs expansively throughout a city can help cool the air. Traditional rooftops reach temperatures as high as 90°C (190°F), but green roof temperatures stay below 50°C (120°F). Figure 7.16 shows temperatures of the layers of a green roof and a traditional roof on a summer day in Ottawa, Canada (Liu, 2002). The traditional roof reaches temperatures of 65°C (150°F) while the green roof reaches only about 30°C (90°F). Plants keep the roof cooler because they create shade and use the sun's energy to evapotranspire moisture through their leaves.

If roof temperatures are cooler, then less heat is transferred to the air above them, keeping urban temperatures lower as well. A climatological model of Toronto, Canada, predicts that if green roofs were introduced on 10 per cent of the rooftops in the city, air temperatures in the urban boundary layer could decrease by up to 2.8°C (5°F) (Bass, 2002).

Energy savings

Another benefit of a green roof is energy savings in the building below. A green roof not only reduces the roof surface temperature, but the soil and roof system layers add insulation to slow down the flow of heat through the roof. This means that less heat is transferred from the roof into the building, and therefore less cooling energy may be used to remove this heat.

Figures 7.17 and 7.18 look at the heat flow through a traditional roof and a green roof on a building in Toronto, Canada, in summer and winter (Liu and Baskaran, 2005). Figure 7.17 shows that the traditional roof collects heat during the day and releases heat at night on a



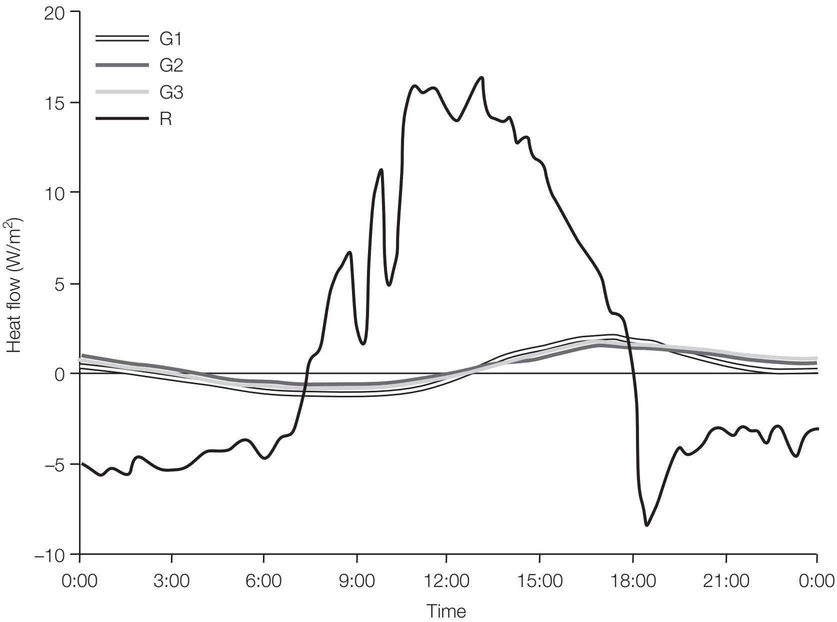
Source: Liu, 2002.

Figure 7.16 Temperatures of the layers of an extensive green roof with 6 inches of soil and a reference roof of modified bitumen on a clear summer day with air temperatures reaching 95ºF (35ºC) in Ottawa, Canada

typical summer day. The green roof also stores and releases heat over the course of the day, but at levels 70 to 90 per cent lower than those of the traditional roof. The daily heat flow pattern is delayed on the green roof, since it takes time for its soil to heat up and cool down. Figure 7.18 shows the same roof on a typical winter day, when the roof is covered with about 25mm (about 1 inch) of snow. Both the traditional roof and the green roof are losing heat all day during the winter, but the soil of the green roof reduces this heat loss by 10 to 30 per cent.

Retaining stormwater and improving water quality

Rainfall in forests or grasslands follows a very different path than rainfall in an urban area (Scholz-Barth, 2001). In natural systems, 30 per cent of stormwater is stored in shallow aquifers and used over time to feed plants. Another 30 per cent percolates to deeper aquifers, eventually supplying springs and rivers. The remaining 40 per cent is almost immediately returned to the atmosphere by plant evapotranspiration. In urban areas, where impermeable surfaces can cover 75–100 per cent of the land, only 5 per cent of stormwater reaches shallow aquifers, 5 per cent is



Note: R, reference 'traditional' roof section; G1, G2, G3, three measurements made on an extensive green roof section.

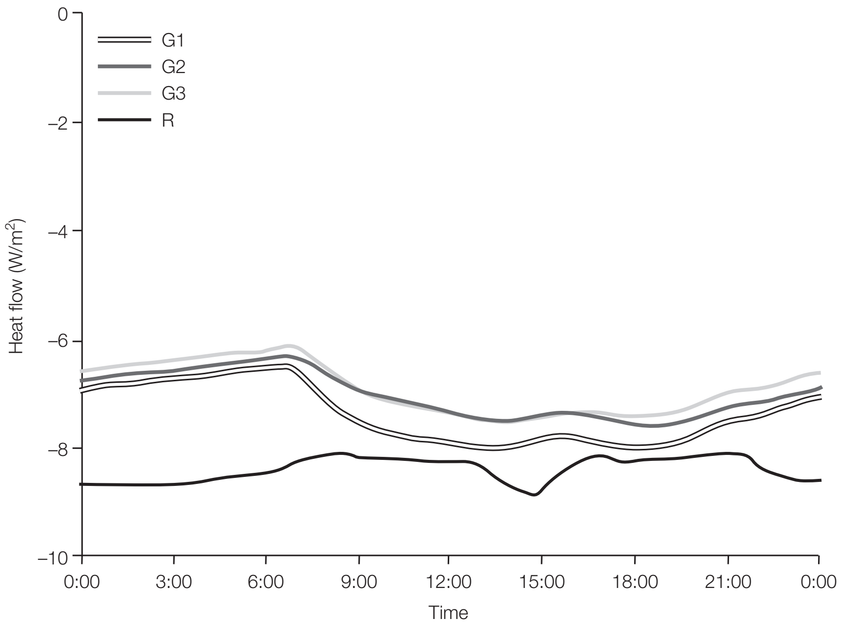
Source: Liu and Baskaran, 2005.

Figure 7.17 Typical summer heat flow through the roof of the Eastview Neighbourhood Community Centre in Toronto, Canada on 26 June 2003

stored in deeper aquifers, and 15 per cent is used immediately by vegetation. The remaining 75 per cent of the rainfall becomes surface run-off. This run-off must generally be collected by sewer systems and drained to local streams and ponds. As it flows over roofs and streets, run-off collects particulate matter, oils and other pollutants that can degrade the quality of local bodies of water.

Green roofing helps to reduce the amount of stormwater run-off. The plants and soil of a green roof soak up water that would normally have become run-off. An intensive green roof can hold as much 15cm (6 inches) of rainfall over its surface (Bass and Peck, 2000), capturing all of the water that falls on it from the majority of rainstorms. Extensive roofs with thinner layers of soil can capture between 10 and 75 per cent of rainwater, depending on the amount of soil used and the intensity of the rainstorm (Scholz-Barth, 2001; Hutchinson et al, 2003). Because of their benefits in controlling stormwater, the city of Portland, Oregon, has designated green roofs (or 'eco-roofs') as an approved technique to meet stormwater management requirements for new development and redevelopment (Portland, 2002).

The plants and soil of a green roof not only retain stormwater, but also filter out many of the pollutants that run-off normally collects. Various research projects are underway to monitor the quality of water run-off from green roofs, such as at Pennsylvania State University's Green Roof Research Center (http://hortweb.cas.psu.edu/research/greenroofcenter) and at Portland, Oregon's, Eco-Roof program. Preliminary results from Portland showed reductions in phosphorus and copper levels in green roof run-off (Liptan and Strecker, 2003), but a follow-up study was less conclusive (Hutchinson et al, 2003). A study carried out at North Carolina State University found that the soils in two green roofs were actually adding nitrogen and phosphorus to the water flowing from the roof (Moran et al, 2005). This illustrates the importance of using ecologically appropriate soil mixes.



Note: R, reference 'traditional' roof section; G1, G2, G3, three measurements made on an extensive green roof section

Source: Liu and Baskaran, 2005

Figure 7.18 Typical winter heat flow through the roof of the Eastview Neighbourhood Community Centre in Toronto, Canada on 5 January 2003, with about 25mm (1 inch) of snow

Air quality improvements

Plants on green roofs improve air quality, just as all trees and vegetation do. Vegetation on green roofs is expected to remove particulate matter, nitrogen oxides, sulphur oxides and ozone from the air. For more details, refer to the section on reduced air pollution as a result of trees and vegetation earlier in this chapter. According to the Green Roofs for Healthy Cities website (www.peck.com/grhcc), a 100m^2 (1000ft^2) green roof can remove about 20kg (40lb) of particulate matter from the air in a year. Plants on a green roof also produce oxygen and remove CO_2 from the atmosphere, as described in the earlier section of this chapter on carbon dioxide reduction.

Ecosystems and aesthetics

Green roofs also bring some less tangible benefits to urban spaces. Even small green roofs can provide habitats for insects, birds and other local wildlife. Using native vegetation is recommended, since it is not only adapted to the climate, but is generally attractive to local wildlife.

Green roofs are also attractive to people. People in taller, neighbouring buildings are likely to prefer to look down at a rooftop garden instead of a traditional roof. Allowing public access to rooftop gardens also provides urban residents with another green space to enjoy.

Green roof considerations

Green roof costs

Green roofs are more expensive than traditional roofs. Initial costs are expected to run between \$10 and \$30 per square foot for a simpler, extensive roof and between \$25 and \$200 per square foot for an intensive rooftop garden (Peck and Kuhn, 2001). Costs depend on the amount of

Table 7.9 Green roof guides on the internet

Name	Site	Description
Greenroofs.com	http://www.greenroofs.com	Green roof industry resources, including practical tips, plant lists, references and an international database of projects
Green Roofs for Healthy Cities	http://www.greenroofs.org	Canadian website includes numerous resources and information on green roof installation, benefits and projects. Publishes the *Green Roof Infrastructure Monitor*
Center for Green Roof Research	http://hortweb.cas.psu.edu/ research/greenroofcenter	Ongoing research at Pennsylvania State University into plant growth and hardiness, stormwater management, water quality and energy use in test structures with green roofs
Greenroof Research	http://www.bae.ncsu.edu/ greenroofs/	Research centre at North Carolina State University's department of Biological and Agricultural Engineering has two demonstration roofs being studied for stormwater retention, water quality and plant survival
Earth Pledge Green Roof Initiative	http://www.earthpledge.org/ GreenRoof.hmtl	Information about green roofs for the New York region, includes information, resources and links, and sponsored research into green roof costs and benefits
Emory Knoll Farms	http://www.greenroofplants.com	A plant supplier that focuses exclusively on plants for extensive green roofs

soil, the type of roofing membrane, the extent of the drainage system, the use of fencing or railings, and the type and quantity of plants chosen.

Green roof weight

The components of a green roof weigh more than traditional roofing materials. Not only are the roofing membranes and other materials heavier, but the weight of water-saturated plants and soil must also be taken into account. These additional loads can be as low as 63kg/m^2 (13lb/ft^2) for a saturated, green roof with 5cm (2 inches) of soil, about the same weight as a gravel-ballasted roof. A saturated roof with 17cm (6.75 inch) of soil can weigh 220kg/m^2 (50lb/ft^2) (Wilson and Pelletier, 2001). Roofs with thicker layers of soil can weigh much more.

The roof deck must be designed to support the extra loads of roof materials, soil and plants, as well as potentially supporting the live loads of people if public access is allowed. Building structural supports must also be strengthened. Reinforcing roof supports on existing buildings adds to the project cost, but can usually be worked into building retrofit or renovation plans. It can be easier to put green roofs on new buildings, since the requirements for the added roof load can be part of the initial design parameters.

Green roof maintenance and repair

A green roof requires the same attention as any garden. Most of this care takes place in the first couple of years after installation, as the plants establish themselves and begin to mature. For an intensive roof, maintenance costs of \$0.75–\$1.50 are expected for the first 2–3 years, and these should become smaller over time (Peck and Kuhn, 2001). The cost of maintaining an extensive roof is usually lower, with some plants requiring only regular watering until they are established.

Repairing a green roof can be difficult. Should a leak occur, the process of finding it, removing the plants, soil and roofing layers and making repairs is labour-intensive. For this reason, most green roof systems are applied very carefully. Waterproofing membranes are thicker and more durable on green roofs than on traditional roofs. The roof membrane is actually very well protected from solar degradation and other types of damage by layers of materials and soil, and if correctly installed, it is expected to have a life of 30–50 years (Peck and Kuhn, 2001). There are a few modular green roof systems on the market that allow easier removal of roof sections if repairs become necessary.

Green roof fire safety

If a green roof is saturated with water, it has been found to retard the spread of fire (Peck and Kuhn, 2001), but dry plants on a green roof can be a fire hazard. There are three ways to increase fire safety:

- use fire-resistant plants, such as sedums
- construct fire breaks on the roof, i.e. 60cm (2ft) widths of concrete or gravel at 40 metre (130ft) intervals
- install sprinkler irrigation systems and hook them up to a fire alarm.

More green roof information

Various websites containing useful information about green roof research, technology, products and projects are listed in Table 7.9.

Notes

1 Note that the process of carbon storage and sequestration can be quantified by referring either to the amount of carbon stored or to the amount of CO_2 removed from the air, but these values differ due to the atomic weights of the molecules. Carbon has an atomic weight of 12 and carbon dioxide has an atomic weight of 44 (one carbon plus two oxygen molecules = 12 + 2 × 16 = 44). One metric ton of sequestered carbon represents 44/12 = 3.67 tons of sequestered CO_2, or one ton of CO_2 represents 12/44 = 0.272 tons of carbon.

References

Akbari, H. (1997) *A Cost–Benefit Analysis of Urban Trees*. Berkeley, CA, Lawrence Berkeley National Laboratory: 5

Akbari, H., S. Bretz, J. Hanford, A. Rosenfeld, D. Sailor, H. Taha and W. Bos (1992) *Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Project Design and Preliminary Results*. Berkeley, CA, Lawrence Berkeley National Laboratory: 229

Akbari, H., S. Bretz, J. Hanford, D. Kurn, B. Fishman, H. Taha and W. Bos (1993) *Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations, and Results*. Berkeley, CA, Lawrence Berkeley National Laboratory: 146

American Forests (2000) *Urban Ecosystem Analysis for the Houston Gulf Coast Region*. Washington DC, American Forests: 12

American Forests (2001a) *Regional Ecosystem Analysis for the Willamette/Lower Columbia Region of Northwestern Oregon and Southwestern Washington State*. Washington DC, American Forests: 16

American Forests (2001b) *Urban Ecosystem Analysis for the Atlanta Metro Area*. Washington DC, American Forests: 8

American Forests (2002a) *CITYgreen 5.0 User Manual*. Washington DC, American Forests

American Forests (2002b) *Urban Ecosystem Analysis for the Washington DC Metropolitan Area*. Washington DC, American Forests: 16

American Hydrotech (2000) *The Garden Roof Planning Guide*. Chicago, IL, American Hydrotech, Incorporated: 48

Bass, B. (2002) *Mitigating the Urban Heat Island with Green Roof Infrastructure*. Toronto, North American Urban Heat Island Summit, Toronto Atmospheric Fund

Bass, B. and S. Peck (2000) *Green Roof Infrastructure Workshop: Establishing Common Protocols for Building and Aggregate Level Green Roof Benefits Research*. Toronto, Green Roofs for Healthy Cities, Environment Canada, City of Toronto Public Works, Toronto Conservation Authority, University of Toronto: 50

Benjamin, M. T. and A. M. Winer (1998) 'Estimating the ozone-forming potential of urban trees and shrubs'. *Atmospheric Environment* **32**(1): 53–68

Benjamin, M. T., M. Sudola and A. M. Winer (1996) 'Low-emitting urban forests: A taxonomic methodology for assigning isoprene and monoterpene emission rates'. *Atmospheric Environment* **30**(9): 1437–1452

Business Week (1998) *It's a Real Pleasure to Work Here*. Business Week Online. Special Report: Architecture Awards

Carman, N., W. Hamilton and J. Elioseff (1999) *Trees and Our Air, the Role of Trees and Other Vegetation in Houston-Area Air Pollution*. Houston, TX, Galveston-Houston Association for Smog Prevention: 67

Davis (1998) *Parking Lot Shading Guidelines and Master Parking Lot Tree List Guidelines*. City of Davis, California: 11

Grant, R. H., G. M. Heisler and W. Gao (2002) 'Estimation of pedestrian-level UV exposure under trees'. *Photochemistry and Photobiology* **75**(4): 369–376

Huang, J., H. Akbari et al (1990) *The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements*. ASHRAE Winter Meeting, Atlanta, Georgia, American Society of Heating, Refrigerating and Air-Conditioning Engineers

Hutchinson, D., P. Abrams, R. Retziaff and T. Liptan (2003) *Stormwater Monitoring Two Ecoroofs in Portland, Oregon, USA*. Chicago, Greening Rooftops for Sustainable Communities

Kurn, D., S. Bretz, B. Huang and H. Akbari (1994) *The Potential for Reducing Urban Air Temperatures and Energy Consumption Through Vegetative Cooling*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Liptan, T. and E. Strecker (2003) *Ecoroofs (Greenroofs) – A More Sustainable Infrastructure*. National Conference on Urban Stormwater: Enhancing Programs at the Local Level, Chicago, IL, US Environmental Protection Agency

Liu, K. (2002) 'A National Research Council Canada study evaluates green roof systems' thermal performances', *Professional Roofing*, September

Liu, K. and B. Baskaran (2005) *Thermal Performance of Extensive Green Roofs in Cold Climates*, World Sustainable Building Conference, Tokyo, Japan, 27–29 September, National Research Council Canada: 1–8

Maco, S. and E. G. McPherson (2003) 'A practical approach to assessing structure, function and value of street tree populations in small communities'. *Journal of Arboriculture* **29**(2): 84–97

McPherson, E. G. (1998a) 'Atmospheric carbon dioxide reduction by Sacramento's urban forest'. *Journal of Arboriculture* **24**(4): 215–223

McPherson, E. G. (1998b) 'Estimating cost effectiveness of residential yard trees for improving air quality in Sacramento, California, using existing models'. *Atmospheric Environment* **32**(1): 75–84

McPherson, E. G. (2002) *Green Plants or Power Plants?* Davis, CA, Center for Urban Forest Research

McPherson, E. G. (2003) 'A benefit–cost analysis of ten street tree species in Modesto, California, US'. *Journal of Arboriculture* **29**(1): 1–8

McPherson, E. G. and J. R. Simpson (1999a) *Carbon Dioxide Reduction Through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters*. Albany, CA, Pacific Southwest Research Station, Forest Service, US Department of Agriculture: 237

McPherson, E. G. and J. R. Simpson (1999b) *Reducing Air Pollution through Urban Forestry*. 48th Annual Meeting of the California Forest Pest Council, Sacramento, CA, 18–19 November

McPherson, E. G., D. J. Nowak and R. Rowntree (1994) *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*. Radnor, PA, US Department of Agriculture Forest Service, Northeastern Forest Experiment Station: 201

McPherson, E. G., J. R. Simpson, P. J. Peper and Q. Xiao (1999a) 'Benefit–cost analysis of Modesto's municipal urban forest'. *Journal of Arboriculture* **25**(5): 235–248

McPherson, E. G., J. R. Simpson, P. J. Peper and Q. Xiao (1999b) *Tree Guidelines for San Joaquin Valley Communities*. Sacramento, CA, Local Government Commission and Western Center for Urban Forest Research and Education: 68

McPherson, E. G., J. R. Simpson, P. J. Peper, K. Scott and Q. Xiao (2000) *Tree Guidelines for Coastal Southern California Communities*. Sacramento, CA, Local Government Commission and Western Center for Urban Forest Research and Education: 106

McPherson, E. G., J. R. Simpson, P. J. Peper, Q. Xiao, D. R. Pettinger and D. R. Hodel (2001) *Tree Guidelines for Inland Empire Communities*. Sacramento, CA, Local Government Commission and Western Center for Urban Forest Research and Education: 124

McPherson, E. G., S. Maco, J. R. Simpson, P. J. Peper, Q. Xiao, A. M. Van Der Zanden and N. Bell (2002) *Western Washington and Oregon Community Tree Guide: Benefits, Costs and Strategic Planting*. Davis, CA, Center for Urban Forest Research, USDA Forest Service, Pacific Southwest Research Station: 84

Meier, A. (1990) *Measured Cooling Savings from Vegetative Landscaping*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Moran, A., B. Hunt and J. Smith (2005) *Hydrologic and Water Quality Performance from Greenroofs in Goldsboro and Raleigh, North Carolina*. Washington DC, Green Roofs for Healthy Cities

Neece, J. D. (1998) *VOC and NOx Emissions in Texas: 1996 SIP Modeling Emissions Inventory*. Austin, TX, Texas Natural Resource Conservation Commission

Nowak, D. J. and J. F. Dwyer (2000) 'Understanding the benefits and costs of urban forest ecosystems', in Kuser, J. E. (ed), *Handbook of Urban and Community Forestry in the Northeast*. New York, Kluwer Academic/Plenum Publishers: 11–25

Peck, S. and M. Kuhn (2001) *Design Guidelines for Green Roofs*. Toronto, National Research Council Canada: 23

Pillsbury, N. and S. Gill (2003) *Community and Urban Forest Inventory and Management Program*. San Luis Obispo, CA, Urban Forest Ecosystems Institute, California Polytechnic State University: 37

Portland (2002) *City of Portland EcoRoof Program: Questions and Answers*. Portland, OR, Bureau of Environmental Services, Office of Sustainable Development, City of Portland, Oregon: 12

Sacramento (2003) *Tree Shading Requirements for Surface Parking Lots*. Ordinance No. 2003–027, Sacramento, CA, City of Sacramento

Scholz-Barth, K. (2001) 'Green roofs: Stormwater management from the top down'. *Environmental Design and Construction* 15 January

Scott, K., E. G. McPherson and J. R. Simpson (1998) 'Air pollutant uptake by Sacramento's urban forest'. *Journal of Arboriculture* **24**(4): 224–234

Scott, K., J. R. Simpson and E. G. McPherson (1999) 'Effects of tree cover on parking lot microclimate and vehicle emissions'. *Journal of Arboriculture* **25**(3): 129–142

Simpson, J. R. (1998) 'Urban forest impacts on regional cooling and heating energy use: Sacramento County case study'. *Journal of Arboriculture* **24**(4): 201–214

Simpson, J. R. and E. G. McPherson (1998) 'Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento'. *Atmospheric Environment* **32**(1): 69–74

Simpson, J. R. and E. G. McPherson (2001) *Tree Planting to Optimize Energy and CO_2 Benefits*. National Urban Forest Conference, Washington DC, American Forests

Thompson, R. (2002) 'Chicago means green'. *Conscious Choice, The Journal of Ecology and Natural Living* April

Thompson, R., R. Hanna, J. Noel and D. Piirto (1999) 'Valuation of tree aesthetics on small urban-interface properties'. *Journal of Arboriculture* **25**: 225–234

Tree City USA (2001) *Tree Care Information*. Nebraska City, NE, National Arbor Day Foundation: 7

USDA Forest Service (2002) *STRATUM, Street Tree Resource Analysis Tool for Urban Forest Managers*. Davis, CA, Center for Urban Forest Research, Pacific Southwest Research Station, USDA Forest Service: 2

Weatherhead, E. C. (2000) *Ultraviolet Radiation*. Geneva, World Meteorological Organization, Ozone and UV Data Center

Wilson, A. and M. R. Pelletier (2001) 'A garden overhead: The benefits and challenges of green roofs'. *Environmental Building News* **1**: 10–18

Wolf, K. (1998a) *Growing with Green: Business Districts and the Urban Forest*. Seattle, WA, Center for Urban Horticulture, College of Forest Resources, University of Washington

Wolf, K. (1998b) *Trees in Business Districts: Comparing Values of Consumers and Business*. Seattle, WA, Center for Urban Horticulture, College of Forest Resources, University of Washington

Wolf, K. (1998c) *Trees in Business Districts: Positive Effects on Consumer Behavior*. Seattle, WA, Center for Urban Horticulture, College of Forest Resources, University of Washington

Wolf, K. (1998d) *Urban Forest Values: Economic Benefits* *of Trees in Cities*. Seattle, WA, Center for Urban Horticulture, College of Forest Resources, University of Washington

Wolf, K. (1998e) *Urban Nature Benefits: Psycho-Social Dimensions of People and Plants*. Seattle, WA, Center for Urban Horticulture, College of Forest Resources, University of Washington

Xiao, Q., E. G. McPherson, J. R. Simpson and S. L. Ustin (1998) 'Rainfall interception by Sacramento's urban forest'. *Journal of Arboriculture* **24**(4): 235–244

8

Community Benefits from Heat Island Mitigation

Introduction

Using heat island mitigation strategies can make communities more habitable. The widespread implementation of cool roofing and cool paving and the planting of trees and vegetation in a neighbourhood can make it healthier, more beautiful and less costly to operate and maintain. This chapter describes the seven main community-wide benefits of heat island mitigation:

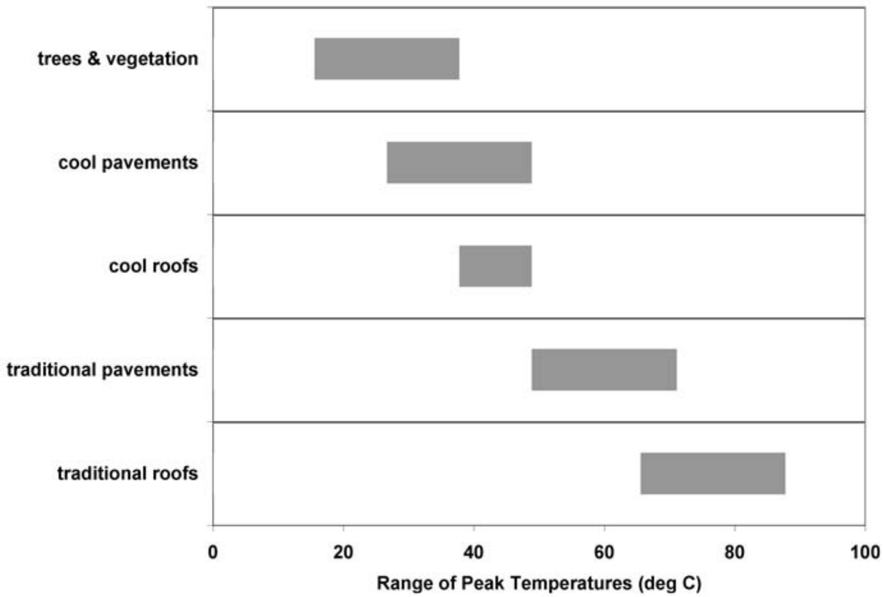
- temperature reductions
- energy savings
- air quality improvements
- human comfort and health improvements
- stormwater run-off reductions
- maintenance and waste reduction
- aesthetic benefits.

Temperature reductions

Construction materials traditionally used in most cities today become quite hot in the summer sun. Heat island mitigation measures reduce the surface temperatures of roofs and pavements. Figure 8.1 shows how hot these surfaces can get, versus their cooler counterparts. Without shade, roofing materials can heat up to 90°C (190°F) and pavements can reach 70°C (160°F). Cooler roofing and paving materials heat to less than 50°C (120°F), while well-irrigated trees and vegetation, and the shaded areas below them, stay below 38°C (100°F).

If cool surfaces and vegetation are widely used in a community, the average surface temperature can be reduced by more than 14°C (25°F). Table 8.1 shows how the overall surface temperature in Sacramento, California, could be cooled by 16°C (29°F) if heat island strategies were aggressively implemented. The 'as-is' scenario is based on a study of land-use coverage by Lawrence Berkeley National Laboratory (Akbari and Rose, 1999). The 'cool' scenario assumes the use of cool roofing and pavements and doubles the coverage of trees and vegetation by adding landscaping to parking lots, streets and other paved areas, as well as to miscellaneous barren areas.

Cooler surfaces, in turn, transfer less heat to their surroundings. If enough surfaces are cooled throughout a community, air temperatures become noticeably cooler. Scientists at Lawrence Berkeley National Laboratory have done meteorological modelling to see how cooler surfaces and more vegetation affect peak daily air temperatures. As shown in Table 8.2, studies of three cities in the US found that peak air temperatures were reduced as much as 2°C (4°F). A similar study of Los Angeles found that cooling surfaces even more brought about further air cooling (Taha, 1997). If the surface solar reflectance of LA was raised by 0.15, peak air temperatures would decrease by 2°C (3.6°F). For an even higher solar reflectance gain of 0.3, peak air temperatures would decrease by 4°C (8°F) in Los Angeles.



Source: Lo et al, 1997; Quattrochi et al, 1997; Gorsevski et al, 1998; Luvall and Quattrochi, 1998; Estes et al, 1999.

Figure 8.1 Peak temperature ranges of different surface materials

Table 8.1 Cooling the peak surface temperatures of Sacramento, California, by doubling trees and vegetation and using cool roofs and pavements

	As-is scenario		Cool scenario	
	Area	Temperature	Area	Temperature
T and V	21%	27°C (80°F)	42%	27°C (80°F)
Roof area	20%	71°C (160°F)	20%	43°C (110°F)
Paved area	44%	54°C (130°F)	28%	38°C (100°F)
Miscellaneous area	15%	52°C (125°F)	10%	52°C (125°F)
Average temperature		*52°C (125°F)*		*36°C (96°F)*

Note: T and V, trees and vegetation.

Source: Akbari and Rose, 1999.

Energy savings

By reducing the amount of solar energy a building absorbs, cool roofing and shade trees directly reduce the cooling energy use of individual buildings. Cool roofing, cool paving and vegetation also cool the air around buildings. This indirectly reduces the need for cooling inside the building. When multiplied throughout an entire community, these direct and indirect cooling reductions add up to significant drops in the electrical energy use and peak electricity demand over the region. Conversely, these measures *increase* the amount of energy needed to heat buildings. However, in most climates, this heating penalty is thankfully small in comparison to the reductions in cooling energy use.

Various studies by Lawrence Berkeley National Laboratory evaluated the city-wide energy saving potential of cool roofs and shade trees around buildings. Energy savings, electricity

Table 8.2 Air temperature reductions in three cities due to heat island mitigation

	Air temperature reduction at 6:00am	Air temperature reduction at 4:00pm
Baton Rouge	0.0°C (0.0°F)	0.8°C (1.4°F)
Sacramento	1.0°C (1.8°F)	1.2°C (2.2°F)
Salt Lake City	1.0°C (1.8°F)	2.0°C (3.6°F)

Note: Mitigation measures assumed in each city: residential roofs – solar reflectance increased by 0.3; commercial and industrial roofs – solar reflectance increased by 0.3; roads and parking lots – solar reflectance increased by 0.25; sidewalks – solar reflectance increased by 0.2; residential and commercial areas – four trees added around each building; industrial areas – six trees added around each building.
Source: Taha et al, 2000.

demand reductions and heating penalties were estimated from the 'direct' effects of cooler roofs and more shade and the 'indirect' effects of cooler air temperatures.

Table 8.3 lists the climatic characteristics of six North American cities. Figures 8.2, 8.3 and 8.4 show how the use of cool roofs and shade trees would save electrical energy and reduce electricity demand, but increase the use of heating energy. This study assumed that rooftop solar reflectance increased from 0.2 to 0.5 on residences and from 0.2 to 0.6 on commercial and industrial buildings. Eight shade trees were 'planted' around homes and offices, and four shade trees around stores (Konopacki and Akbari, 2000, 2001, 2002).

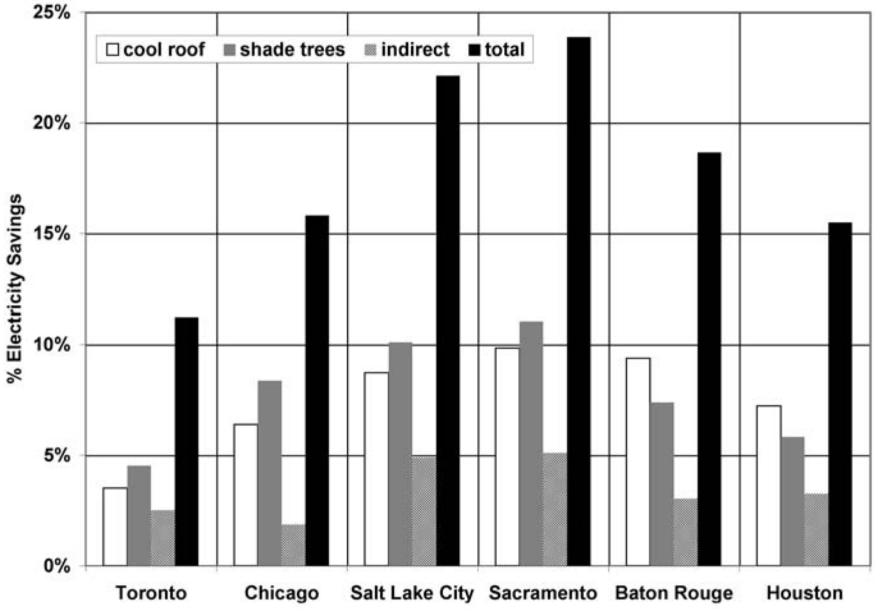
Air quality improvements

Heat island mitigation improves a community's air quality in three different ways. First, cooler communities use less energy and produce less pollution from power plants. Second, additional trees and vegetation remove more pollutants from the air. Third, cooler air temperatures slow down the formation of smog.

Table 8.3 Climatic characteristics of six North American cities that have been studied for their potential energy savings as a result of heat island mitigation

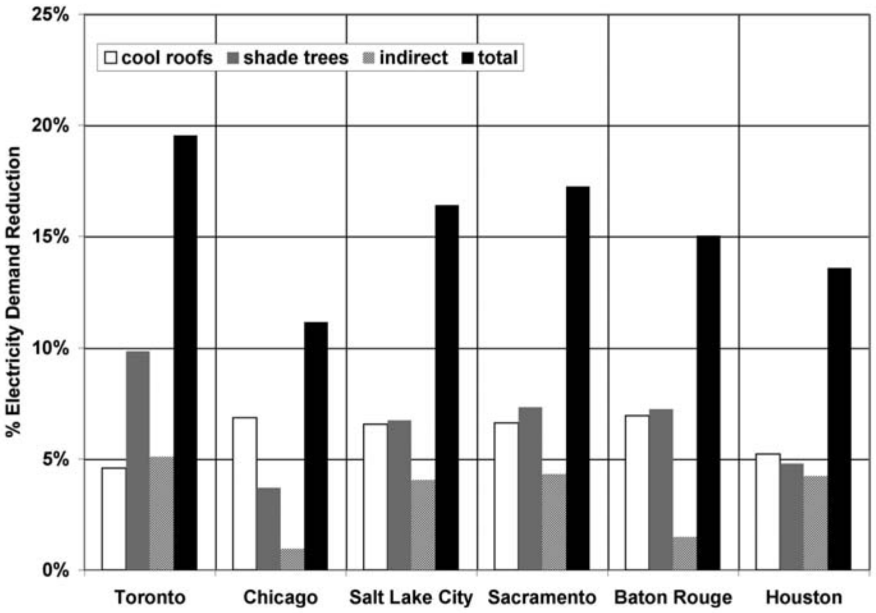
	Toronto	Chicago	Salt Lake City	Sacramento	Baton Rouge	Houston
Heating degree–days	3644	3607	3115	1481	967	847
@ 18.3°C (65°F)	(6560)	(6493)	(5607)	(2666)	(1740)	(1525)
Cooling degree–days	346	464	605	693	1458	1607
@ 18.3°C 65°F)	(623)	(835)	(1089)	(1248)	(2625)	(2893)
Peak temperature °C (°F)	26.5°C	28.6°C	32.6°C	33.6°C	33.3°C	34.2°C
Percentage possible	(79.7°F)	(83.5°F)	(90.6°F)	(92.4°F)	(91.9°F)	(93.6°F)
sunshine*	55	54	66	78	60	59
Afternoon relative						
humidity	85	80	67	83	91	90

Note * Percentage possible sunshine: The maximum possible sunshine varies according to latitude and time of year. The percentage possible sunshine measures how much sunshine reaches the ground, and is a measure of cloud cover and/or pollution, the higher the value, the clearer the atmosphere.



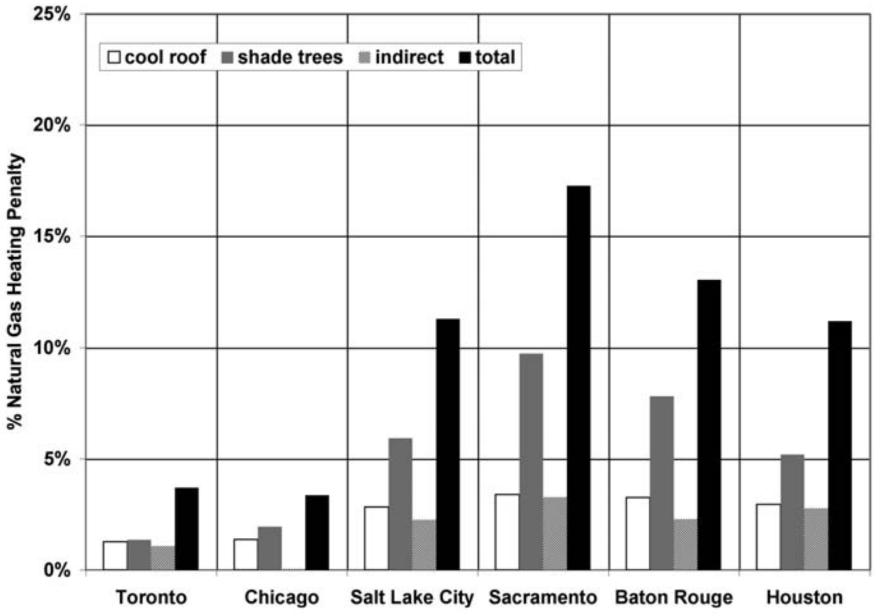
Source: Konopacki and Akbari, 2000, 2001, 2002.

Figure 8.2 The potential annual electricity savings in six North American cities as a percentage of the total electricity use



Source: Konopacki and Akbari, 2000, 2001, 2002.

Figure 8.3 The potential savings in peak annual electricity demand in six North American cities as a percentage of the total electricity demand



Source: Konopacki and Akbari, 2000, 2001, 2002.

Figure 8.4 The potential penalty in annual natural gas use for heating in six North American cities as a percentage of the total natural gas use

Direct emission reductions

When fossil fuels are burnt to create electricity or produce heat, various harmful by-products are emitted. If heat island measures are implemented, less energy is used during the summer and emissions can be reduced. In the winter, heat island mitigation measures tend to increase the amount of heat needed and increase fossil fuel emissions. However, in most cities, despite slightly higher wintertime emissions, the total annual emissions are reduced.

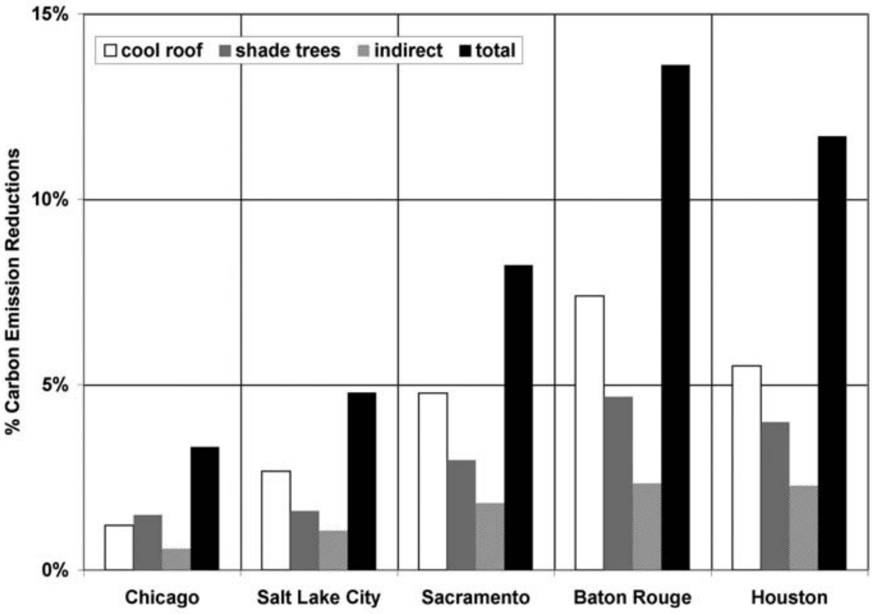
One by-product of fossil fuel combustion is carbon dioxide, a so-called 'greenhouse gas' that traps more heat in the Earth's atmosphere. Figure 8.5 shows how carbon emissions could be reduced by heat island mitigation in five cities in the US. These net reductions include both summertime decreases and wintertime increases in fossil fuel emissions.

Estimates for other emissions from fossil fuel combustion, such as sulphur dioxides and nitrogen oxides, have not been made. These emissions depend heavily on the amount of sulphur and nitrogen in the fuels being burned and the efficiency of power plants, boilers and heaters.

Pollutant removal by trees and vegetation

Trees and vegetation improve the quality of the atmosphere in two ways. First, during the process of photosynthesis plants absorb carbon dioxide from the air, storing the carbon for growth and emitting the oxygen back to the atmosphere. Second, leaves remove various pollutants from the air by a process called dry deposition. Pollutants removed include nitrogen oxides, sulphur oxides, particulates and ground-level ozone.

The magnitude of these two effects varies from city to city depending on the types of plants present, their level of maturity and growth



Source: Konopacki and Akbari, 2000, 2001, 2002.

Figure 8.5 The potential reduction in carbon emissions for five North American cities as a percentage of total carbon emissions

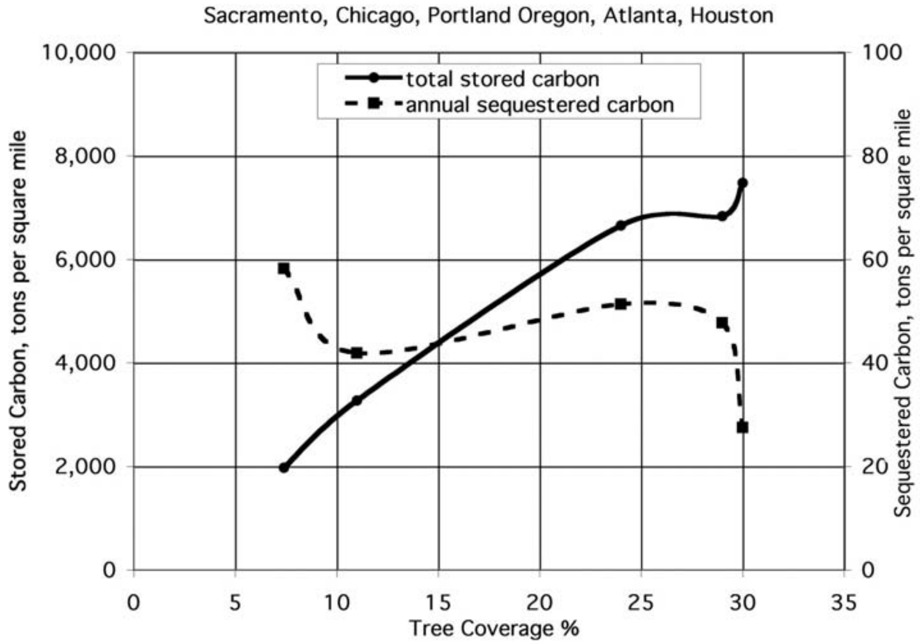
rate, and the local climate. Figures 8.6 and 8.7 show how much carbon and other pollutants are removed from the air by the trees in five different cities in the US. More details about these analyses are included in Chapter 7.

Decrease in ozone formation

The effects of heat island mitigation on ozone are extremely complex, because the formation of ozone is a complicated process. Ozone, which is the primary component of smog, does not come directly out of factory chimneys or car exhaust pipes, but is formed by a chemical reaction between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the air. The reaction depends on how much of these pollutants are in the air, how well they are mixed together and how hot the air is. The hotter the day, the more quickly the reaction occurs and the more smog is formed. Heat island mitigation measures have two effects on ozone formation. On one hand, cooler air temperatures reduce smog formation; on the other hand, some types of trees and vegetation emit VOCs to the air, increasing smog formation.

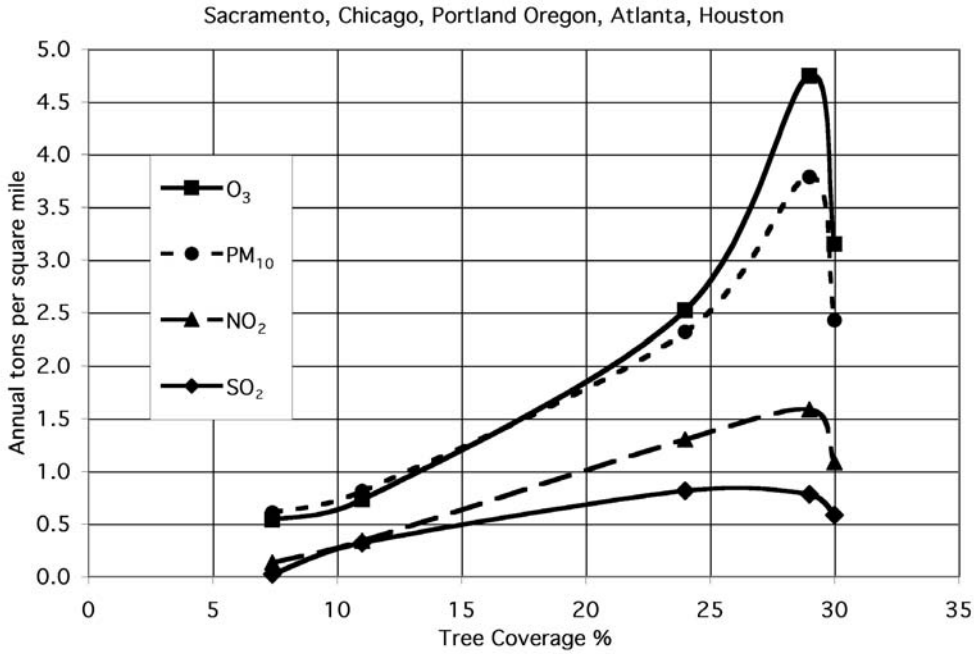
VOC emissions from trees and vegetation represent a sizable portion of the total VOC emissions in any area. For example, trees and vegetation emit 42 per cent of the total VOCs present in the Dallas–Fort Worth area and 65 per cent of the total in the Houston–Galveston area (Neece, 1998). As discussed previously in Chapter 7, VOC emissions from plants vary widely from species to species. Adding the wrong type of trees and vegetation to reduce the heat island can end up increasing ozone formation, so it is important to select trees and vegetation carefully.

Studies of various cities in the US show that heat island mitigation may reduce the rate of smog formation. A simulation of the meteorology and air quality in Los Angeles found that cooling the city by 6°F with cool surfaces and trees reduced smog by 10 per cent in certain areas of the city (Akbari and Douglas, 1995; Akbari et al, 1996). A similar study of



Source: McPherson et al, 1994; McPherson, 1998; American Forests, 2000, 2001a, 2001b.

Figure 8.6 Total stored carbon and annual carbon sequestration per square mile as a function of tree coverage percentage in five metropolitan areas in the US



Source: McPherson et al, 1994; Scott et al, 1998; American Forests, 2000, 2001a, 2001b.

Figure 8.7 Annual pollutant reduction due to deposition on trees in five metropolitan areas in the US as a function of tree coverage

Sacramento found that adding trees, cool roofing and cool paving lowered peak air temperatures by about 3°F and ozone concentration by 10 parts per billion, or 6.5 per cent (Taha et al, 2000). The effects of heat island mitigation on air quality have also been estimated for Baton Rouge, Salt Lake City and the Northeast corridor (Douglas et al, 2000; Taha et al, 2000). The estimated impacts for Baton Rouge and Salt Lake City are smaller than in Los Angeles, and are very mixed in the Northeast corridor.

One important finding from many of these studies is that smog reductions in one area of a city, usually the urban core, are usually accompanied by smog *increases* in downwind suburban or rural areas. Air quality modelling methodology is still subject to much scrutiny and refinement, as in work being done in Los Angeles (Emery et al, 2000). Work is ongoing to improve modelling techniques and to model regions with high ozone levels, particularly Houston and Los Angeles where ozone levels tend to be the highest in the US.

Human comfort and health improvements

Heat island mitigation measures can help to improve human comfort and health in three ways. First, they reduce heat-related problems, such as heat stress and related mortality. Second, they help to reduce air quality-related health problems, such as asthma. Third, they can reduce problems related to sunlight, such as skin cancer.

Heat-related health problems

As warm-blooded creatures, humans are constantly producing heat. The more active a person is, the more heat they generate, from about 100W (340 Btu/h) for a sedentary person up to as much as 1000W (3400Btu/h) for a person exercising strenuously (ASHRAE, 1993). To keep the body within a constant, healthy temperature range, this heat must be constantly dissipated to the environment.

Heat is transferred from the body through the skin, sweat and respiration. At comfortable temperatures and low activity levels, most heat is transferred from the skin, some heat is lost through respiration and very little sweating is needed. When the surrounding temperatures get higher and/or activity levels rise, the body is less able to transfer heat through the skin and respiration. The body must then begin to sweat in order to keep itself in balance. When the air becomes hotter than the skin at about 34°C (93°F), somewhat cooler than the core body temperature of 37°C (98.6°F), the air starts to heat the body instead of cooling it, and sweating becomes the only way for the body to cool itself. Drinking fluids is therefore very important to prevent heat stress.

Heat stress, or a rise in the body temperature, can occur fairly easily in hot weather, especially without proper hydration or when exercising. The results of prolonged heat stress range from mild to severe and include cramps, fainting, heat exhaustion, heat stroke and death.

Heat-related deaths have been found to increase strikingly during heat waves. One of the most notorious heat waves, a 5-day heat event in Chicago during July 1995, was deemed responsible for at least 700 excess deaths (Global Change, 1996; Kunkel et al, 1996; Livezey and Tinker, 1996; Klinenberg, 2002). Though it is rare to have such a large number of deaths associated with a heat wave, heat wave mortality is far from uncommon, as cities such as Philadelphia, New York, St Louis and Toronto can attest (Smoyer, 1998; Smoyer et al, 1999; EPA, 2000; Curriero et al, 2002; Sheridan, 2002; Wood, 2002).

Many simple indices of heat stress and mortality have been developed over the years to help predict when humans are most likely to be at risk (Quayle and Doehring, 1981). A more recent index has been developed by researchers at the University of Delaware and the National Oceanic and Atmospheric Administration (Gillis and Leslie, 2002). This index improves upon old indices in various ways (Kalkstein and Valimont, 1986; Kalkstein and Greene, 1997; Sheridan, 2002). First, individual indices are developed for each city, since each city has its own weather patterns and citizens seem to be somewhat adapted to them. Second, variables such as the duration of the heat wave and night-time minimum temperatures are included to better gauge the cumulative effects of heat stress. Also, the time of year is included, since heat waves in spring or early summer seem to cause more problems than high temperatures later in the summer.

The new index is now at work in many cities, such as Philadelphia, New York and Toronto, as the core of various heat and health watch programs (Kalkstein et al, 1996; Kalkstein, 2001; Kalkstein and Frank, 2001; Basrur, 2002; Hill, 2002). An alert system notifies the public about dangerous heat conditions and how to cope with them, and social service agencies open air-conditioned shelters and check on at-risk residents. Many of these programs are also implementing heat island mitigation in order to minimize urban temperatures and the risk of heat stress. For example, the Cool Aid program in Philadelphia is installing cool roof coatings on rowhouses to help keep occupants cool without increasing their use of air conditioning (Wood, 2002).

Heat island mitigation can offer a lot of help in reducing heat stress. Use of cool roofs and shade trees can keep indoor air temperatures much cooler during long-term heat events. As seen in the 1995 Chicago heat wave, many of the people who died lived in top-floor apartments under hot roofing, with windows facing south and west (Global Change, 1996; Huang, 1996). The addition of cool roofs, cool paving and trees and vegetation can cool outdoor air temperatures as well, potentially lowering temperatures by as much as 10°F. Even small temperature differences of a degree or two can make a life-saving difference by preventing heat stress.

Air quality-related health problems

Many studies have looked at the potential effects of global warming on air quality and human health. Global warming and heat islands are two separate phenomena, but some of the conclusions about the effects of higher temperatures due to global warming apply to the heat island as well. Of particular concern are effects on lung function and allergies.

As already outlined in this chapter, heat island mitigation can help reduce energy use and its associated power plant emissions, and can reduce the formation of ozone. Ground-level ozone has been found to exacerbate respiratory diseases by damaging lung tissue, reducing lung function and sensitizing the lungs to other irritants (Patz et al, 2000). Studies of children in California have found that high ozone levels not only increase the likelihood of asthma attacks, but reduce lung growth and function (CAARB, 2002a, 2002b). Other air pollutants, such as particulate matter, carbon monoxide, sulphur dioxide and nitrogen oxides can also damage lung tissue, irritate lungs and aggravate respiratory illness and cardiovascular disease (Patz et al, 2000).

In addition to affecting air pollution, heat islands may also increase plant allergens. Warmer urban temperatures enhance pollen production, increasing seasonal allergies such as hay fever and increasing the occurrence and severity of asthma attacks (Patz et al, 2000).

Sunlight-related health problems

The ultraviolet rays in sunlight can have adverse effects on the skin and eyes. Long-term exposure to high levels of ultraviolet rays are linked to higher occurrences of the three main types of skin cancer: basal cell carcinoma, squamous cell carcinoma, and the most serious type of skin cancer, malignant melanoma. As shown in Table 8.4, the incidence of skin cancer has been rising dramatically in the US. The National Cancer Institute now predicts that one in seven people in the US will develop some form of skin cancer in their lifetime (MCW, 2002).

Stratospheric ozone blocks most of the ultraviolet rays in sunlight, but recent declines in the ozone layer may be increasing the amount of ultraviolet energy reaching different parts of the Earth. Over the Antarctic, in addition to the year-round hole in the ozone layer, the concentration of ozone overhead (also called the total column ozone amount) has shown decreases of up to 70 per cent during the springtime. Over the Arctic, decreases of up to 30 per cent in overhead ozone have been measured. At mid-latitudes in the Southern Hemisphere, ozone decreases of about 6 per cent have been observed year-round. In the Northern Hemisphere, the largest ozone decreases of up to 4 per cent happen during winter and spring, with summer and autumn decreases of up to 2 per cent. These overhead ozone decreases have so far translated into increases in ultraviolet radiation of 6–14 per cent at various mid- and high-latitude sites in both hemispheres (UNEP/WMO, 2002).

The reported rise in skin cancer rates may be being exacerbated by increases in the amount of ultraviolet radiation reaching the Earth. Increases of this scale are predicted to increase the rate of non-melanoma skin cancers by as much as 36 per cent throughout the world, with melanoma skin cancers increasing as much as 0.6 per cent for every 1 per cent reduction in ozone (Urbach, 1991).

Shade from trees and other vegetation can protect against excessive sun exposure. People are currently warned to wear sunscreen, protective clothing and hats to reduce exposure, but shade from trees can add more protection. The level of ultraviolet protection from trees varies widely based on how much sunlight the tree transmits. The transmissivity of trees was found to vary from 8 to 38 per cent for different tree species in full leaf (Brown and Gillespie, 1990).

Areas where people congregate often lack tree cover. School yards, playgrounds, sports fields, squares and other public spaces can use a few strategic trees to give the option of protection from the sun. It is especially important to protect children from the sun, since exposure to ultraviolet rays early in life may lead to skin cancer years later.

Table 8.4 Incidence of skin cancer in the US

	1995	2001	Increase
Non-melanomas	~800,000	> 1,000,000	25%
Malignant melanoma	34,100	51,400	50%

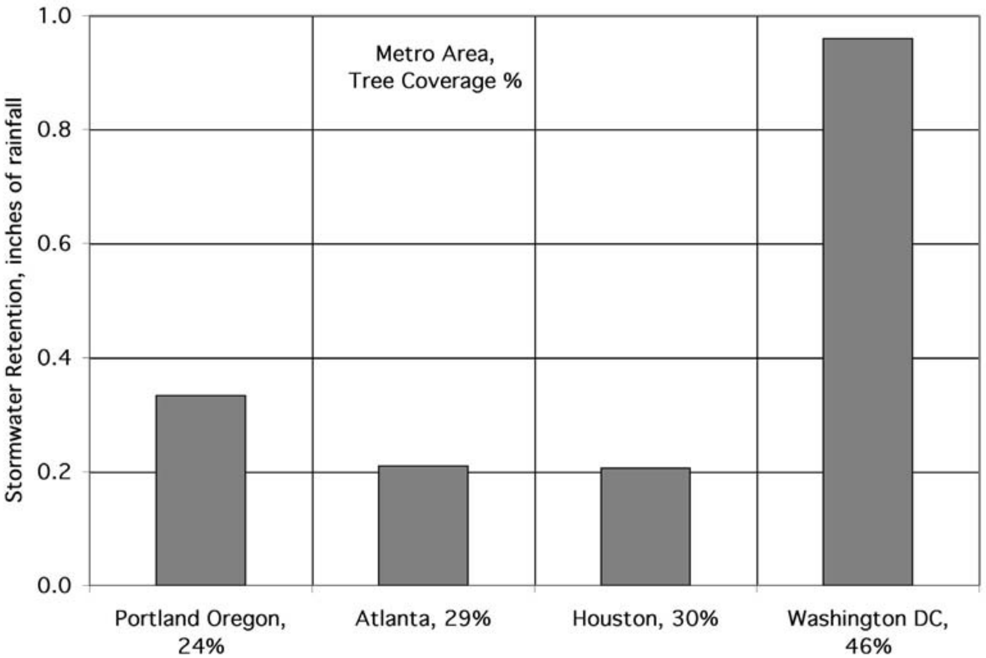
Source: MCW, 2002.

Stormwater run-off reductions

Two strategies for mitigating the heat island can also reduce the amount of stormwater run-off: (1) trees and vegetation and (2) permeable pavements. Exposed soil can soak up only so much water during a rainstorm. If the rain falls too fast or the ground becomes saturated, the remaining rainfall becomes run-off. Run-off problems are exacerbated in cities and suburbs by the large amounts of paved, impervious surfaces. In most communities, the remaining exposed soil cannot absorb rain that drains from adjacent paved surfaces and buildings. Expensive drains and sewers must be engineered to manage the stormwater and prevent flooding.

Reducing stormwater run-off can decrease the size of, or even the necessity for, expensive drain systems. This can reduce the energy needed to pump stormwater to its final destination and also save the money and labour used to run and maintain these systems

Trees and vegetation catch rainfall on their leaves, branches and trunks, reducing and slowing the amount of water hitting the ground. In a Sacramento study, evergreens and conifers were found to intercept up to 36 per cent of summer rainfall in Sacramento (Xiao et al, 1998). The urban forest can retain significant amounts of rainwater. Figure 8.8 shows the estimated stormwater retention per square mile due to the tree cover in the cities of Portland, Atlanta, Houston and Washington DC, where trees cover 24, 29, 30 and 46 per cent of these urban areas, respectively. Urban trees are able to capture between 5 and 25mm (0.2 and 1.0 inches) of rainfall, enough to help manage the water from small rainstorms.



Source: American Forests, 2000, 2001a, 2001b, 2002.

Figure 8.8 Stormwater retention, in inches of water, for urban forests in four metropolitan areas in the US

Green roofs are another way to absorb stormwater. Roofs with 200 to 400mm (8–16 inches) of soil can retain between 100 and 150mm (4 and 6 inches) of rainwater over the roof surface. In Portland, Oregon, green roofs have been found to capture between 10 and 100 per cent of the rainwater that falls on them, depending on how saturated the roof's soil is. In dry summer weather, close to 100 per cent of the rainfall can be absorbed, but in wetter winter conditions only 10–20 per cent of rainfall can be retained by the roof (Dawson, 2002; Portland, 2002).

Permeable pavements, or pavements that allow water to soak into the pavement, are also effective at reducing stormwater run-off. Outdoor testing and laboratory measurements have found that permeable pavements can reduce run-off by up to 90 per cent (James, 2002). The amount of water that can be collected varies depending on the type of soil used and the size of the interstices in the pavements, as well as on the absorption ability of the materials supporting the pavement. There are many types of porous or permeable pavements available. Block pavers can be filled with soil and grass or with small rocks. Traditional asphalt and concrete pavements can also be made porous by leaving out sand and small aggregates from the concrete mix.

Besides being difficult to manage, stormwater run-off also tends to bring pollutants and heat from urban surfaces to local streams. Run-off, not being filtered by the soil, tends to retain higher levels of nitrates, acid, heavy metals, oil and grease (James, 2002). Pavements can also significantly warm rainfall. Tests have shown that run-off from 23°C (73°F) rainfall can be heated to over 35°C (95°F) by pavement temperatures of about 38°C (100°F) (James and Verspagen, 1996). The pollution and warmer temperatures of stormwater run-off degrade the water quality and aquatic life of streams and ponds.

Maintenance and waste reduction

Asphalt-based roofing and paving materials tend to suffer from the effects of sun and heat. Ultraviolet radiation from the sun fosters a chemical reaction that degrades asphalt-based materials, and the warmer the material, the faster this reaction occurs. Daily temperature swings, from hot during the day to cold at night, cause materials to swell and contract repeatedly. Over time, these chemical and mechanical processes make many roofs and pavements brittle, and the recurring thermal stresses cause materials to crack.

Cooling asphalt-based roofing and paving materials can give them a significantly longer life. Tests on asphalt pavements have shown that pavements that are 11°C (20°F) cooler last 10 times longer, and pavements that are 22°C (40°F) cooler took 100 times longer to show permanent damage (Pomerantz et al, 2000). A test of worn asphalt-based roofing materials found that covering the roof with a cool elastomeric coating completely stopped the asphalt underneath from degrading further (Antrim et al, 1994).

A longer life means that the materials will not need to be repaired or replaced as often. This can save an enormous amount of money on repaving and re-roofing. Tables 8.5 and 8.6 show expenditures for road improvements during 1999 and roofing industry sales during 2001, both in the US. Work to maintain 17,964 miles of existing roads was projected to cost $7.05 billion in 1999. Re-roofing and repair and maintenance of existing roofs cost $22.15 billion in 2001. If the use of cool materials made pavements and roofing last just 10 per cent longer, a potential $3 billion would be saved annually in the US alone.

The use of longer lasting roofing and paving materials also has the potential to reduce the amount of waste being sent to landfills. Table 8.7 shows how much paving and roofing debris is produced, recycled and thrown away annually in the US. A significant portion of the 114 million tons of pavement and roofing debris produced annually in the US is being recycled. Most of the asphalt pavement, and probably most of the concrete pavement, is recycled back into road base or new pavement, or is used as fill under building construction projects (Schroeder, 1994). At this point, very little roofing waste is recycled, but the potential exists to recycle it into asphalt pavement, road base or road patching compounds (CIWMB, 2001). However, even with material recycling, at least 31 million tons of road and roofing materials is sent to landfills every year. Not only does this take up dwindling landfill space, but the cost of dumping waste ranges between $18 and $60 a ton (Foo et al, 1999). If roads and roofs lasted 10 per cent longer, 3 million tons of waste disposal could be avoided annually, for a conservative saving of $60 million.

Table 8.5 Cost of US road improvement projects authorized in fiscal year 1999

Improvement type	Number of miles	Cost	Percentage of total cost
New construction	349	$1.90 billion	13.8%
Relocation	162	$0.35 billion	2.5%
Reconstruction – added capacity	1029	$2.31 billion	16.7%
Reconstruction – no added capacity	1869	$1.94 billion	14.1%
Major widening	734	$1.73 billion	12.6%
Minor widening	704	$0.44 billion	3.2%
Restoration and rehabilitation	3980	$2.13 billion	15.5%
Resurfacing	12,115	$2.98 billion	21.6%
Total	*20,942*	*$13.78 billion*	*100%*

Source: USDOT, 2000.

Table 8.6 Roofing industry sales in the US during 2001

	Low-slope roofing	Steep-slope roofing	Total
New construction	$4.75 billion	$3.28 billion	$8.03 billion
Re-roofing	$11.76 billion	$6.66 billion	$18.42 billion
Repair and maintenance	$2.5 billion	$1.23 billion	$3.73 billion
Total	*$19.01 billion*	*$11.17 billion*	*$30.18 billion*

Source: Hinojosa and Kane, 2002.

Table 8.7 Estimates of pavement debris and roofing debris produced and recycled annually in the US

	Debris produced annually	Debris recycled annually	Debris to landfills annually
Concrete pavement	3 million tons	unknown	unknown
Asphalt pavement	100 million tons	80 million tons	20 million tons
Roofing shingles	11 million tons	< 0.1 million tons	11 million tons
Total	*114 million tons*	*at least 80 million tons*	*at least 31 million tons*

Source: Schroeder, 1994; CIWMB, 1996, 1999, 2001; Foo et al, 1999.

Quality of life benefits

Heat island mitigation brings many aesthetic benefits to a community, including noise reduction, improvement of the ecosystem and aesthetic improvements.

Noise reduction is an especially useful benefit for urban areas. Table 8.8 lists the decibel levels of common sounds in the urban environment. Heat island mitigation measures are useful for reducing outdoor noise levels, such as those of street traffic. Various studies have found that a well-placed tree can reduce urban noise by as much as 15 decibels, about as well as a typical masonry sound barrier (Nowak and Dwyer, 2000). Porous pavements such as open-graded asphalt and permeable concrete have also been found to reduce traffic noise by 2–8 decibels and to keep noise levels below 75 decibels (Glazier and Samuels, 1991; Hughes and Heritier, 1995; Pipien, 1995). The pores in these pavement surfaces absorb the noise of tyres rolling along the pavement.

Adding trees and vegetation to urban areas – either in parks, along streets, in parking lots or in a garden roof – improves the local ecosystem by giving birds, animals and insects a home. The quality of this home is even better if native plant species are chosen and reintroduced to the urban

Table 8.8 Common sounds in decibels

Sound	Decibel level	Listener's perception
Whisper	10	Barely audible
Quiet conversation	30	Faintly heard
Average office	50	Moderate level
Summer nocturnal insects	60	Moderate level
Noisy office	70	Loud
Average street traffic	85	Very loud
Jackhammer	100	Extremely loud
Jet aircraft taking off	120	Physical pain

landscape. Humans have a better home as well, since community gardens and parks have been found to reduce physiological stress, improve well-being, reduce domestic conflict and decrease school aggression (Wolf, 1998).

Our communities do not have to be lifeless and drab. The use of landscaping, green roofing and cool paving can bring colour, design and beauty to traditionally barren areas of our communities.

References

Akbari, H. and S. G. Douglas (1995) *Modeling the Ozone Air Quality Impacts of Increased Albedo and Urban Forest in the South Coast Air Basin*. Berkeley, CA, Lawrence Berkeley National Laboratory: 150

Akbari, H. and L. S. Rose (1999) *Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento, California*. Berkeley, CA, Lawrence Berkeley National Laboratory: 48

Akbari, H., A. Rosenfeld. H. Taha and L. Gartland (1996) *Mitigation of Summer Heat Islands to Save Electricity and Reduce Smog*. American Meteorological Society Annual Meeting, Atlanta, GA, American Meteorological Society

American Forests (2000) *Urban Ecosystem Analysis for the Houston Gulf Coast Region*. Washington DC, American Forests: 12

American Forests (2001a) *Regional Ecosystem Analysis for the Willamette/Lower Columbia Region of Northwestern Oregon and Southwestern Washington State*. Washington DC, American Forests: 16

American Forests (2001b) *Urban Ecosystem Analysis for the Atlanta Metro Area*. Washington DC, American Forests: 8

American Forests (2002) *Urban Ecosystem Analysis for the Washington DC Metropolitan Area*. Washington DC, American Forests: 16

Antrim, R., C. Johnson, W. Kirn, W. Platek and K. Sabo (1994) *The Effects of Acrylic Maintenance Coatings on Reducing Weathering Deterioration of Asphaltic Roofing Materials*. ASTM Symposium on Roofing Research and Standards Development, Montreal, American Society for Testing of Materials

ASHRAE (1993) *Handbook of Fundamentals*. Atlanta, GA, American Society of Heating, Refrigerating and Air-Conditioning Engineers

Basrur, S. (2002) *Community Response to Extreme Summer Heat*. North American urban Heat Island Summit, Toronto, Toronto Atmospheric Fund

Brown, R. D. and T. J. Gillespie (1990) 'Estimating radiation received by a person under different species of shade trees'. *Journal of Arboriculture* **16**(6): 158–161

CAARB (2002a) *Fact Sheet – The Children's Health Study*. Sacramento, CA, California Air Resources Board

CAARB (2002b) *New Findings Link Reduced Lung Growth and Air Pollution*. Sacramento, CA, California Air Resources Board

CIWMB (1996) *Market Status Report: Recycled Inerts*. Sacramento, CA, California Integrated Waste Management Board

CIWMB (1999) *Asphalt Pavement Recycling*. Sacramento, CA, California Integrated Waste Management Board

CIWMB (2001) *Asphalt Roofing Shingles Recycling: Introduction*. Sacramento, CA, California Integrated Waste Management Board

Curriero, F. C., K. S. Heiner, J. M. Sarnet, S. L. Zeger, L. Strug and J. A. Patz (2002) 'Temperature and mortality in 11 cities of the eastern United States'. *American Journal of Epidemiology* **155**(1): 80–87

Dawson, D. (2002) 'Plant-covered roofs ease urban heat'. *National Geographic News* 15 November

Douglas, S. G., A. B. Hudischewskyj and V. Gorsevski (2000) *Use of the UAM-V Modeling System as an Air Quality Planning Tool for Examining Heat Island Reduction Strategies*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Emery, C., H. Taha and G. Gero (2000) *City of Los Angeles Cool Communities Program, Technical Review of Air Quality Modeling*. Los Angeles, CA, Environmental Affairs Department

EPA (2000) *Vegetated Roof Cover, Philadelphia, Pennsylvania*. Washington DC, US Environmental Protection Agency, Office of Water: 3

Estes, M. G., V. Gorsevski, C. Russell, D. Quattrochi and J. Luvall (1999) *The Urban Heat Island Phenomenon and Potential Mitigation Strategies*. Proceedings of American Planning Association, Seattle, WA, American Planning Association

Foo, K.Y., D. I. Hanson and T. A. Lynn (1999) 'Evaluation of roofing shingles in hot mix asphalt'. *Journal of Materials in Civil Engineering* February

Gillis, C. and J. Leslie (2002) 'NOAA unveils new method to warn of heat waves, save lives'. *NOAA Magazine* 21 June

Glazier, G. and S. Samuels (1991) 'Effects of road surface texture on traffic and vehicle noise'. *Transportation Research Record* **1312** (Energy and Environmental Issues): 141–144

Global Change (1996) 'Heat waves take heavy toll on urban poor'. *Global Change* February: 12–13

Gorsevski, V., H. Taha, D. Quattrochi and J. Luvall (1998) *Air Pollution Prevention Through Urban Heat Island Mitigation: An Update on the Urban Heat Island Pilot Project*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Hill, D. (2002) *Castaways on the Urban Heat Island*. North American Urban Heat Island Summit, Toronto, Toronto Atmospheric Fund

Hinojosa, O. and K. Kane (2002) 'A measure of the industry'. *Professional Roofing* April: 24–28

Huang, J. (1996) *Urban Heat Catastrophes: The Summer 1995 Chicago Heat Wave*, Center for Building Science Newsletter, Lawrence Berkeley National Laboratory, Berkeley, CA, Fall

Hughes, J. and B. Héritier (1995) 'Tapiphone – A technique for reducing noise in towns'. *Revue Générale des Routes et Aérodromes* **735**: 37–40

James, W. (2002) 'Green roads: Research into permeable pavers, investigations of infiltration capacity, pavement leachate, and runoff temperature'. *Stormwater, The Journal for Surface Water Quality Professionals* March/April: 49–50

James, W. and B. Verspagen (1996) *Thermal Enrichment of Stormwater by Urban Paving*. Stormwater and Water Quality Modelling Conference, Toronto, 22–23 February

Kalkstein, L. S. (2001) *Heat Health Watch Warning Systems*. Newark, DE, University of Delaware, Center for Climatic Research

Kalkstein, L. S. and K. L. Frank (2001) *The Health Implications of Greenhouse Gas Emissions*. Emerging Growth Issues Workshop, Newark, DE, University of Delaware, Center for Climatic Research

Kalkstein, L. S. and J. S. Greene (1997) 'An evaluation of climate/mortality relationships in large US cities and the possible impacts of climate change'. *Environmental Health Perspectives* **105**: 84–93

Kalkstein, L. S. and K. M. Valimont (1986) 'An evaluation of summer discomfort in the United States using a relative climatological index'. *Bulletin of the American Meteorological Society* **67**(7): 842–848

Kalkstein, L. S., P. F. Jamason, J. S. Greene, J. Libby and L. Robinson (1996) 'The Philadelphia hot weather-health watch/warning system: Development and application, summer 1995'. *Bulletin of the American Meteorological Society* **77**(7): 1519–1528

Klinenberg, E. (2002) *Heat Wave: A Social Autopsy of Disaster in Chicago*. Chicago, University of Chicago Press

Konopacki, S. and H. Akbari (2000) *Energy Savings Calculations for Heat Island Reduction Strategies in Baton Rouge, Sacramento and Salt Lake City*. Berkeley, CA, Lawrence Berkeley National Laboratory: 71

Konopacki, S. and H. Akbari (2001) *Energy Impacts of Heat Island Reduction Strategies in Toronto, Canada*. Berkeley, CA, Lawrence Berkeley National Laboratory

Konopacki, S. and H. Akbari (2002) *Energy Savings for Heat Island Reduction Strategies in Chicago and Houston (Including Updates for Baton Rouge, Sacramento, and Salt Lake City)*. Berkeley, CA, Lawrence Berkeley National Laboratory: 48

Kunkel, K., S. Changnon, B. Reinke and R. Arritt (1996) 'The July 1995 heat wave in the Midwest: A climatic perspective and critical weather factors'. *Bulletin of the American Meteorological Society* **77**(7): 1507–1517

Livezey, R. and R. Tinker (1996) 'Some meteorological, climatological and microclimatological considerations of the severe U.S. heat wave of mid-July 1995'. *Bulletin of the American Meteorological Society* **77**(9): 2043–2054

Lo, C. P., D. Quattrochi and J. Luvall (1997) 'Application of high-resolution thermal infrared remote sensing and GIS to assess the urban heat island effect'. *International Journal of Remote Sensing* **18**(2): 287–304

Luvall, J. and D. Quattrochi (1998) *Thermal Characteristics of Urban Landscapes*. 23rd Conference on Agricultural and Forest Meteorology, Albuquerque, NM

McPherson, E. G. (1998) 'Atmospheric carbon dioxide reduction by Sacramento's urban forest'. *Journal of Arboriculture* **24**(4): 215–223

McPherson, E. G., D. J. Nowak and R. Rowntree (1994) *Chicago's Urban Forest Ecosystem: Results of the Chicago Urban Forest Climate Project*. Radnor, PA, US Department of Agriculture Forest Service, Northeastern Forest Experiment Station: 201

MCW (2002) *Skin Cancer Cases, Often Preventable, Are on the Rise*. Milwaukee, WI, Medical College of Wisconsin

Minnesota Landscape Arboretum (1993) *Third Annual Parking Lot Conference*. Parked Art, Beyond Asphalt and Plants, the Parking Lot as a Piece of Art! Minnesota Landscape Arboretum, University of Minnesota

Neece, J. D. (1998) *VOC and NOx Emissions in Texas: 1996 SIP Modeling Emissions Inventory*. Austin, TX, Texas Natural Resource Conservation Commission

Nowak, D. J. and J. F. Dwyer (2000) 'Understanding the benefits and costs of urban forest ecosystems', in Kuser, J. E. (ed), *Handbook of Urban and Community Forestry in the Northeast*. New York, Kluwer Academic/Plenum Publishers: 11–25

Patz, J. A., M. A. McGeehin, S. M. Bernard, K. L. Ebi, P. R. Epstein, A. Grampsch, D. J. Gubler, P. Reiter, I. Romieu, J. B. Rose, J. M. Samet and J. Trtanj (2000) 'The potential health impacts of climate variability and change for the United States: Executive summary of the report of the health sector of the U.S. national assessment'. *Environmental Health Perspectives* **108**(4)

Pipien, G. (1995) 'Pervious cement concrete wearing course offering less than 75 dB(A) noise level'. *Revue Générale des Routes et Aérodromes* **735**: 33–36

Pomerantz, M., H. Akbari amd J. T. Harvey (2000) *Durability and Visibility Benefits of Cooler Reflective Pavements*. Berkeley, CA, Lawrence Berkeley National Laboratory: 23

Portland (2002) *City of Portland EcoRoof Program Questions and Answers*. Portland, OR, Bureau of Environmental Services, Office of Sustainable Development, City of Portland, Oregon: 12

Quattrochi, D., J. Luvall, S. Q. Kidder, C. P. Lo, H. Taha, R. D. Bornstein, R. R. Gillies, K. Gallo and M. G. Estes (1997) *Project ATLANTA – A Remote Sensing-Based Study of Past and Future Land Use Change Impacts on Climate and Air Quality of the Atlanta, Georgia, Metropolitan Region*. Huntsville, AL, Global Hydrology and Climate Center, National Aeronautics and Space Administration: 67

Quayle, R. and F. Doehring (1981) 'Heat stress, a comparison of indices'. *Weatherwise* June: 120–124

Schroeder, R. L. (1994) *The Use of Recycled Materials in Highway Construction*. Washington DC, Federal Highway Administration, US Department of Transportation: 13

Scott, K., E. G. McPherson and J. R. Simpson (1998) 'Air pollutant uptake by Sacramento's urban forest'. *Journal of Arboriculture* **24**(4): 224–234

Sheridan, S. C. (2002) *The Development of the New Toronto Heat–Health Alert System*. North American Urban Heat Island Summit, Toronto, Toronto Atmospheric Fund

Smoyer, K. E. (1998) 'A comparative analysis of heat waves and associated mortality in St. Louis, Missouri: 1980–1995'. *International Journal of Biometeorology* **42**: 44–50

Smoyer, K. E., D. G. C. Rainham and J. N. Hewko (1999) *Integrated Analysis of Heat-Related Mortality in the Toronto–Windsor Corridor*. Waterloo, Ontario, Environment Canada

Taha, H. (1997) 'Modeling the impacts of large-scale albedo changes on ozone air quality in the south coast air basin'. *Atmospheric Environment* **31**(11): 1667–1676

Taha, H., S. C. Chang and H. Akbari (2000) *Meteorological and Air Quality Impacts of Heat Island Mitigation Measures in Three U.S. Cities*. Berkeley, CA, Lawrence Berkeley National Laboratory

UNEP/WMO (2002) *Executive Summary, Scientific Assessment of Ozone Depletion: 2002*. Geneva, World Meteorological Organization

Urbach, F. (1991) 'Potential health effects of climatic change: Effects of increased ultraviolet radiation on man'. *Environmental Health Perspectives* **96**: 175–176

USDOT (2000) *Highway Statistics 1999*. Washington DC, US Department of Transportation: 192

Wolf, K. (1998) *Urban Nature Benefits: Psycho-Social Dimensions of People and Plants*. Seattle, WA, Center for Urban Horticulture, College of Forest Resources, University of Washington

Wood, A. R. (2002) 'Saving lives with white roofs, A pilot program in Philadelphia could be used in other cities'. *Philadelphia Inquirer* 5 May, Philadelphia, PA

Xiao, Q., E. G. McPherson, J. R. Simpson and S. L. Ustin (1998) 'Rainfall interception by Sacramento's urban forest'. *Journal of Arboriculture* **24**(4): 235–244

9

Cool Community Action Plan

This chapter outlines the steps a community can take to develop and implement a heat island mitigation action plan. Here we lay out six steps to spur heat island mitigation: (1) Motivate, (2) Investigate, (3) Educate, (4) Demonstrate, (5) Legislate, and (6) Initiate.

The three main heat island mitigation strategies, cool roofing, cool paving and trees and vegetation, are far from being standard practice in the construction industry. For example, in the US, cool roofing is installed on less than 10 per cent of roofs (Hinojosa and Kane, 2002); cool paving, excluding concrete pavements, is almost non-existent, and concrete covers less than 25 per cent of paved surfaces (USDOT, 2000; Hawbaker, 2002). The planting of trees and vegetation has been somewhat more successfully implemented, but there is still an estimated deficit of 634.4 million urban trees in the US (American Forests, 2002).

The main reason these measures are not being widely adopted is a lack of knowledge about heat islands in general and these measures and their benefits in particular. Education and the building of support must be the core of any successful push for change. While it is tempting for a small group of people to jump straight in to writing ordinances and legislation, these efforts will be more successful if background work is done first.

Motivate

A successful cool community program involves members of the community, educates and motivates them, and uses their energy and connections. For a good start to your program, the following steps are strongly recommended:

Form an organization

A cool community program needs a home base and staff. Successful cool community programs have been housed in non-profit organizations or in local government environmental or energy departments. For example, the Sacramento Cool Community Program was a project of the non-profit Sacramento Tree Foundation, the Salt Lake City program was part of the Utah Office of Energy Services and the Los Angeles Cool Community Program was established within the Los Angeles Department of Environmental Health.

While a program could certainly operate on its own, there are certain advantages to being part of a larger organization. First, that organization may be willing to make a commitment to staff and fund a new program, at least until it brings in its own funding or perhaps even into the foreseeable future. Second, a larger organization already has standing in and knowledge about the community, experienced staff and alliances with other community groups. Third, the important logistics of office space and equipment are generally supplied and overhead costs for staff may be covered.

Depending on funding levels, a cool community office is typically operated by one full-time program leader and a few part-time staff or interns. To make real progress on cool community issues, it is recommended that a program be staffed with at least one full-time project leader with no other conflicting duties.

Find partners

A cool community program will be most effective if it works with other parties from the local community to oversee, plan and participate in the work. These partners can sit on a steering committee and/or on work groups related to various projects. It is important to bring in representative partners from local government, industry, non-profit organizations and neighbourhood groups to keep the community aware of your progress and to involve all sectors in the effort. Look for partners from the following places:

- from local government and school districts:
  - facilities or general services
  - transportation
  - public works
  - tree specialists
  - public electric and water utilities.
- from industry:
  - roofing contractors, distributors, manufacturers and trade groups
  - paving contractors, distributors, manufacturers and trade groups
  - landscaping/horticultural firms and associations
  - developers
  - architects and architectural trade associations
  - private electric utilities
  - large companies that own property in your community.
- from the non-profit sector:
  - environmental organizations
  - air quality management districts
  - tree protection/promotion groups.
- from the community:
  - neighbourhood groups
  - local planning councils.

Look for partners who can provide financial contributions or other in-kind services. A partner may not be able to donate money to the program, but may agree to sponsor a website, provide mailing addresses or cover the cost of mailings. Other partners may be able to provide meeting space, sponsor a breakfast or lunchtime seminar, or any number of other useful services. Remember that for a successful alliance, partners must benefit from their donation of time and other contributions. Recognize that your partners expect something in return, such as information and education about new technologies, access to new products, positive publicity, new customers and especially progress in the community. By ensuring that partners benefit directly or indirectly from their affiliation with the program, the long-term success of your program also benefits. It is useful to have partners sign a memorandum of agreement laying out the goals of the partnership, the roles of each partner, the time commitment involved, the nature of any financial or in-kind contributions being made, and the length of the partnership.

Pass a resolution

One way to inform and motivate the community about a cool community program is to get the City Council or other organizations (for example, air quality boards and planning commissions) to pass a resolution of support. A resolution does not necessarily mean the city will support the program with funding, but it does show that a community is aware of and interested in addressing the heat island problem.

A resolution generally contains a list of 'whereas' phrases that state the nature of the heat island problem and the expected benefits of reducing it, then a 'be it resolved' closing outlining any commitments from the city and recognizing your program as the leader in managing heat island solutions. To pass a resolution, expect to attend at least two council meetings, one to make an informative presentation about heat island mitigation and your new organization, and at least one more meeting to bring up and pass a resolution of support. A council presentation is a great opportunity to educate both the council and the community. Try to generate a large audience for the meeting by giving notice to the press and sending announcements to potentially interested industry and community members. Bring in a national expert if possible and line up the press for interviews.

If politics and budgets are favourable, the resolution can potentially include a commitment of funding for your program. To increase the likelihood of obtaining funding, remember that governments are often more likely to fund a program if there are other partners and support already committed to the program. It is also best to request funding only for a finite time period, usually no more than a couple of years.

Obtain funding

Finding support for your program is vitally important to its ultimate success. There are two types of support that must be obtained: operational support to cover staff salaries and day-to-day expenses, and project support to cover specific implementation activities. Operational support is often used at the beginning of a program to pay for some active progress, but also to cover the writing of proposals and other types of fundraising. Project support is used as the program matures to fund existing staff or bring in more staff to work on specific jobs.

Several funding opportunities have already been mentioned, such as finding an existing organization to house the program and cover staff salaries, finding partners to donate funds or in-kind services and asking for funds from local government councils. Other common forms of support include grants and fundraising events.

There are many grants potentially suitable for various aspects of heat island mitigation from federal, state and local energy and environmental agencies. However, instead of applying out of the blue to any likely request for proposal (RFP), it helps tremendously to have an inside track with agencies before applying. By the time an RFP is posted, an agency typically has already developed the framework for what type of projects they will fund. It is important to learn about the work of the agency, see what projects they have traditionally funded, and meet with their staff to learn about their interests and find potential common ground. It may be helpful to give a seminar about heat island mitigation to the funding agency. In order to find a funding match, and not waste too much effort responding to unlikely sources, it is necessary to make sure that potential funding sources are aware of the problems associated with heat islands and the possible mitigation strategies available.

Potential funding agencies to investigate include:

- international, national, regional or local governmental environmental, energy and transportation agencies, such as the International Energy Agency, European Environment Agency, US Department of Energy and the US Environmental Protection Agency
- public utilities commissions or industry overseer agencies
- air quality management districts
- public or private utilities.

There are also many corporations and non-profit organizations that provide local grants for environmentally beneficial projects. Familiarize yourself in advance with these groups as much as possible. You are more likely to get grants from locally headquartered corporations or from organizations that fund your specific community than from any national RFPs. However, it is important to know in advance what the goals of the organization are and to tailor your grant proposal to meet those goals.

Writing a proposal is an opportunity to be creative, yet flexible, while laying out a project that benefits both the cool community program and the grantor. Certain types of proposals have a greater chance of receiving funding. Consider writing a proposal to retrofit the granting agency's property as a demonstration. Tree planting in economically depressed neighbourhoods is often viewed favourably. Educational projects for schoolchildren or retrofits of schools are also popular.

For many RFPs it is essential to bring in other partners, since some grants cover only a percentage of a project's budget. It may be possible to find contractors or manufacturers who are willing to discount their services in order to demonstrate a new product or application.

There are many other methods of fundraising. Many organizations hold annual fundraising events such as a black-tie dinner. For events with a cool community theme, auction or raffle off a new cool roof or 'sell' paving stones or trees that will be installed in a community garden or pavilion.

There is one more funding possibility to keep in mind. The City of Chicago funded their heat island program after winning a $25 million settlement against their local utility company, Commonwealth Edison, for power outages during the 1995 heat waves (Washburn, 1999). The State of California's cool roof program was funded in the wake of its energy demand crisis of 2000 through legislation setting aside money for peak electricity load reductions (Ducheny, 2000). Be prepared to take action and push for positive change in the aftermath of crises.

Investigate

A well-run cool community program must be aware of the community's roofing, paving, landscaping, energy use, air quality and human health statistics, as well as any research about the local heat island and climate. To understand community dynamics, gather this information as you begin your program and use it as a starting point for future comparison. Below are lists of various types of information to gather and some potential data sources.

Roofing industry

National and regional roofing market

The National Roofing Contractors Association (NRCA) publishes annual reports of the national market and broad regional markets in the US. These reports do not indicate the market share of cool roofing products (yet), but they do estimate the size of new construction and re-roofing markets, as well as the market share of products in the low-slope and steep-slope roof markets. The US Census Bureau also collects data on local building characteristics, including some information about roofing, surveying major cities every four years or so. Similar organizations report these statistics for other countries and regions of the world.

Local low-slope roofing

Survey local roofing contractors who serve the low-slope commercial building market to find out about traditional material preferences, prices and warranties in your area. Estimate the life span and maintenance costs of traditional roofing materials.

Local steep-slope roofing

Survey local roofing contractors who serve the residential steep-slope roof market to find out about traditional material preferences, prices and warranties in your area. Estimate the life span and maintenance costs of various roofing materials.

Local low-slope cool roofing

Check the Cool Roof Rating Council product list and the US EPA Energy Star roofing product list to call manufacturers of cool products and find distributors in your area. Find local contractors who are certified or trained to install cool products and ask what warranties the contractors and/or manufacturers offer. What are material life spans and maintenance costs?

Local steep-slope cool roofing

Check the Cool Roof Rating Council and US EPA Energy Star roofing product lists for manufacturers of steep-slope roofing to find out if they distribute to your area. Also call other major steep-slope roofing manufacturers and distributors to see if they produce any cool products not yet on the Energy Star list, since some products may be awaiting 3-year test results. Find out which contractors are certified or trained to install cool steep-slope roof products in your area and what warranties are commonly given. What are material life spans and maintenance costs?

Market barriers

Survey roofing contractors and building owners to see what they know or think about cool roofing. How many people have heard of or can correctly define cool roofing? How many people have had it installed? What do they think the benefits are? What do they expect it to cost? How many people would install it if it were available at the same price as traditional materials? How much more would they pay for it? What do people think could go wrong with a cool roof material?

Roofing ordinances and codes

Check local building and energy codes for information about fire ratings, roofing weight or layering restrictions; required or recommended insulation levels; and any other restrictions on the colour or appearance of roofing materials.

Paving industry

National and regional paving market

Contact regional and national transportation departments for paving statistics. For example, the US Department of Transportation publishes an annual report, Highway Statistics, that lists the surface characteristics of urban and rural public roads for each state in the US. Also contact trade associations such as the Asphalt Institute and the American Concrete Pavement Association to see if they can share statistics about the quantity and the type of pavements used on public and private roadways, parking lots, driveways, sidewalks and other paved areas. Similar reports exist for most other countries.

Local paving market

Contact local transportation departments, public works departments and paving contractors to get information about local paving preferences. A random examination of local pavements can also be done, but be aware that it is often difficult to know what is below the top surface of a pavement. Find out costs of installing and maintaining traditional materials in typical applications, such as roads with different traffic loads, parking lots, driveways, sidewalks, bike paths, fire lanes and other paved areas. Estimate the total surface area within the community covered by roads, parking lots, driveways and other paved areas and whether the paved area is publicly or privately owned. Also investigate how stormwater run-off is being mitigated, including the costs of installing and maintaining drainage systems. It may be possible to demonstrate substantial cost savings by judicious use of permeable pavements.

Local cool paving market

Survey local transportation, public works and paving contractors to see how much of the pavement they install is lighter coloured or pervious, and if they know what its solar reflectance and thermal emittance is upon initial installation and over time. Compile a list of local cool pavement installations. Find out the costs of these cooler pavements in typical installations, such as roads with different traffic loads, parking lots, driveways, sidewalks, bike paths, fire lanes and other paved areas. Also call manufacturers of various pervious or cool pavement systems to see if they have distributors or installers in your area, or if they can point to any local projects.

Market barriers

Survey local transportation, public works and paving contractors as well as building and property owners to find out what they know or think about cool paving alternatives. How many people know what cool paving is? What do they think the benefits are? What do they expect it to cost? Who would install it if it were available at the same price as traditional materials? How much more would they pay for it? What do people think could go wrong with a cool paving material?

Paving codes and ordinances

Find out what local ordinances and codes apply to paved surfaces, including structural requirements, friction and noise ratings, and any colour and/or glare restrictions. Also determine types and costs of drainage systems that currently must be installed to deal with stormwater run-off from the increased run-off that impermeable pavement creates.

Landscape industry

Tree and vegetation cover

Look to local tree and landscaping organizations or the horticulture department of local universities for statistics about local vegetation cover. For example, American Forests has compiled information about tree cover for each urban area in the US (American Forests, 2002) to come up with their estimated deficit of 634.4 million trees. They have also surveyed various urban areas to determine coverage of other vegetation types for use in ecosystem analysis using their CITYgreen software. In addition, the Lawrence Berkeley National Laboratory (LBNL) has surveyed a few urban areas in the US to determine tree and vegetation cover. (Note that the LBNL values may not tally with the American Forests values, most likely because the study areas used are different.) Also check to see what information exists about the prevalence of different tree and vegetation species, the age distribution of trees, and the local trends regarding planting and removal of trees and vegetation.

Ecosystem study

Check with local tree and landscaping organizations or horticulture departments of local universities to see if the benefits of the community's trees have been estimated. Look for statistics on oxygen production, biogenic emissions, air pollution removal, stormwater retention and energy savings provided by the local urban forest.

Local landscape sectors

Determine how much land in your community is publicly owned and maintained and how much is privately owned and maintained. How is your community zoned, i.e. how much land area is commercial, industrial, retail, residential or parkland? What are the general landscaping practices in each zone?

Local landscape market and industry

Survey public works departments, landscapers, tree specialists and nurseries to find out how many trees and other landscape plants are sold annually by each type of firm, as well as the most common species in use. Also survey public works and tree removal agencies to find out how many trees are removed and the major reasons for their removal. Find out typical costs of planting trees in various installations. Do tree organizations, utilities or local government have any special tree planting programs? Are educational programs available from local government, tree organizations or local universities?

Market barriers

How are trees and vegetation perceived in the community? Survey public works departments and owners of various commercial and residential properties to find out what people think about trees and vegetation, such as what their benefits are, what their disadvantages are, how much they cost to plant and maintain, how they are best cared for and how likely the respondent is to plant or remove a tree in the future? How do they feel about issues such as water conservation, tree trimming and maintenance, potential infrastructure damage and visibility issues?

Local landscaping codes and ordinances

Check with local government to find out what laws apply to the planting of trees along streets, in parking lots and around homes. What restrictions, if any, apply to tree removal? What types of irrigation systems are required?

Energy use

Check with your local utility or energy commission for annual statistics and trends on electrical energy use, peak electricity demand, natural gas use, and other types of fuels used. Are power outages due to a lack of electrical supply a problem? What type of power plants supply your area's electricity? What fuels do they use and what emissions and other environmental problems do they produce? Are there plans underway to build new power plants?

Air quality

Check with your local air quality management district or environmental protection agency for annual statistics on monitored pollutants such as particulate matter, sulphur dioxides, nitrogen oxides, volatile organic compounds and ozone. Is your community meeting clean air standards? Is there a plan to reduce air pollution and are heat island mitigation measures part of this plan?

Human comfort and health

Local weather information

Check with local climatologists or meteorologists for an analysis of local weather patterns and heat wave statistics and how they may be changing over time. Are there any comfort indices or heat warning systems for your community? If so, get statistics from these programs.

Local health information

Check with health officials for statistics on the incidence of asthma, heat stroke and skin cancer as well as mortality rates due to these conditions.

Existing heat island research

Thermal images

There may not be any high-resolution thermal images of the community from specially equipped aircraft flyovers, but chances are good that lower-resolution visual and thermal images taken by a satellite are available. Check with the National Aeronautics and Space Administration (NASA); many images are on their website (www.nasa.gov) and can be easily downloaded. If the community's images are not on the website, call NASA to see if a researcher can find them.

Heat island strength

Have any researchers analysed the local heat island, i.e. measured surface or air temperatures in urban versus rural areas or studied wind or storm patterns in relationship to urban development? Check also with local climatologists, meteorologists and geographers. A literature search on the web or at a good scientific library may also unearth research focusing on your community. Good journals to check include the *Bulletin of the American Meteorological Society*, *Atmospheric Environment*, the *Journal of Applied Meteorology*, the *International Journal of Remote Sensing* and *Boundary Layer Meteorology*.

Estimates of energy savings

Many studies have been done to investigate the energy savings that would occur in various cities if cool roofs were installed and trees and vegetation were planted. Check the heat island bibliography to find energy research that may focus on your community. Also check with the major researchers in these areas, such as Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, the Florida Solar Energy Center, the Western Center for Urban Forest Research, the US Department of Agriculture's Forest Service and American Forests.

Estimates of air quality improvements

A few studies have investigated the air quality improvements that might result from the widespread implementation of heat island mitigation measures in various communities. Check with the leading researchers in this field at Lawrence Berkeley National Laboratory; the US Environmental Protection Agency; Environ International Corporation of Novato, California; and ICF Consulting of Washington DC, as well as searching in scientific journals.

Educate

Once sufficient information has been gathered about your area's heat island and its potential for mitigation, it is necessary to educate the community. There are many ways to convey information, including holding seminars, sending out information sheets and posting information on a website.

Remember that information contained in a brochure is not nearly as convincing as a talk by a motivating expert. Concentrate on making personal educational contacts through workshops, seminars and meetings, and let any informational sheets or websites serve as additional reference material. Below we list some standard information to prepare, and give tips on reaching your audience.

Useful educational information

Below are various types of information to prepare and keep on hand for talks and other outreach opportunities.

Fact sheets

Prepare fact sheets or informational brochures about heat islands, your program and each of the technologies you promote, including cool roofing for low-slope roofs, cool roofing for steep-slope roofs, cool pavements, and the use of trees and vegetation in various applications such as around houses and in parking lots.

Presentations

Put together a few standard presentations for audiences with different backgrounds, such as a talk about heat island mitigation for a general audience, a more technical presentation about mitigation options for facilities and maintenance personnel, and an educational seminar about cool roofing and/or cool paving for contractors.

Experts list

Develop a list of experts you can call on to make seminar presentations, or to whom you can refer questions. This list should include scientific researchers, industry representatives, and building owners and facility managers who have experience with cool technologies. Check with these experts before sending questions their way, since not everyone can afford the time to answer lots of inquiries. Consider setting aside money in your budget to cover speaker fees and transportation costs or to pay for time spent fielding questions.

Product lists

Prepare lists of roofing and paving products. The Cool Roof Rating Council and US EPA Energy Star roofing product lists are good places to start for roofing materials, but you may want to narrow the list down to only those products that are available in your area.

Contractor lists

As a convenience to your community, you may want to compile lists of contractors who are experienced with cool roofing, cool paving and effective landscaping installation. Qualifying for this list can be as easy or involved a process as you determine; just decide in advance what the system will be and figure out how to deal with potential customer complaints, inferior work and dissatisfied contractors.

Project sheets

Find projects in your community that demonstrate heat island mitigation and prepare informational sheets about them. Try to include information on installation and maintenance procedures; costs and benefits; energy, water and monetary savings; avoided air pollution; and the opinions of the owner and users of the project area.

Tree lists

Develop a list of the best trees for your area, including information about mature tree size, biogenic emission rates, water needs, and other factors such as fruiting or flowering behaviour and root growth. Local landscapers and tree specialists may already have recommended lists available.

Sample materials

Collect sample roof and paving materials and pictures of the best tree species. These are wonderful for passing around during seminars or for display in a booth at a trade show or community fair. Sample materials have a tendency to disappear, so try to collect a lot of them.

Posters

Full-size posters are useful when giving seminars or for display at a trade show or community fair. Large thermal images of urban areas are well appreciated, especially if it is an image of the local area.

Website

Most of the information above can easily be stored on a website for access by your community and others around the world. It is easier, faster and less expensive to refer callers to a website for information than it is to mail out brochures or information sheets.

School programs

Heat islands make an excellent topic for schoolchildren to study. Students learn about the sun, their local climate, and the effect of plants and building materials on temperatures. They can perform their own experiments by comparing temperatures of different materials, finding hot

Figure 9.1 Salt Lake City's Kool Kids kit with lesson plans, an infrared analyser, thermometers, thermal maps and two model houses, one with a light roof and one with a dark roof

and cool spots around their school, or measuring changes in temperature over time. For example, the 'Kool Kids' program kit, developed by the Utah Energy Office (see Figures 9.1 and 9.2), includes four lessons about heat islands and the Utah climate, plus hands-on measurement tools (Utah Energy Office, 2002).

Students can also plant trees or landscaping as part of a heat island mitigation project. The 'Cool Schools' program in Los Angeles, California, has worked with schoolchildren to plant trees around schools (Little, 1999).

Outreach tips

Hold seminars and workshops regularly to target and educate various sectors of your community, such as government and community leaders, contractors and developers, architects, landscapers, environmentalists and others. In addition to more formal presentations at community and trade group meetings, hold hands-on workshops at demonstration sites.

Remember that your audience of building and construction professionals does not always have time to attend workshops. Make sure your workshops and seminars are informative and concise, prohibit sales pitches, and try to schedule meetings at convenient times. Breakfast and lunch meetings have the added draw of providing food. It also helps to coordinate seminars and seminar publicity with local building groups and trade organizations in order to optimize your time and the likelihood that professionals will attend (see Figure 9.3).

Source: Utah Energy Office.

Figure 9.2 Schoolchildren measuring temperatures in a playground

Source: Dig City Coop.

Figure 9.3 Participants get hands-on experience at the Berkeley, California Ecohouse living roof workshop

Demonstrate

Before everybody starts to use a new technology, they need to see somebody else using it successfully. You need to find successful demonstration projects that already exist in your community, or organize some new ones.

Find existing demonstration projects

Good demonstrations of various cool technologies are probably already present in your community. Cool roofs have been installed on low-slope roofs in most communities. Examples of successful landscaping around buildings, along streets, in parking lots, in school yards and in parks can be found in any community. There may be one or two green roofs or a few installations of cool or permeable pavements. In rare cases, cool steep-slope roofing may be in use on a few homes.

Find, investigate and document as many local cool projects as you can. Approach the building owners and contractors involved in each cool project to see if they will share project information. Try to obtain information on installation procedures, maintenance, costs, energy savings and other perceived benefits. If the projects are not working well, learn from their mistakes. If the projects are successful and can provide valuable information, use them to showcase cool technology.

If there are no projects of a certain type in your community, look outside your community. Collect whatever information you can about project costs, installation and maintenance, and long-term performance.

Create new demonstration projects

Often there are no useful examples of certain cool technologies in a community. In this case, demonstration projects need to be developed.

Start by identifying innovative property owners, designers and contractors in your area. Bring in manufacturers and experts in various technologies and start coalitions to brainstorm and investigate potential projects. Look for grant opportunities to help fund these projects. Remember that in a successful coalition everybody benefits – manufacturers open new markets, contractors and designers learn new skills and develop new markets, and property owners get to try new technologies, often at a reduced cost.

An advantage of running new demonstration projects is the ability to catalogue and monitor the project from start to finish. Be sure to take pictures or video before, during and after construction. Measure energy use and air temperatures before and after construction. Consider holding seminars at the site during construction to educate the greater community. Invite the press and get some free publicity.

Sometimes your demonstration projects will not come to fruition. Costs may be too high, partners may back out, or projects can be installed and turn out to be a failure. Although discouraging, this is part of the normal learning process with new technology. Make sure to understand why a project failed and try to work these issues out when pursuing new projects. Unexpected problems are also common with new technology. It is helpful to realize that demonstrations are an important part of learning about and working out the bugs of a technology before widespread implementation. Successful projects will teach everybody something new.

The City of Chicago, Illinois, undertook two demonstration projects: a green roof on City Hall and the installation of porous paving systems. The City Hall green roof, shown in Figure 9.4, is a complete layered green roof system, with the necessary watertightness and structural stability to support the garden and its water storage and irrigation systems.

Another interesting project in Chicago was the use of a porous paving system in an alley. The system includes an aggregate base layer topped with a lattice-like support grid filled and covered with gravel. The lighter-coloured gravel replaces the original dark, heat-absorbing pavement to reduce the heat island effect and eliminates chronic flooding without using sewers. The new surface, shown in Figure 9.5, also supports car and service vehicle traffic.

Source: City of Chicago.

Figure 9.4 Green roof on the City Hall of Chicago

Source: © Peter Wynn Thompson, 2007, New York Times.

Figure 9.5 Reconstructed alley in Chicago uses gravel over a block paver system

Initiate

There are many different ways to jump-start the use of cool technologies without resorting to legislation. Below are some heat island mitigation project examples you can follow to make your community cooler and healthier.

Increase cool product supply

Some cool products are not readily available in communities. There may be no distributors of cool roofing products (especially for steep-slope roofs), porous pavers, cooler pavement sealants or other cool manufactured products. It may be useful to intervene in the market for cool products. Encourage manufacturers, distributors and suppliers to provide cool roofing and paving products for your community. Work to educate contractors about these products and stimulate demand. Consider sponsoring a cool product fair, or holding training sessions about new, cool technologies.

Change public sector building standards

Once heat island mitigation products have been adequately demonstrated in a community, it is time for local governments to adopt them on public buildings. The receptiveness of local governments varies. In some communities, local government is an innovator in the energy and environmental movement, and may already have been involved in demonstration projects. Other governments are more resistant to change, or have had negative experiences with new technologies. Regardless, local government is often the chief agent of change in a community, and is a very useful partner.

Encourage your local government to adopt a policy of implementing cool technologies in all publicly owned buildings. For example, cities or local governments can resolve to use cool roofing products on all publicly owned buildings, as did the city of Tucson, Arizona (EPA, 2002). Landscaping for shade in public parking lots, around public buildings, in parks and around schools can also be required. You can work to craft the language of these resolutions and to shape qualifications for these resolutions to meet.

Government requests bids from contractors and suppliers for most construction projects. Be ready to provide bid specifications that can be inserted into project requests. For example, a request for bids on a roof project may need language requiring minimum levels of solar reflectance and thermal emittance for the roof, specifying a material's inclusion on the Cool Roof Rating Council list, setting minimum warranty levels or specifying a certain type of roofing material. Requests for bids on buildings or parking lots might need to specify additional landscaping requirements in terms of shade tree coverage, minimum tree well sizes and soil composition.

Influence private sector building standards

While local government can be very influential, the vast majority of construction projects are in the private sector. It can be extremely worthwhile to provide ideas and advice about heat island mitigation to local architects and developers. Keep your ideas concise and practical, promoting specific cool technologies that are cost-effective and potentially attractive to a project's clients. Remember that developers will be more concerned with initial project costs, since long-term costs are generally passed on to owners or tenants.

It may also be useful to contribute to local design standards. For example, Salt Lake City's Cool Communities program worked with various entities to add cool community guidelines to urban design guidelines. They worked to include tree planting and the use of cool paved surfaces as part of the Best Available Control Technology Parking Lot rule for the State of Utah (Redisch, 2002). They gave input to architects and landscape designers for the Highlands, Utah, master plan about where to add trees and cool surfaces (Anderson, 2000). They also collab-

Table 9.1 LEED credits available for the use of heat island mitigation measures

Credits	Technologies	Description
Stormwater Management SS Credit 6.1 – 1 point	Green or garden roof, Permeable pavements	Keep stormwater discharge rates low by using green roofs and pervious paving materials
Heat Island Effect – Non-roof SS Credit 7.1 – 1 point	Shade trees, High albedo pavements, Permeable pavements	Shade, use pavement with at least a 29% solar reflectance index (SRI) or use open-grid pavement over at least 50% of non-roof surfaces
Heat Island Effect – Roof SS Credit 7.2 – 1 point	Cool roofing Green roofing	Install a roof with an SRI of 75% or more over 75% of the roof area, or a green roof over at least 50% of the roof area
Optimize Energy Performance EA Credit 1 – up to 10 points	Cool roofing	Implement energy-efficient technologies, such as cool roofing, to improve the energy performance of the building above the ASHRAE 90.1-2004 standard, where cool roofs are still voluntary and earn a trade-off with insulation (ASHRAE, 2004)
Building Reuse MR Credit 1.1 – 1 point	Cool roofing	Reuse at least 75% of the building's existing walls, floor and roof. Various cool roofing systems can be used over existing roofing to preserve the underlying structure
Building Reuse MR Credit 1.2 – 1 point	Cool roofing	An additional point awarded for reusing 95% of the building's shell

Note: SS, Sustainable Sites; EA, Energy and Atmosphere; MR, Materials and Resources.

Source: USGBC, 2005a, 2005b.

orated with Envision Utah, a non-profit organization focused on urban growth issues, to include a section on urban heat islands in the regional guidelines in *Urban Planning Tools for Quality Growth* (Envision Utah, 2002).

Another good design guideline example is the sustainable energy policy of San Jose, California (San Jose, 2003), which encourages the use of cool roofing and trees and vegetation.

Promote LEED compliance

The US Green Building Council runs a program to certify the sustainability of buildings. The Leadership in Energy and Environmental Design (LEED) rating system certifies buildings that install sustainable measures in their buildings. When the program began in 1999, there was a single rating system for all buildings. In 2005, rating systems were introduced for different building types and life-cycle phases, such as new construction/major renovation of commercial and institutional buildings, the operation of existing buildings, and new home construction.

In the new construction rating system, a total of 69 points are available, and 6 or more points can be awarded for implementing heat island measures (USGBC, 2005b). It takes at least 26 points for a new building to be LEED-certified, 33 points to get a 'silver' certification, 39 for 'gold' and 52 for 'platinum' certification. In the existing building standard there are a total of 85 available points, with 32 needed for a minimum certification (USGBC, 2005a). Both of these rating systems include 6 or more points that can be awarded for installing heat island mitigation measures, as listed below in Table 9.1.

Encourage owners and developers of public and private buildings to get LEED certifications, and make special note of buildings using heat island mitigation measures. Work with LEED-accredited professionals to make sure that they

Figure 9.6 Miami, Dade County, rooftop with Cool Community slogans, adjacent to the Metrorail

are aware of all the cool technologies buildings can use to reach certification.

Hold events to raise awareness

There are many ways to raise awareness about the heat island and its effects. In Miami, a rooftop adjacent to public transit was covered with a bright white cool roof and painted with slogans to promote cooling measures (see Figure 9.6). An estimated 95,000 Metrorail riders saw this billboard every month. This billboard was used to help publicize two cool roofing promotions: a contest to give away a free cool roof coating and a development of new homes built with white roofs instead of red tile.

Another heat island mitigation idea has become something of a Tokyo event. *Uchimizu* is the ancient Japanese custom of sprinkling water on a hot day to cool the ground and reduce dust. The Tokyo Metropolitan Government revived this practice in 2003 with an invitation for all residents to sprinkle water at noon on August 8. In just a couple of years, this has grown into an event where young Japanese café maids gather to sprinkle water in late July through mid-August, to much fanfare and attention (see Figure 9.7). The Uchimizu Project has been an incredibly successful campaign to educate the citizens of Tokyo, including cab drivers (Masanori, 2007), about heat islands.

Use advertising and the press effectively to capture your audience's attention. Remember

Source: Choo, 2007.

Figure 9.7 Japanese café maids sprinkling water during the *Uchimizu* event in Tokyo, Japan, on 5 August 2007

Figure 9.8 This parking lot of black asphalt, without a speck of vegetation, is a prime candidate for a cool community hall of shame award

that controversy captures the attention of the press, and hence your audience, so a 'best and worst' list to recognize good cool design, or point out hot and unhealthy design (see Figure 9.8), might make the evening news in the middle of a heat wave.

Tree planting programs

Tree planting programs are generally very popular and effective ways to mitigate heat islands. There are many different types of tree planting programs to consider (Summit and Sommer, 1998). Plant trees during a one-day event in a neighbourhood, park or school yard. Organize an annual Arbour Day event and sponsor tree planting at several locations throughout your community.

For example, in the wake of Hurricane Andrew in 1992, and following many years of urban sprawl, the Miami area had only 10 per cent tree cover (Moll, 1998). The Dade County Cool Communities program sponsored some successful tree planting events around Miami (see Figure 9.9), including planting 220 shade trees around homes in a five-block-square area in 1998, planting 237 trees in six neighbourhoods during 1998–1999, and planting 198 trees in four more neighbourhoods during 1999–2000.

The Sacramento Municipal Utility District has run longer-term shade tree planting programs (Hildebrandt and Sarkovich, 1998). Their programs, implemented by the non-profit Sacramento Tree Foundation, include Neighborwoods to target tree planting in specific neighbourhoods and Sacramento Shade

Figure 9.9 Tree planting by neighbourhood volunteers in a Miami suburb

to plant trees around homes to maximize shade and energy savings.

Whatever type of tree planting program is developed, make sure that the trees are not planted and forgotten. Train program participants in proper tree planting techniques and care, and get community members to pledge to maintain and protect the trees that are planted (Acosta, 1989). Set aside project funds to make sure this important follow-up care is provided.

Cool roof incentive programs

Throughout the world, electrical utilities are having increasing trouble meeting the demand for power, especially during summer heat waves. Cool roofs save energy when it is needed most, during hot and sunny summer afternoons. Very few buildings currently use cool roofing, so it has a large untapped conservation potential.

California has been a leader in cool roof incentive programs, largely as a response to California's energy demand crisis in 2000 (Ducheny, 2000). Beginning in 2001, the State of California and some publicly owned municipal utilities offered incentives for installing cool products on the low-sloped roofs of commercial buildings (Rudman, 2003). Private utilities, funded by the California Public Utilities Commission, picked up these programs between 2003 and 2005 under their utility-run Express Efficiency and Savings by Design programs. These programs were discontinued after a new California energy code, Title 24, made cool roofing obligatory in October 2005 (CEC, 2005). These programs paid incentives of \$0.10–\$0.20 per square foot of cool roofing installed, or per kilowatt hour saved, on air-conditioned buildings.

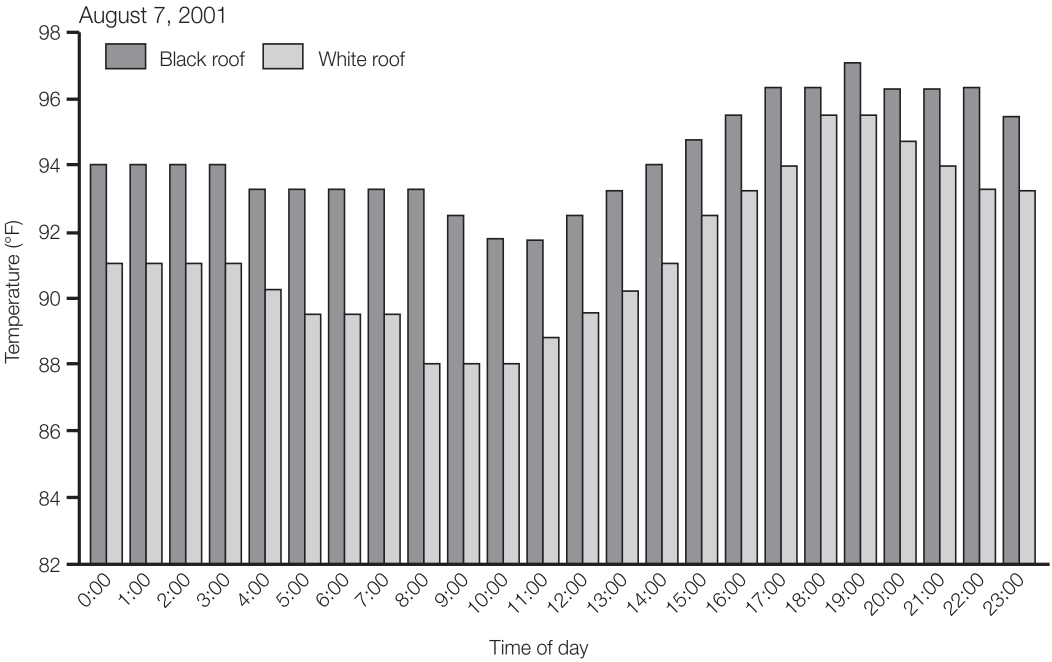
In 2006, California utilities also began offering cool roof incentives to homeowners. Incentives of \$0.10–\$0.20 per square foot are available for owners of air-conditioned buildings who install cool roofing (PG&E, 2006). This program includes rebates for low-slope roofs with more than 70 per cent solar reflectance and for steep-slope roofs with solar reflectance over 25 per cent (tier 1, with \$0.10 per square foot rebate) or over 40 per cent (tier 2, with \$0.20 per square foot rebate). There are very few steep-slope products available that meet these reflectance requirements, so hopefully this program is stimulating roofing manufacturers to provide more cool products.

Heat alert and health system

After numerous deaths due to locally intense heat storms in North America, many cities have begun implementing heat alert systems. New York City, Philadelphia, Toronto and other cities have begun issuing heat alerts when weather conditions are likely to place undue stress on human health (Kalkstein et al, 1996; Hill, 2002; Sheridan, 2002). These alert systems not only provide information about how to stay cool during a heat storm, they also designate cool shelters where people can go to escape the heat. Consult with your community's public health department about the possibility of starting a similar program.

A good example of an effective program was Philadelphia's Cool Aid program, run by the non-profit Energy Coordinating Agency of Philadelphia. Cool Aid had three functions: (1) to put cool roofs on the homes of low-income residents (as shown in Figure 9.10), (2) to implement heat emergency telephone announcements, and (3) to provide energy education and social services to make sure residents are properly cared for during heat waves.

Figure 9.10 A cool coating being applied to the black roof of a rowhouse in Philadelphia



Source: Kalkstein and Frank, 2001.

Figure 9.11 Indoor air temperatures on the second floor of Philadelphia rowhouses with and without cool roofing

The Cool Aid program reduced temperatures inside and outside the re-roofed homes. Figure 9.11 shows that air temperatures on the second floor of such houses with cool roofing were 0.5–2.8°C (1–5°F) cooler throughout the day than houses with traditional roofing systems (Kalkstein and Frank, 2001). On one Philadelphia block where all 30 roofs were given cool coatings, the average air temperature along the street was about 0.5°C (1°F) cooler on average than a nearby block with black-roofed homes (Wood, 2002).

The Cool Aid program works in conjunction with a heat alert and health warning system developed by Dr Laurence Kalkstein (Kalkstein et al, 1996) and in place since 1995. This system determines whether an air mass is likely to be dangerous by analysing National Weather Service forecasts for Philadelphia. The system factors in variables such as temperature, humidity, cloud cover, the duration and timing of a predicted heat wave and the threshold temperature in Philadelphia at which the death rate tends to escalate.

Legislate

This section reviews current legislation relating to various heat island mitigation measures. Codes and ordinances have historically been used to specify safe and effective building practices, but they can also be used to impel a community to adopt heat island mitigation measures. Codes and ordinances exist to specify the use of cool roofing, lay out rules for street tree planting and removal, and give guidelines for parking lot tree planting or the installation of green roofing. So far, no known codes or ordinances specify the use of cool or permeable pavements.

Passing codes and ordinances requires a lot of work. The technical foundations must be sound, the legislation must be drafted and approved by many parties, and political support must be garnered to ensure its passage. Changes involving heat island mitigation directly impact many industries and can be expected to generate considerable controversy. For example, a push to raise roof solar reflectance standards in Chicago was successfully deferred by the National Roofing Contractors Association (Dupuis and Graham, 2005). Aim to phase in changes gradually over time and give incentives for early adopters.

Tree and vegetation legislation

Tree and landscaping ordinances serve four common functions in urban areas (Bernhardt and Swiecki, 1991). First, tree planting rules regulate how and where to plant trees and other vegetation. These rules are motivated by a desire for attractive landscaping that does not interfere with public safety. Second, tree protection clauses defend trees from casual removal by requiring permits to cut down or even sometimes to prune trees. Third, view-protection rules govern disputes between neighbours about trees that block views or sunlight. Finally, tree shade regulations ensure a minimum amount of tree cover along public rights of way and sometimes in parking lots.

The tree and landscape rules in any community generally combine different grades of the above four functions. Regulations to protect trees and provide shade are the most crucial for heat island mitigation. Consider updating local tree regulations to adopt some of the ordinances exemplified below.

Tree protection legislation

Premature loss of a mature tree is to be avoided, since mature trees are most effective at providing the benefits of shade, cooling and pollution removal. Tree protection ordinances try to safeguard trees in different ways.

Typical tree protection ordinances, such as those for Nashville, Tennessee, require a permit from the city forester or tree specialist before any tree can be removed (Nashville, 1994). This provision will have varying degrees of effectiveness at protecting mature trees, depending on how strict the tree specialist is in allowing tree removal permits.

The City of Atlanta, Georgia, protects not just the tree, but the primary root zone of the tree, by not allowing disturbances to the ground under the crown area of a tree (Atlanta, 1989). This includes keeping toxic chemicals away and not paving around the tree without leaving at least 16 square feet of soil open to the air.

Street tree legislation

Effective street tree legislation does more than just specify the numbers of trees to plant along a street. The best legislation also gives guidelines on tree selection, siting and maintenance in order to lengthen a street tree's life and minimize problems with pavements, electrical wires and buildings.

For example, Orlando, Florida, specifies that trees be planted along both sides of the street with one tree every 15–30 metres (50–100 feet) (Florida, 2000). The selected trees must also provide a minimum amount of tree canopy coverage.

Atlanta, Georgia, requires that street trees be planted in strips that are at least 1 metre (3 feet) wide, with at least one tree every 7.5 metres (25 feet) (Atlanta, 1989). Trees must also be kept specified distances from hydrants, driveways, street lights and utility poles.

Parking lot shade legislation

Parking lot shade regulations are designed to shade and cool pavement and cars, reducing the heat island effect and minimizing emissions from parked cars. Sacramento, California, has a parking lot shade tree ordinance that has been in place since the mid-1980s. This ordinance requires new parking lots, or significantly altered existing parking lots, to plant enough trees to shade 50 per cent of the lot area after 15 years of tree growth. A recent study of Sacramento parking lots found that on average lots were achieving only 27 per cent shading (McPherson, 2001). Updates were made to the ordinance to increase the size of tree wells and make other changes to help trees grow and achieve better shade coverage over time.

Orlando, Florida, also has a parking lot shading provision in its ordinance (Florida, 2000). Parking lot areas are required to have tree coverage of one 'tree point' per 9 square metres (100 square feet). In this classification system, a 3-metre (10-foot-tall) tree is worth one tree point and a 9 metre (30-foot) tree is worth four tree points.

Trees and energy codes

Currently, no building energy code incorporates the effects of tree shading on building energy efficiency. While much work has been done to support a tree component of an energy code (Meier, 1990; Meerow and Black, 1991; Akbari et al, 1992, 1993; McPherson and Simpson, 1995; Hildebrandt et al, 1996; Simpson, 1998; Simpson and McPherson, 1998), current building codes are only prepared to incorporate the energy efficiency of components and systems contained within the building envelope.

Cool roofing legislation

Before 1995, the only legislation regulating cool roofing mandated that roof colour not cause undue glare. In 1995, the State of Georgia added the first provisions for using cool roofing as an efficiency option in its energy code, followed by similar ordinances in Florida and California. The City of Chicago began requiring cool roofing on all new buildings in 2002, with a plan to raise the solar reflectance requirement over time. It is expected that cool roofing will be added to energy codes throughout the US, first as an option and eventually as a mandatory energy efficiency measure. Examples of legislation that impact the implementation of cool roofing are described below.

Energy code legislation

Several US states and municipalities are recognizing the energy saving potential of cool roofing by adding provisions for cool roofs to their building energy codes. While this is an important step towards the acceptance of cool roofing in the marketplace, most energy codes apply only to new building construction.

The State of Georgia was the first to add cool roofs to their energy code. Their code assigns more credit for roof insulation if a cool roof is used. The actual roof insulation level can be factored upwards by up to 1.16 if a cool roof with at least 75 per cent solar reflectance and thermal emittance is installed (Georgia, 1995). This means that a lower level of insulation can be used to meet the overall building energy standard. It is important to note that in this code the use of a cool roof is optional, and if the insulation level is reduced when a cool roof is used there may be no net energy savings.

The State of Florida adopted rules similar to the Georgia code (Florida, 2001). Buildings using a roof with 65 per cent minimum solar reflectance and 80 per cent minimum thermal emittance are eligible for both a cooling credit and a heating credit, as long a radiant barrier is not also installed in the roof plenum or attic space.

The City of Chicago tried to take a larger step by requiring that all new non-residential buildings use cool roofing unless they have a green roof or photovoltaic cells on the roof. The first draft of this code stated that a cool roof must have at least 65 per cent solar reflectance and 90 per cent thermal emittance (Chicago, 2001). The roofing industry made an effective push against this legislation (Dupuis and Graham, 2005), forcing the minimum solar reflectance to 25 per cent through 2008 (Chicago, 2003), with increases thereafter.

In 2001, in response to electrical power shortages, the State of California updated its Title 24 building energy code, adding cool roofing as an energy efficiency option on non-residential buildings (CEC, 2001). This code was updated in 2003 and took effect in 2005, with cool roofing becoming essentially mandatory on non-residential buildings (CEC, 2003). If cool roofing is not installed, building owners must increase a building's energy efficiency in some other way to compensate. This California code does not just apply to new construction, but even more importantly, applies to the re-roofing of all existing buildings as well.

Roof colour legislation

A few communities have ordinances that place restrictions on the colour of roofs. These restrictions are typically intended to provide a uniform appearance for visible rooftops on homes in keeping with the architectural heritage of the area. In other communities there may be a restriction against using glaring roof colours, such as the bright white of a cool roof. This restriction is intended to keep rooftops unobtrusive, especially if they are visible from the street, from taller buildings or from hills overlooking the building.

Roof colour legislation can become a serious obstacle to improving the energy efficiency of buildings. Until more cool coloured materials are developed, or unless this legislation is repealed, some areas will not be able to implement bright white cool roof materials.

Cool paving legislation

There currently is no legislation requiring pavements to meet colour or solar reflectance standards in the US. A few communities have written guidelines to specify the use of cooler, lighter-coloured pavements and to promote the adoption of permeable pavements for improved stormwater management. It is anticipated that demonstrations of the benefits of cool and permeable pavements will lead to their gradual adoption into new ordinances and specifications.

Cool design guidelines

The city of Highland, Utah, working with the Cool Community Program of Utah's Department of Energy Services, wrote new design guidelines for their Town Center development that include the use of lighter-coloured pavements (Anderson, 2000).

Permeable pavement demonstrations

The management of stormwater and the avoidance of flooding are becoming more serious concerns for many communities. Permeable pavements have been demonstrated to reduce stormwater run-off successfully (Booth, 2000; Cote et al, 2000). If permeable pavements continue to perform well over time, expect to see ordinances specifying their use in communities.

Green roofing legislation

The installation of green roofs is motivated by various environmental concerns in different communities, including the desire to lessen heat islands, manage stormwater, restore the ecosystem and provide more green space for residents. There are different ways of encouraging green roofs, such as by reducing stormwater management requirements or fees, paying subsidies for green roofs or by simply requiring them on certain buildings.

Direct green roof subsidies

The region of North Rhine Westphalia in Germany paid subsidies or rebates to those installing green roofs. The motivation for these subsidies was to help control stormwater and reduce flooding. The Ministry of Environment, Consumer Protection, Nature Conservation and Agriculture (MUNLV) offered payments of €15 per square metre for installed green roofs. Between 1999 and 2003, they paid out over €12 million for about 825,000 square metres of green roof coverage (Ngan, 2004).

Indirect green roof subsidies

The city of Cologne, Germany, is in the above-referenced North Rhine Westphalia region, so green roofs installed there were eligible for direct subsides. After suffering from five damaging floods in 15 years, Cologne went a step further by reducing stormwater management fees for buildings with green roofs (Ngan, 2004). Fees were reduced by up to 90 per cent, depending on how much a project is able to reduce run-off from a building site.

The city of Portland, Oregon, has also been promoting green roofs (or 'ecoroofs') to help reduce stormwater run-off (Portland, 2002). Installation of green roofs is one option that can be taken to comply with stringent stormwater restrictions for new building construction.

Green roof requirements

The city of Tokyo, Japan, has been heating up at four times the rate of global warming, with temperatures rising 3°C on average over the past century. This is attributed to the intense heat island created by the rapid pace of urban development in Tokyo. To combat urban warming, Tokyo now requires that all new metropolitan buildings have a green roof (Scanlon, 2002).

The city of Linz, Austria, began requiring green roofs on new buildings in 1985 (Ngan, 2004). The requirements apply to all buildings over 100 square metres with a roof slope of less than 20°, and to underground parking structures as well. Many developers were initially frustrated by the higher costs of this requirement, so green roof subsidies have also been paid since 1989. To help ensure compliance and long-term maintenance, only 50 per cent of the subsidy is paid up front. The remaining 50 per cent of the subsidy is only paid after the roof plants have been established.

More action opportunities

Many opportunities exist to further heat island research and develop mitigation measures. Many communities lack information about heat island effects, and advocates of heat island mitigation often find themselves promoting technology that has not been fully investigated and products that may not yet exist. Below is a wish list of scientific and applied research needed to support cool community programs as of the writing of this book (autumn 2007).

Community heat island research

There is always useful work to be done to investigate the effects of the heat island and heat island mitigation options on a specific community. Potential projects include:

- studying heat island urban/rural temperature differences
- collecting existing high-resolution thermal images from flyovers or lower-resolution images from satellites
- analysing possible energy savings of cool roofs and shade trees
- evaluating community tree cover and the air pollution and stormwater benefits of trees
- modelling potential cooling effects of heat island mitigation
- estimating the air quality improvement potential of heat island mitigation.

While research addressing a specific community is not essential, it can make it easier to promote cool technologies and evaluate program progress. Try to encourage leading national researchers or local experts to study your community. Help researchers obtain funding for local projects by including them in coalitions, helping develop grant proposals and by writing letters of support for their endeavours.

Create more thermal images

Existing infrared images produced by the National Aeronautic and Space Administration show the surface temperatures of a handful of metropolitan areas around the country (Atlanta, Baton Rouge, Salt Lake City and Sacramento). These thermal images are bird's-eye views with enough detail to spot individual rooftops, parking areas and other hot spots, as well as cooler areas such as parks. These images, while vital as research data, are also extremely effective at helping communities visualize their heat island problem. High-resolution thermal images are needed for many more metropolitan areas.

In addition, it would be very useful to revisit and remap a few cities. This would allow for the analysis of heat island changes over time. New thermal profiles will enable researchers and local communities to directly evaluate progress in heat island mitigation efforts. Sequential thermal images can be used to track changes over time that are the result of the adoption of cool roofing and pavement, the growth of trees and vegetation, and new development that incorporates cool building products.

Improve cool roof modelling

Although three web-based tools exist for estimating cool roof energy savings (see Chapter 3), all would benefit from some improvements. The algorithms underlying these programs are not necessarily based on a sound footing. More transparency about these algorithms is needed. Comparing the tools' results to those from actual buildings, and to each other, would be a good start.

The most popular building energy model, DOE-2, developed for the US Department of Energy by Lawrence Berkeley National Laboratory, under-predicts energy savings from cool roofs because it makes three problematic assumptions: (1) it ignores radiative transfer in the plenum or attic space, (2) it holds the thermal conductivity of roof insulation constant, instead of allowing it to increase as the insulation temperature rises and (3) it uses an artificially high convection correlation to represent the effect of wind on the roof. It is not clear whether the model poised to supersede DOE-2, EnergyPlus, has more accurate modelling detail or not. Equations in EnergyPlus need to be investigated to find out.

Figure 9.12 Asphalt shingle roofs, in varying colours, are the roofing material of choice in this neighbourhood of bungalows in Oakland, California

Develop affordable cool roofing for steep-slope roofs

While there are literally hundreds of different cool products available for low-slope roofs (typically used for commercial buildings), there are only a handful of cool products available for steep-slope roofs (common on residential buildings). As was discussed in Chapter 5, the products that do exist use special pigments that reflect the sun's invisible infrared rays. This means the roofs can come in various colours (not just bright white) yet still reflect away more than 25 per cent of the sun's energy, as required by the Energy Star program, or even more than 40 per cent, as required by other programs.

So far the only cool, coloured products available for steep-slope roofs are clay tiles, concrete tiles and coated metal roofing. These roofing materials are long-lasting and of very high quality, but are quite expensive. Even with their traditional non-cool finishes, these roofing materials typically cost two to three times as much as a traditional asphalt shingle roof. The non-cool versions of these products made up a total of only 30.4 per cent of the new roofing market in the US and 23.2 per cent of the re-roof market for steep-slope roofs in 2001 (new roof market: clay tiles 3.4 per cent, concrete tiles 3.3 per cent and metal roofing 23.7 per cent; re-roof market: clay tiles 2.0 per cent, concrete tiles 2.9 per cent and metal roofing 18.3 per cent) (Hinojosa and Kane, 2002).

The most affordable roofing materials for steep-slope roofs, and the most widely used, are asphalt shingles. Asphalt shingles dominate the steep-slope roof market, with a 49.7 per cent share of the new roofing market and a 55.5 per cent share of the re-roofing market (Hinojosa and Kane, 2002). However, unlike other roofing materials, there currently are no cool asphalt shingle products in production, despite work for many years trying to convince the industry to manufacture them.

In the 1990s, Lawrence Berkeley National Laboratory and the Florida Solar Energy Center attempted to convince asphalt shingle producers to manufacture a bright, white shingle. White asphalt shingle samples were produced by different methods and found to have solar reflectance values ranging between 31 and 51 per cent, compared to the 26 per cent reflectance of a standard white shingle (Parker et al, 1993; Berdahl and Bretz, 1997). But these more reflective white shingles were never mass-produced because the roofing industry did not believe there was a large market for white roof materials.

Lawrence Berkeley National Laboratory is still working with various asphalt shingle manufacturers to stimulate production of cool coloured shingles using pigments that reflect invisible infrared energy. To date no manufacturer has risen to the challenge of producing and marketing a truly cool asphalt shingle. The potential for saving energy and increasing the life of asphalt shingles is very large, and could revolutionize the steep-slope roof market.

Cool paving research

Asphalt concrete is the most widely used type of pavement in the world. For example, in the US in 1996, 80 per cent of public urban roads were paved with asphalt concrete, 6 per cent were white-topped with Portland cement concrete over asphalt concrete, 9 per cent were paved with Portland cement concrete, and 5 per cent were unimproved, graded or covered with gravel (USDOT, 1996). Since such a great percentage of roads use asphalt, it is wise to expend more effort researching methods for cooling it.

Preliminary research shows that cooling asphalt pavement can significantly improve its rutting, shoving and ageing behaviour (Pomerantz et al, 2000). This research needs to be expanded at qualified pavement research laboratories and verified in the field.

Of the various types of cooler asphalts proposed, none are commonly used, and many questions must be addressed prior to widespread adoption. These questions include how cool will these asphalts be, how long will they last and what will they cost initially and over their life cycle? It has been assumed that lighter-coloured, more reflective aggregates could be used to

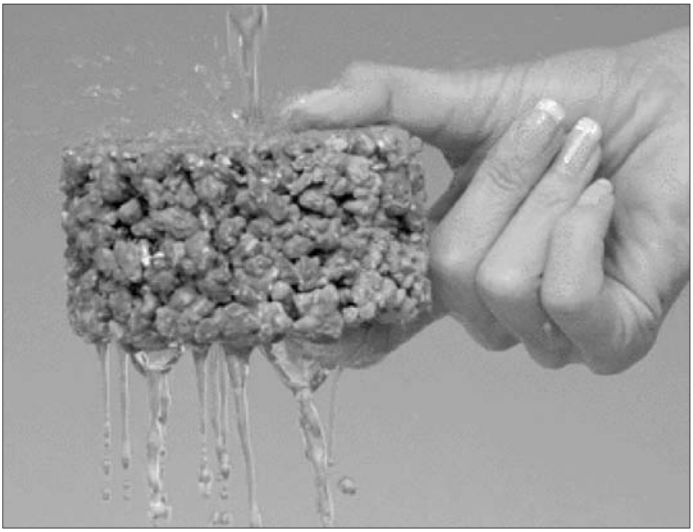


Figure 9.13 Pervious concrete allows water through to the soil underneath

lighten and cool asphalt mixes, but there is little information about what specific aggregates exist and their availability and cost. Are more reflective aggregates structurally suitable for use in road surfaces?

There is also very little information about the costs of cool additives such as lighter-coloured pigments. How well do additives wear, how much cooler do pavements with additives stay, and what effect do additives have on pavement longevity and maintenance expenses? Significant new research is needed to answer these questions.

Preliminary cost–benefit analyses for various cool paving options have so far been incomplete and inconsistent (Pomerantz et al, 1997, 2000; Ting et al, 2001). Since many of the paving options analysed in the laboratory are rarely installed, the costs, benefits and life span of these possible options are still unknown. It is not easy to compare the construction and maintenance costs of different paving methods, since prices depend on the site, type of soil or road base, size of the job, time of the year, the contractor chosen and other factors. Back-to-back comparisons of traditional and cool paving options need to be made for a number of typical standardized sites.

Caution must be used especially when comparing asphalt concrete technology with Portland cement concrete. These pavements use very different construction and maintenance techniques. Comparison results can vary considerably depending on the time period chosen for study. These industries are also extremely competitive with each other, and studies underwritten by any faction of the industry are likely to be biased.

There are many permeable pavements that may also double as cool pavements, such as porous concrete (see Figure 9.13), open-graded asphalt, and grass or aggregate block pavers. Some work has been done to evaluate the performance of permeable pavements as cool materials (Asaeda et al, 1996; Asaeda and Ca, 2000), but more questions remain. How cool do permeable pavements stay, and how much does their temperature depend on their moisture level? If they use grass or other vegetation, how cool does the vegetation stay?

Permeable pavements are used primarily for their ability to absorb water and reduce stormwater run-off. Since these installations are still fairly rare, more information is needed about how much water they can collect. Can conventional drainage systems be eliminated, and if so,

Source: Courtesy Dr Nina Bassuk.

Figure 9.14 Willow oaks on Pennsylvania Avenue in Washington DC. Although planted at the same time, the trees on the right in the open grassed area have grown bigger than the trees to the left planted in tree wells

can money be saved on construction and maintenance costs? How can problems with dirt clogging the pavement pores be avoided?

Permeable pavements such as open-graded asphalt have been found to reduce traffic noise (Glazier and Samuels, 1991; Pipien, 1995; Smith, 1999), and appear to be suitable for high traffic areas. Other permeable pavements, such as grass pavers, are designed for low traffic areas or occasional parking. More research is needed to evaluate the durability and suitability of permeable pavements for different applications.

Tree planting improvements

Many urban design codes and ordinances call for a certain number of trees to be planted along streets and in parking lots, but the planting design, execution or longer-term care is often less than ideal. For example, a study of parking lots in Sacramento found that tree cover was not meeting its specified target of 50 per cent after 15 years of growth (McPherson, 2001). Instead, trees were shading only about 20 per cent of the lot area due to the death of trees, the non-replacement of dead trees and slower than predicted tree growth rates.

Trees are often planted in wells that are too small for healthy root growth and long tree life (see Figure 9.14). Sometimes the tree is not planted correctly, slowing the tree's growth, or waste construction materials are thrown into the wells, further constricting the roots. Newly planted trees are also vulnerable to vandalism, lack of irrigation, and poor or non-existent long-term care. It is relatively easy to plant a tree, but much harder to plant it correctly and nurture its growth to maturity.

Ordinances in Sacramento and Davis, California, are being rewritten to specify improved standards for tree planting and care (McDonald, 2001). Minimum sizes for tree wells are specified, along with healthier planting procedures and irrigation standards. Tree planting design and practice should be reviewed and improved wherever possible for better tree health and longer life.

Tree roots are a common cause of problems. Urban maintenance crews often respond to this problem by cutting out the offending roots and repaving, or by removing the tree entirely. Small tree wells cause a tree's roots to become overly constricted or to grow into any available crack in a search for more soil and moisture, causing upheaval of the sidewalk or pavement around the tree. The use of larger tree wells, along with the installation of root barriers, can help reduce this problem.

Another option for improving root growth and reducing pavement damage is to use structural soils in planting areas. Structural soils are a mixture of soil and larger sized aggregates that can be used under paved surfaces around tree wells and planters (Grabosky and Bassuk, 1995; Grabosky et al, 1996). The aggregate serves as a strong base for the pavement above, while allowing roots to grow safely through the interstices and collect nutrients from the soil. This technique is beginning to be used in various areas of the US, but has not yet been fully investigated. A cost–benefit analysis must be undertaken to find out how much more it costs to install structural soils, and whether trees actually do grow more quickly and live longer with fewer pavement problems.

Vines for shade

While trees are an extremely valuable part of any urban ecosystem, it is not feasible or practical to plant them in every situation. There is not always space for trees to grow, and it can be difficult and expensive to plant them in areas that are already paved.

Vines can grow in many places where trees cannot. Vines need less soil and less space to grow, so they can fit in small places (see Figure 9.15). Vines also grow quickly and many varieties are extremely hardy. Some vine species grow fast enough to provide shade within one season, while most trees take years to supply the same benefit. However, several species of vines grow so hardily that they can be a menace to other plants and must be pruned aggressively.

Figure 9.15 Fast-growing vines can create shade in tight spaces

There are lots of tree selection guides with comprehensive planting and care information. A few listings of vines exist (Thomas, 1999), but more information is needed about soil; water and climate requirements; growth rates; and descriptions of leaves, flowers and berries. Information is especially needed about long-term care and expected life spans, particularly in stressful applications such as parking lots.

Vines can be grown on many different types of supports, depending on the shade needed. Trellises can be oriented vertically to shade walls and provide screens, or horizontally on arbours to shade windows or parking spaces. Quick shade can be provided for parking lots, school yards, playgrounds, driveways and numerous other areas. Vines have different methods of clinging to support, but all grow well on trellises and arbours or even on a simple arrangement of string or wire. Modular vine support systems can be designed for use around parking spaces and buildings. Ideally, a modular system can include planter boxes, trellises, automatic irrigation and perhaps even lighting for quick and easy erection that is adaptable for many applications.

Awareness of the health effects of heat islands

Too few people are aware of how heat interacts with urban design to impact human health. Extreme heat events, very hot weather lasting more than a day or two, are becoming more common, yet only a few communities have plans in place to mitigate heat emergencies or to create urban environments that are more resistant to heat waves. Heat indices and heat emergency relief plans are being implemented in many cities, but these programs need to be adopted in many other locations.

More research is needed to determine the links between hot weather and rates of asthma, heat stroke and heat-related mortality. Some excellent studies already exist (Deosthali, 1999; Deuel et al, 1999; Smoyer et al, 1999), but these studies need to be expanded to more communities and urban areas. Risk factors for adverse health effects can be determined, usually based on daytime high temperatures and night-time lows, the duration of the heat event, humidity levels and pollution levels.

Additional risk factors in urban areas, such as a lack of shade and the use of hot building materials, also need to be identified and taken more seriously. High-risk areas where people gather, such as parks, zoos and plazas, can be improved with additional shade and the use of cooler building materials. Building construction practices and materials also need to be directly linked to health effects, since hot roof and wall constructions coupled with low insulation levels and minimal ventilation can lead to unsafe indoor conditions. For example, heat stroke and deaths were more prevalent in the top floors of buildings under hot roofs during the Chicago heat storm of 1995 (Huang, 1996).

Air quality research

Higher air temperatures lead to the use of more air conditioning energy and directly increase rates of air pollution from power plants. Hot air temperatures also accelerate the chemical reactions that form smog, indirectly increasing air pollution. Detailed models of local meteorology and air quality have been developed for Los Angeles, Houston, Sacramento, Salt Lake City, Baton Rouge and the Northeast corridor of the US (Akbari and Douglas, 1995; Taha, 1995; Douglas et al, 2000; Taha et al, 2000). Preliminary results from these models indicate that there are potential air quality improvements over parts of urban areas, but more work must be done to verify baseline models and investigate heat island mitigation effects.

The Los Angeles and Houston models are currently being examined and improved as part of a process to incorporate heat island reduction strategies into pollution credit trading programs (Emery et al, 2000; Emery and Tai, 2002; Timin, 2004; Taha, 2005). If projected ozone reduction levels are high enough, air pollution programs may be developed to provide heat island mitigation.

Sustainability of cool products

Many new cool products are being developed and used in our buildings and roads. These products may lower energy use and increase product longevity, but these and other aspects of their sustainability require more investigation. What are the environmental impacts of cool roofing and paving, and how do they compare to the impacts of traditional construction materials? Life-cycle analyses must be done to evaluate and compare the manufacture, installation, life span and disposal of products.

Some work has begun to answer these questions (Gajda and Van Geem, 1997; Marceau et al, 2002), but more study is needed. Unbiased reporting by parties not connected or funded by the roofing and paving industries is needed.

If cool products are demonstrated to have improved sustainability, more adherents to the cool community movement can be recruited from the 'green' community. This can help build local community support for more rapid implementation of heat island reduction measures.

The cool revolution

Heat island mitigation holds great promise, not just for making our neighbourhoods more comfortable and habitable, but also for lessening environmental impacts and the costs of building and maintaining our communities.

Most people have an intuitive understanding of the need for heat island mitigation. When brought to a community's attention, it is agreed that hot materials do not make sense. Cooler materials and cooler landscapes are preferred, but they must be practical and cost-effective.

Yet even with cost-effective products that have a proven track record, it is often very difficult to bring new technology into the mainstream. There are many invisible hurdles. The construction industry tends to be resistant to change, and for very good reason. Many contractors have learned the best practices for their area through a painful process of trial and error. When a new product or technique fails, a contractor's livelihood and reputation are at risk. Education for contractors about these new technologies is essential.

Finally, cool technologies must have a market. Without demand from consumers, the manufacturers, distributors, suppliers and contractors will not provide cool technologies. A cool community program needs to influence customer preferences, making the general population aware of and eager for cool technologies and the benefits they can bring.

Please join the greater cool community by choosing and promoting cool roofing, paving and landscaping. Some of these technological advances, such as cool roofing, are poised to revolutionize their industry and greatly improve the way we build our communities.

References

Acosta, A. E. (1989) *Greenstreets or Meanstreets: Challenges to Planting Urban Trees*. Controlling Summer Heat Islands, Berkeley, CA, Lawrence Berkeley Laboratory

Akbari, H. and S. G. Douglas (1995) *Modelling the Ozone Air Quality Impacts of Increased Albedo and Urban Forest in the South Coast Air Basin*. Berkeley, CA, Lawrence Berkeley National Laboratory: 150

Akbari, H., S. Bretz, J. Hanford, A. Rosenfeld, D. Sailor, H. Taha and W. Bos (1992) *Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Project Design and Preliminary Results*. Berkeley, CA, Lawrence Berkeley National Laboratory: 229

Akbari, H., S. Bretz, J. Hanford, D. Kurn, B. Fisman, H. Taha and W. Bos (1993) *Monitoring Peak Power and Cooling Energy Savings of Shade Trees and White Surfaces in the Sacramento Municipal Utility District (SMUD) Service Area: Data Analysis, Simulations, and Results*. Berkeley, CA, Lawrence Berkeley National Laboratory: 146

American Forests (2002) *National Urban Tree Deficit*. Available at http://www.americanforests.org/graytogreen/treedeficit/, American Forests

Anderson, R. (2000) *Local Government and Urban Heat Island Mitigation*. Berkeley, CA, University of California at Berkeley, Environmental Sciences Department: 12

Asaeda, T. and V. T. Ca (2000) 'Characteristics of permeable pavement during hot summer weather and impact on the thermal environment'. *Building and Environment* **35**(4): 363–375

Asaeda, T., V. T. Ca and A. Wake (1996) 'Heat storage of pavement and its effect on the lower atmosphere'. *Atmospheric Environment* **30**(3): 413–427

ASHRAE (2004) *ASHRAE 90.1-2004 Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta, GA, American Society of Heating Refrigerating and Air Conditioning Engineers

Atlanta (1989) *City of Atlanta Trees and Shrubbery Ordinance, Arboricultural Specifications and Standards of Practice*. Atlanta, GA, City of Atlanta, Department of Parks, Recreation and Cultural Affairs

Berdahl, P. and S. Bretz (1997) 'Preliminary survey of the solar reflectance of cool roofing materials'. *Energy and Buildings* **25**(2): 149–158

Bernhardt, E. and T. J. Swiecki (1991) *Guidelines for Developing and Evaluating Tree Ordinances*. Sacramento, CA, Urban Forestry Program, California Department of Forestry and Fire Protection: 76

Booth, D. (2000) *Field Evaluation of Permeable Pavement Systems for Stormwater Management*. Washington DC, US Environmental Protection Agency

CEC (2001) *Energy Efficiency Standards for Residential and Nonresidential Buildings*. Sacramento, CA, California Energy Commission Publication No. P 400-01-024

CEC (2003) *2005 Building Energy Efficiency Standards for Residential and Non-Residential Buildings, Express Terms – 45 Day Language*. Sacramento, CA, California Energy Commission: 190

CEC (2005) 'Q and A on cool roofs'. *Blueprint* **83**: 1–9

Chicago (2001) *Energy Code, City of Chicago*. Chicago, IL, 60298–60977, 60978–61010

Chicago (2003) *Amendment to the Chicago Energy Conservation Code*. Chicago, IL, Department of Buildings, City of Chicago

Choo, D. (2007) '*Uchimizu*'. Available at http://www.dannychoo.com/blog_entry/eng/1015/Uchimizu/

Cote, M. P., J. Clausen, B. Morton, P. Stacey and S. Zaremba (2000) *Jordan Cove Urban Watershed National Monitoring Project*. Boston, MA, US Environmental Protection Agency, Office of Ecosystem Protection: 8

Deosthali, V. (1999) 'Assessment of impact of urbanization on climate: An application of bioclimatic index'. *Atmospheric Environment* **33**: 4125–4133

Deuel, H., P. Guthrie, W. Moody, L. Deck, S. Lange, F. Hameed and J. Castle (1999) *Potential Impacts of Climate Change on Air Quality and Human Health*. Air and Waste Management Association's 92nd Annual Meeting and Exhibition, St Louis, MO, 20–24 June

Douglas, S. G., A. B. Hudischewskyj and V. Gorsevski (2000) *Use of the UAM-V Modeling System as an Air Quality Planning Tool for Examining Heat Island Reduction Strategies*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Ducheny, D. (2000) *Assembly Bill 970*. State of California

Dupuis, R. M. and M. S. Graham (2005) 'Cooling down Chicago: Chicago's attempt to reduce its heat island results in interesting research findings'. *Professional Roofing* December

Emery, C. and E. Tai (2002) *Examination of the Effects on Ozone Air Quality from UHI Reduction Strategies*. Novato, CA, Environ: 39

Emery, C., H. Taha and G. Gero (2000) *City of Los Angeles Cool Communities Program, Technical Review of Air Quality Modeling*. Los Angeles, CA, Environmental Affairs Department

Envision Utah (2002) *Urban Planning Tools for Quality Growth*. Salt Lake City, UT, Envision Utah: 293

EPA (2002) *Tucson Roof Standard*. Washington DC, US Environmental Protection Agency, HIRI News, 24 September

Florida (2000) *Subdivision and Landscaping Ordinance.* Orlando, FL, State of Florida

Florida (2001) *Florida Building Code, Section 607 Space Cooling Systems and Section 608 Space Heating Systems*, Orlando, FL

Gajda, J. and M. Van Geem (1997) *A Comparison of Six Environmental Impacts of Portland Cement Concrete and Asphalt Cement Concrete Pavements*. Skokie, IL, Portland Cement Association: 39

Georgia (1995) *Georgia Amendment to the 1995 CABO Model Energy Code*. State of Georgia, Atlanta, Georgia, Section 704

Glazier, G. and S. Samuels (1991) 'Effects of road surface texture on traffic and vehicle noise'. *Transportation Research Record* **1312** (Energy and Environmental Issues): 141–144

Grabosky, J. and N. L. Bassuk (1995) 'A new urban tree soil to safely increase rooting volumes under sidewalks'. *Journal of Arboriculture* **21**(4): 187–201

Grabosky, J., N. L. Bassuk and H. Van Es (1996) 'Testing of structural urban tree soil materials for use under pavement to increase street tree rooting volumes'. *Journal of Arboriculture* **22**(6): 255–263

Hawbaker, L. (2002) Concrete market share. Skokie, IL, Director Streets and Roads, American Concrete Pavement Association, email communication to L. Gartland

Hildebrandt, E. and M. Sarkovich (1998) 'Assessing the cost-effectiveness of SMUD's shade tree program'. *Atmospheric Environment* **32**(1): 85–94

Hildebrandt, E., R. Kallett and M. Sarkovich (1996) *Maximizing the Energy Benefits of Urban Forestation*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Hill, D. (2002) *Castaways on the Urban Heat Island*. North American Urban Heat Island Summit, Toronto, Toronto Atmospheric Fund

Hinojosa, O. and K. Kane (2002) 'A measure of the industry'. *Professional Roofing*: 24–28

Huang, J. (1996) *Urban Heat Catastrophes: The Summer 1995 Chicago Heat Wave*, Center for Building Science Newsletter, Lawrence Berkeley National Laboratory, Fall

Kalkstein, L. S. and K. L. Frank (2001) *The Health Implications of Greenhouse Gas Emissions*. Emerging Growth Issues Workshop, Newark, DE, University of Delaware, Center for Climatic Research

Kalkstein, L. S., P. F. Jamason, J. S. Greene, J. Libby and L. Robinson (1996) 'The Philadelphia hot weather health watch/warning system: Development and application, Summer 1995'. *Bulletin of the American Meteorological Society* **77**(7): 1519–1528

Little, J. B. (1999) 'Trees help LA schools reduce energy use, increase community pride'. *California Trees* **10**(1)

Marceau, M., J. Gajda and M. Van Geem (2002) *Use of Fly Ash in Concrete: Normal and High Volume Ranges*. Skokie, IL, Portland Cement Association: 6

Masanori (2007) 'Talking with a cab driver'. Available at http://tokyo.metblogs.com/archives/2007/09/talking_with_a.phtml

McDonald, J. (2001) *Parking Lot Tree Shading Design and Maintenance Guidelines*. Sacramento, CA, City of Sacramento**:** 20

McPherson, E. G. (2001) 'Sacramento's parking lot shading ordinance: environmental and economic costs of compliance'. *Landscape and Urban Planning* **57**: 105–123

McPherson, E. G. and J. R. Simpson (1995) 'Shade trees as a demand-side resource'. *Home Energy* March/April: 11–17

Meerow, A. W. and R. J. Black (1991) *Landscaping to Conserve Energy: Annotated Bibliography*. Fact sheet EES-44, University of Florida, Florida Cooperative Extension Service: 12

Meier, A. (1990) *Measured Cooling Savings from Vegetative Landscaping*. ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA, American Council for an Energy Efficient Economy

Moll, G. (1998) 'America's urban forests'. *City Trees, The Journal of the Society of Municipal Arborists* **34**(3)

Nashville (1994) *Nashville City Code Chapter 2.104, Urban Forester*. Nashville, TN, City of Nashville

Ngan, G. (2004) *Green Roof Policies: Tools for Encouraging Sustainable Design*. Saskatoon, Canada, Goya Ngan Landscape Architect, December

Parker, D., J. McIlvaine, S. Barkaszi and D. J. Beal (1993) *Laboratory Testing of Reflectance Properties of Roofing Materials*. Tallahassee, FL, Florida Solar Energy Center

PG&E (2006) *Pacific Gas and Electric Company (PG&E) Launches Residential Cool Roof Rebate Program*. Pacific Gas and Electric, 13 September

Pipien, G. (1995) 'Pervious cement concrete wearing course offering less than 75 dB(A) noise level'. *Revue Générale des Routes et Aérodromes* **735**: 33–36

Pomerantz, M., H. Akbari, A. Chen, H. Taha and A. Rosenfeld (1997) *Paving Materials for Heat Island Mitigation*. Berkeley, CA, Lawrence Berkeley National Laboratory: 21

Pomerantz, M., H. Akbari and J. T. Harvey (2000) *Durability and Visibility Benefits of Cooler Reflective Pavements*. Berkeley, CA, Lawrence Berkeley National Laboratory: 23

Portland (2002) *City of Portland EcoRoof Program Questions and Answers*. Portland, OR, Bureau of Environmental Services, Office of Sustainable Development**:** 12

Redisch, M. (2002) *Grassroots Groups Get Involved in National Research*. North American Urban Heat Island Summit, Toronto, Toronto Atmopheric Fund

Rudman, M. (2003) *AB970, AB29x and SB5x Peak Load Reduction Programs, 2002 Annual Report – Executive Summary*. Sacramento, CA, California Energy Commission, Nexant

San Jose (2003) *City of San Jose Sustainable Energy Policy 2003–04 Action Plan*. San Jose, CA, Environmental Services Department

Scanlon, C. (2002). *Feeling the Heat in Tokyo*. London, BBC News World Edition

Sheridan, S. C. (2002) *The Development of the New Toronto Heat-Health Alert System*. North American Urban Heat Island Summit, Toronto, Toronto Atmospheric Fund

Simpson, J. R. (1998) 'Urban forest impacts on regional cooling and heating energy use: Sacramento county case study'. *Journal of Arboriculture* **24**(4): 201–214

Simpson, J. R. and E. G. McPherson (1998) 'Simulation of tree shade impacts on residential energy use for space conditioning in Sacramento'. *Atmospheric Environment* **32**(1): 69–74

Smith, R. (1999) 'All's finally quiet at Sutter's mill'. *California Asphalt* January/February: 22

Smoyer, K. E., D. G. C. Rainham and J. N. Hewko (1999) *Integrated Analysis of Heat-Related Mortality in the Toronto–Windsor Corridor*. Waterloo, Ontario, Environment Canada

Summit, J. and R. Sommer (1998) 'Urban tree-planting programs – A model for encouraging environmentally protective behavior'. *Atmospheric Environment* **32**(1): 1–5

Taha, H. (1995) 'Ozone air quality implications of large-scale albedo and vegetation modifications in the Los Angeles basin'. *Atmospheric Environment* **31**(11): 1667–1676

Taha, H. (2005) *Urban Surface Modification as a Potential Ozone Air-Quality Improvement Strategy in California. Phase One: Initial Mesoscale Modeling*. Sacramento, CA, California Energy Commission

Taha, H., S. C. Chang and H. Akbari (2000) *Meteorological and Air Quality Impacts of Heat Island Mitigation Measures in Three U.S. Cities*. Berkeley, CA, Lawrence Berkeley National Laboratory

Thomas, R. W. (1999) *Ortho's All About Vines and Climbers*. Des Moines, Iowa, Meredith Books

Timin, B. (2004) *Photochemical Modeling of Urban Heat Island Strategies*. Washington DC, US Environmental Protection Agency

Ting, M., J. Koomey and M. Pomerantz (2001) *Preliminary Evaluation of the Lifecycle Costs and Market Barriers of Reflective Pavements*. Berkeley, Lawrence Berkeley National Laboratory: 67

USDOT (1996) *Highway Statistics*. Washington DC, US Department of Transportation, Bureau of Transportation Statistics

USDOT (2000) *Highway Statistics 1999*. Washington DC, US Department of Transportation: 192

USGBC (2005a) *Green Building Rating System for Existing Building Upgrades, Operations and Maintenance, Version 2*, US Green Building Council, Washington DC, July

USGBC (2005a) *Green Building Rating System for New Construction and Major Renovations, Version 2.2*, US Green Building Council, Washington DC, July

Utah Energy Office (2002) *Kool Kids*. Available at http://www.nef1.org/ea/koolkids/, National Energy Foundation

Washburn, G. (1999) *ComEd Signs $1 Billion Power Pact with City*. Chicago, IL, Chicago Tribune, 24 March, p1

Wood, A. R. (2002) *Saving LIVES with White Roofs: A Pilot Program in Philadelphia Could be Used in Other Cities*. Philadelphia, PA, Philadelphia Inquirer, 5 May

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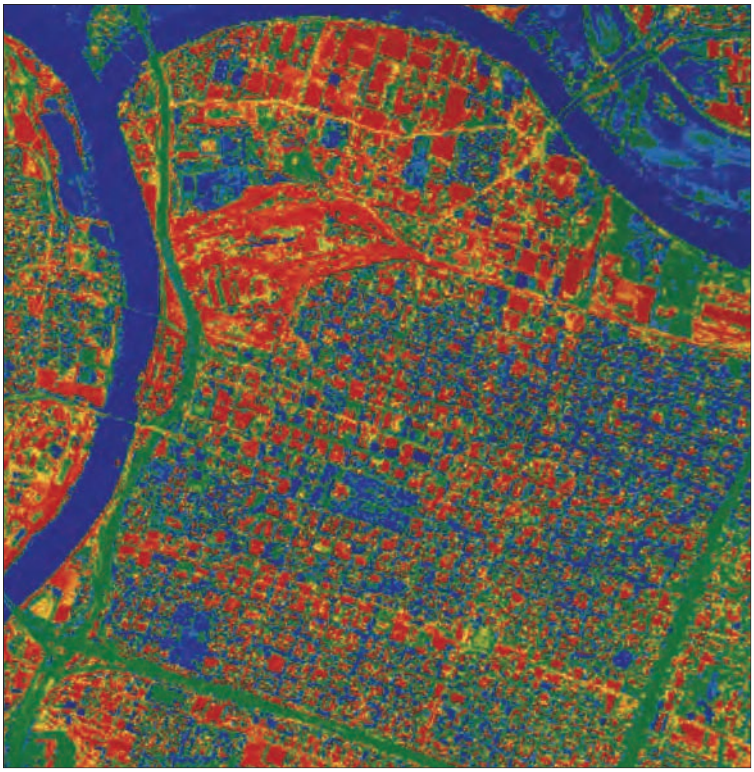
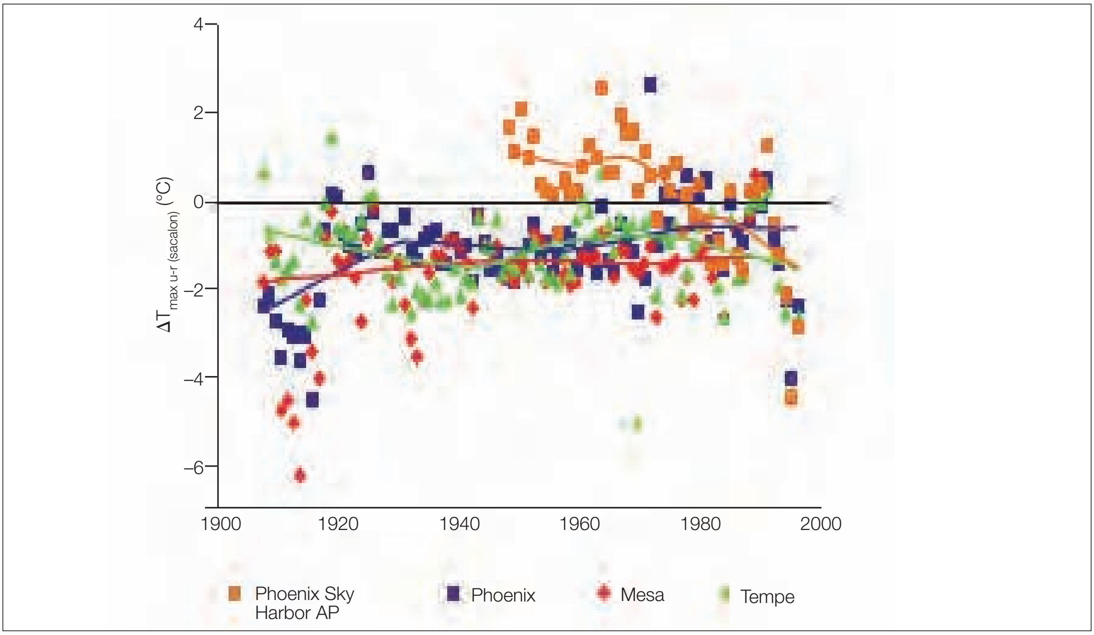
Source: Schott and Schimminger, 1981.

Plate 1 Surface temperature contours (in degrees centigrade) over a map of Buffalo, New York, on 6 June 1978 at 2:00pm EDT derived during the Explorer satellite's heat capacity mapping mission



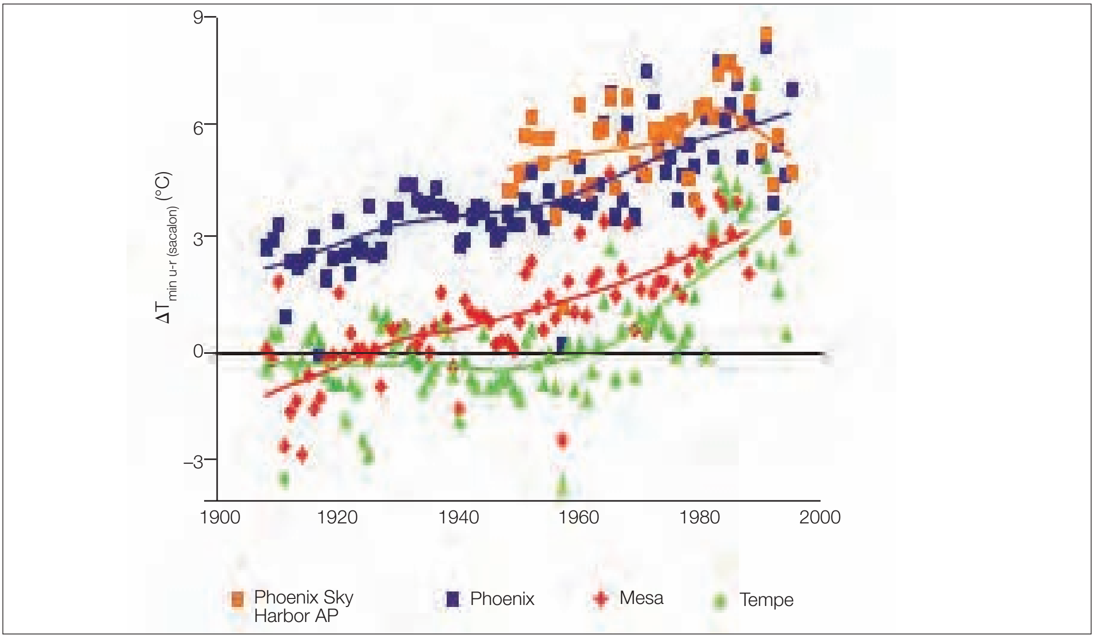
Source: Gorsevski et al, 1998.

Plate 2 Thermal image of downtown Sacramento, California, on 29 June 1998 at noon, derived from a flyover in a Lear jet by NASA's ATLAS program



Source: Brazel et al, 2000.

Plate 3 Differences between the monthly averages of *maximum* temperatures at Phoenix's Sky Harbor airport, and in urban Phoenix, urban Mesa and suburban Tempe, Arizona, and the rural desert of Sacaton, Arizona, over the past century



Source: Brazel et al, 2000.

Plate 4 Differences between the monthly averages of *minimum* temperatures at Phoenix's Sky Harbor airport, and in urban Phoenix, urban Mesa and suburban Tempe, Arizona, and the rural desert of Sacaton, Arizona, over the past century

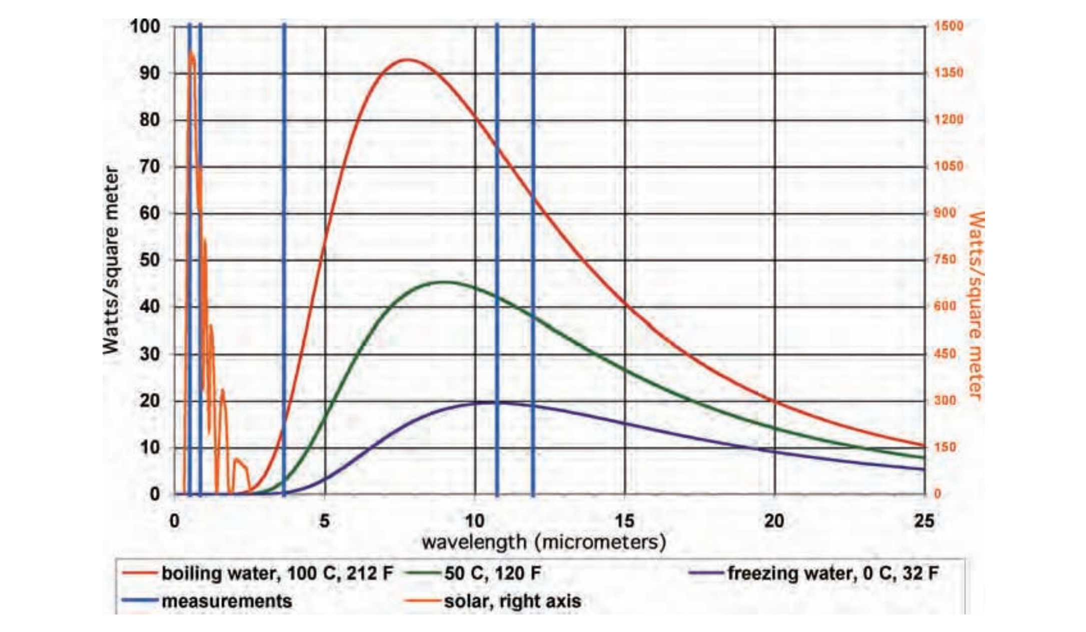


Plate 5 Black body emissions at different temperatures, solar energy reaching the Earth and the five energy wavelengths typically measured by remote sensing

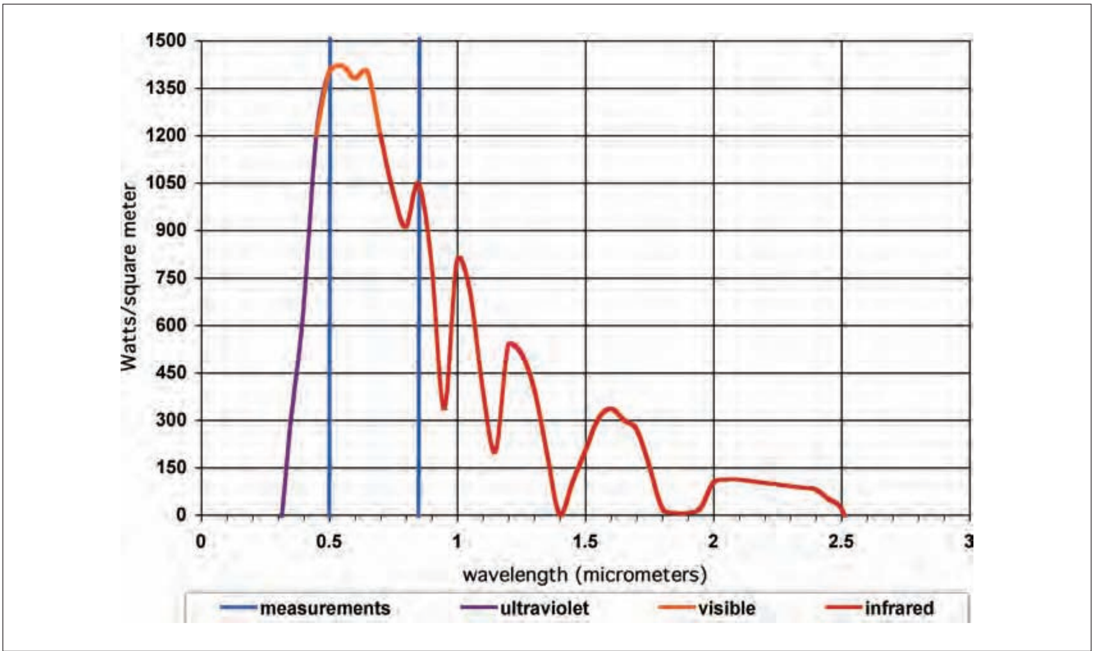
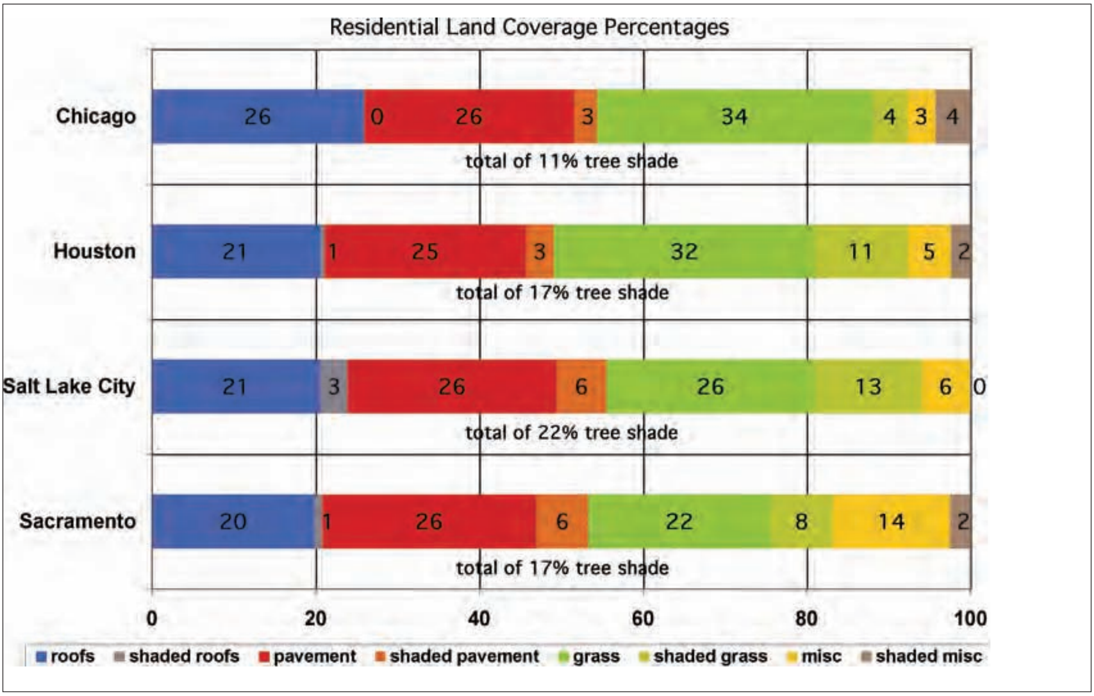
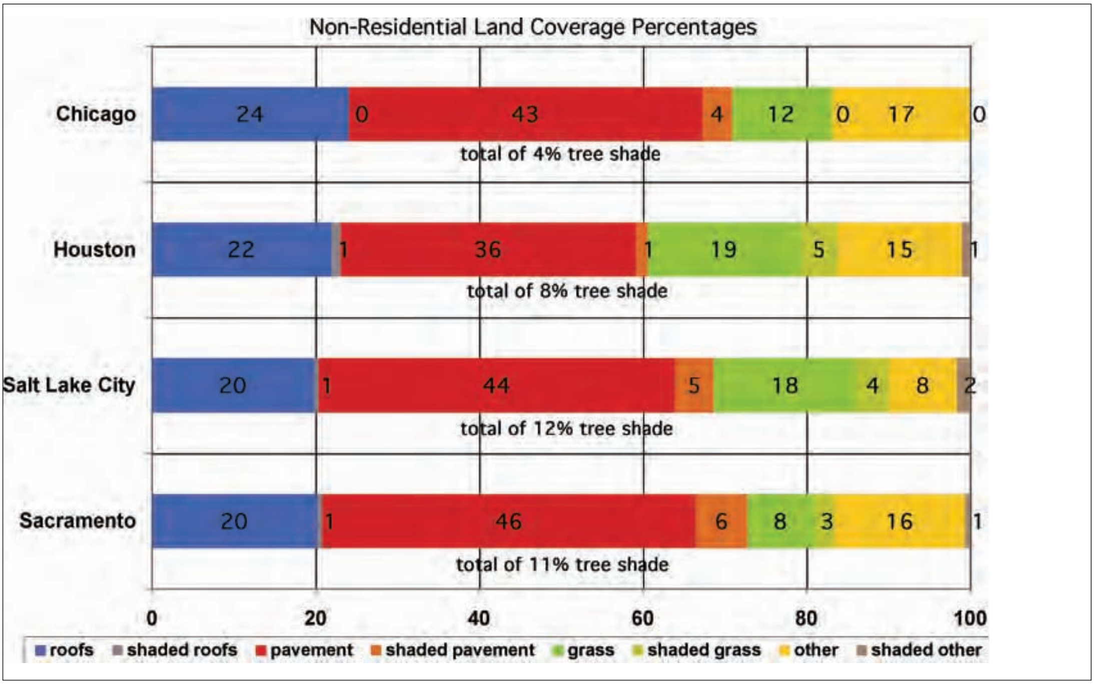


Plate 6 Solar energy reaching the Earth in the ultraviolet, visible and infrared wavelengths, plus the two energy wavelengths that are typically used to measure reflected solar energy



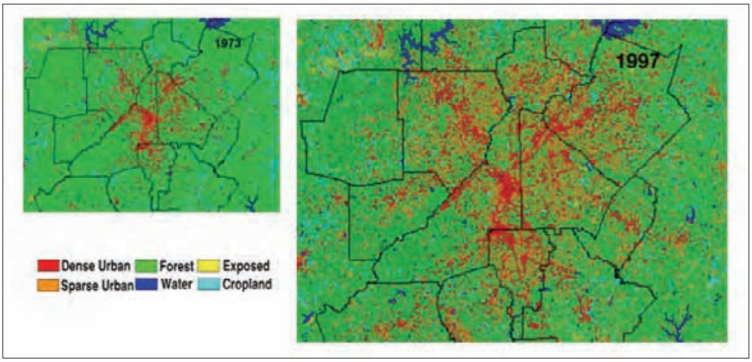
Source: Akbari and Rose, 1999, 2001a, 2001b; Rose et al, 2003.

Plate 7 Coverage of roofing, paving and vegetation in residential areas of Chicago, Houston, Salt Lake City and Sacramento



Source: Akbari and Rose, 1999, 2001a, 2001b; Rose et al, 2003.

Plate 8 Coverage of roofing, paving and vegetation in non-residential areas of Chicago, Houston, Salt Lake City and Sacramento



Source: American Forests, 2001.

Plate 9 Satellite images of Atlanta, Georgia, metropolitan area showing changes in land cover between 1973 and 1997

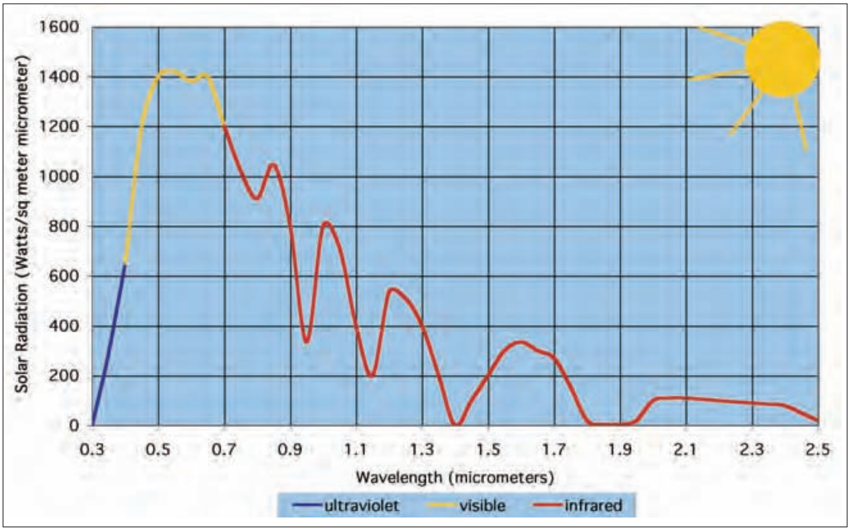


Plate 10 Solar energy versus wavelength reaching the earth's surface

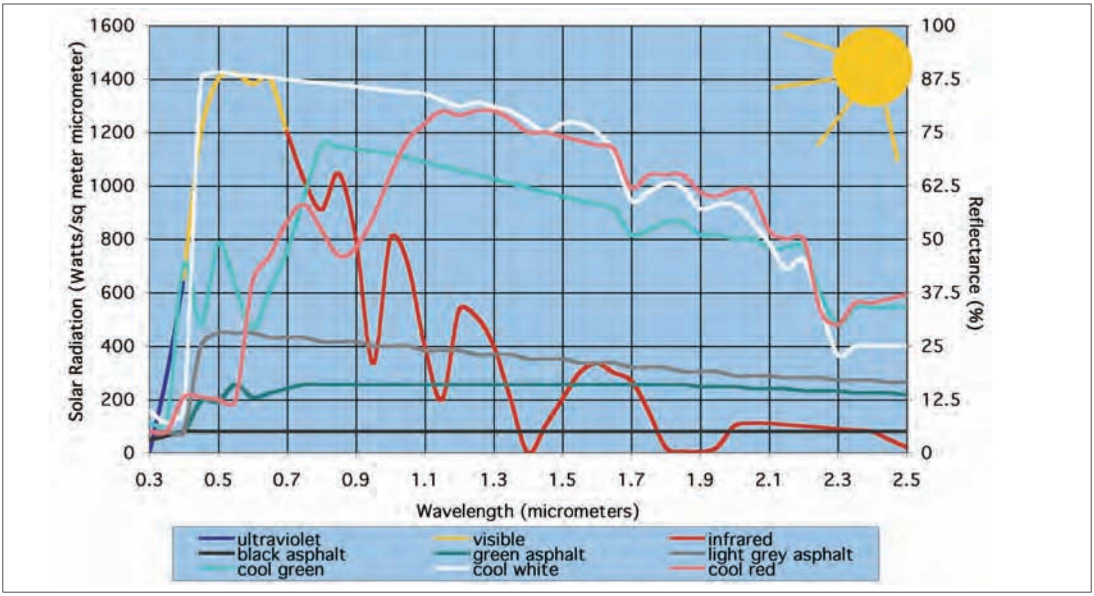


Plate 11 Solar reflectance of different roof materials

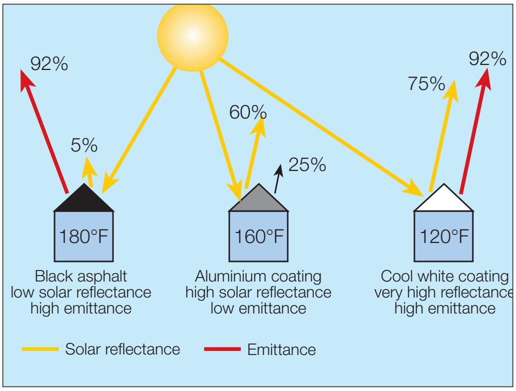


Plate 12 Combined effects of solar reflectance and emittance on roof temperature

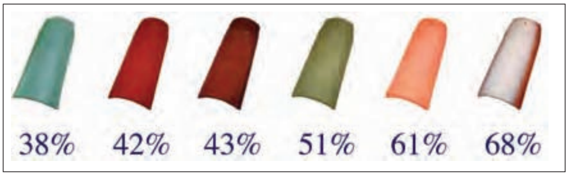


Plate 13 Cool coloured clay tiles and their solar reflectance values

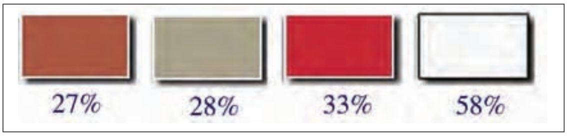
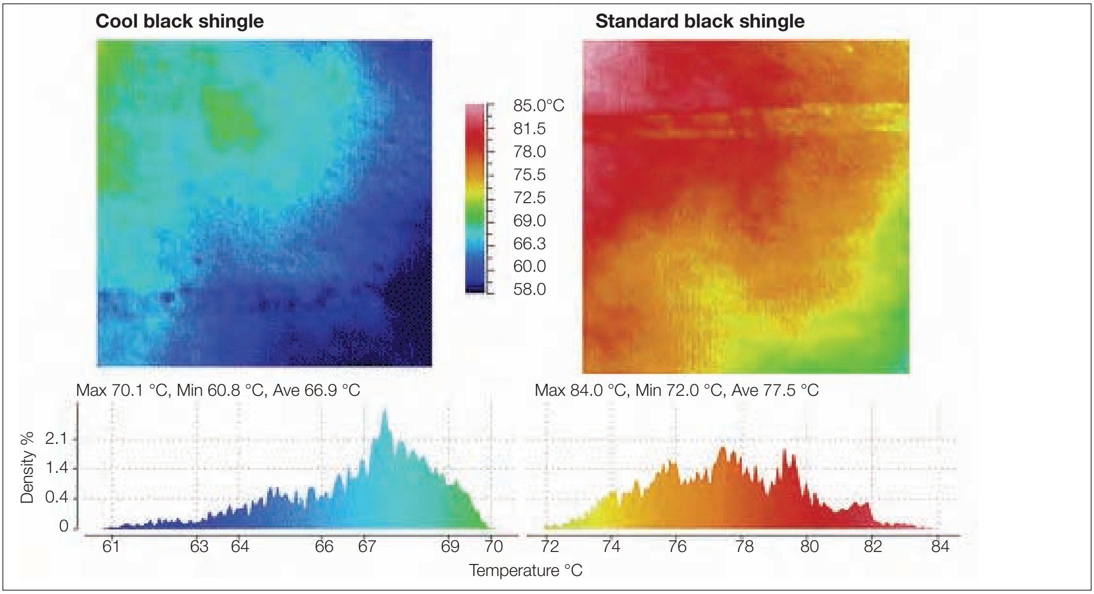
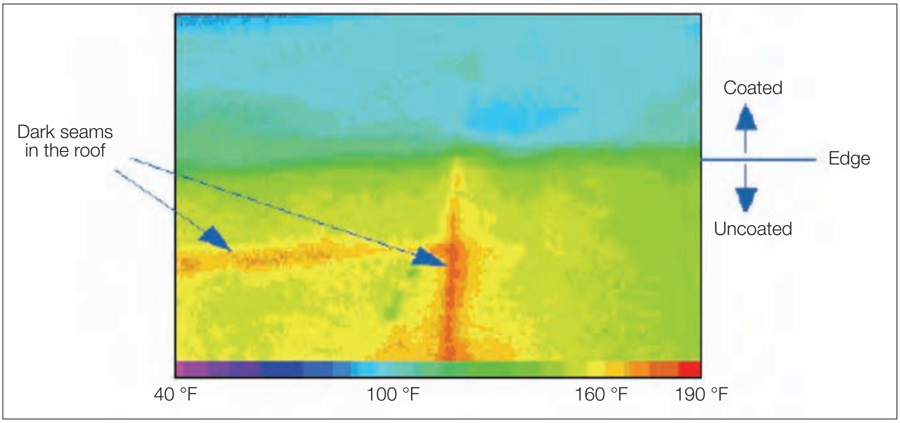


Plate 14 Cool metal roof coatings and their solar reflectance values



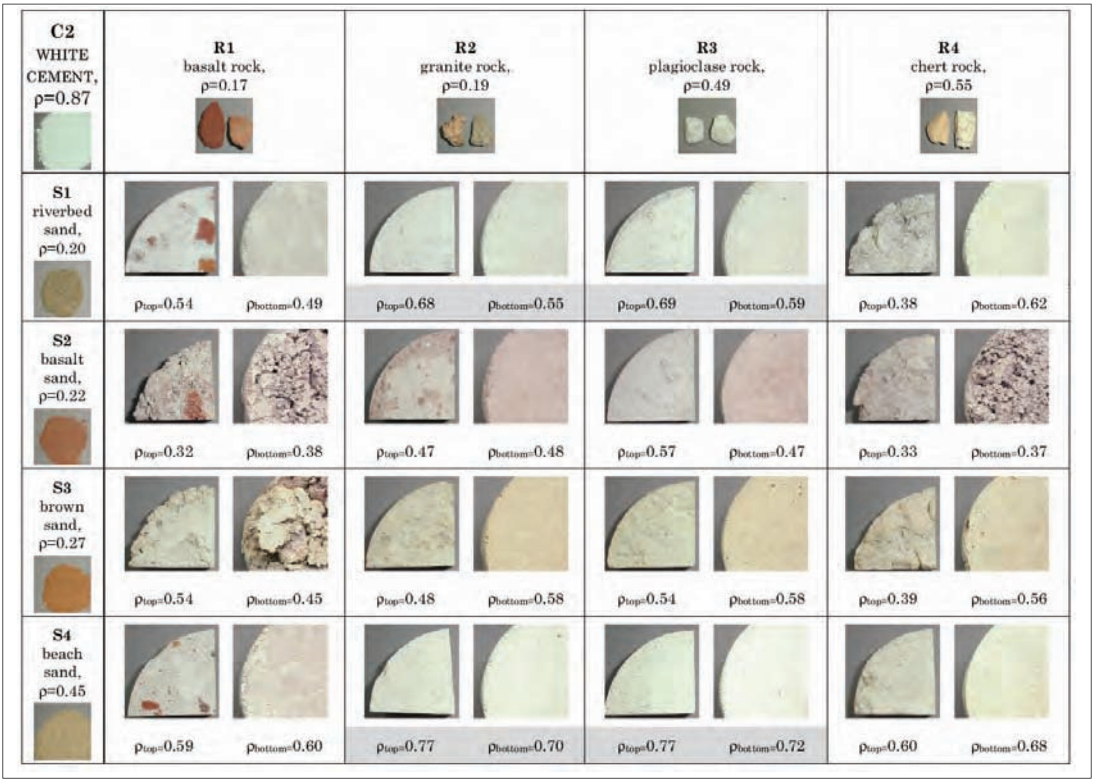
Source: http://solutions.3m.com/wps/portal/3M/en_US/IMPD/Roofing-Solutions/Products/Cool-Roofing-Granules/#palette, accessed in August 2007.

Plate 15 Temperatures of 3M's cool black shingle versus a traditional, hotter, black shingle



Source: Konopacki et al, 1998.

Plate 16 Infrared photograph of a light grey asphalt roof in Gilroy, California, at the edge of a bright white cool coating



Source: Levinson and Akbari, 2001.

Plate 17 Cooler Portland cement concretes

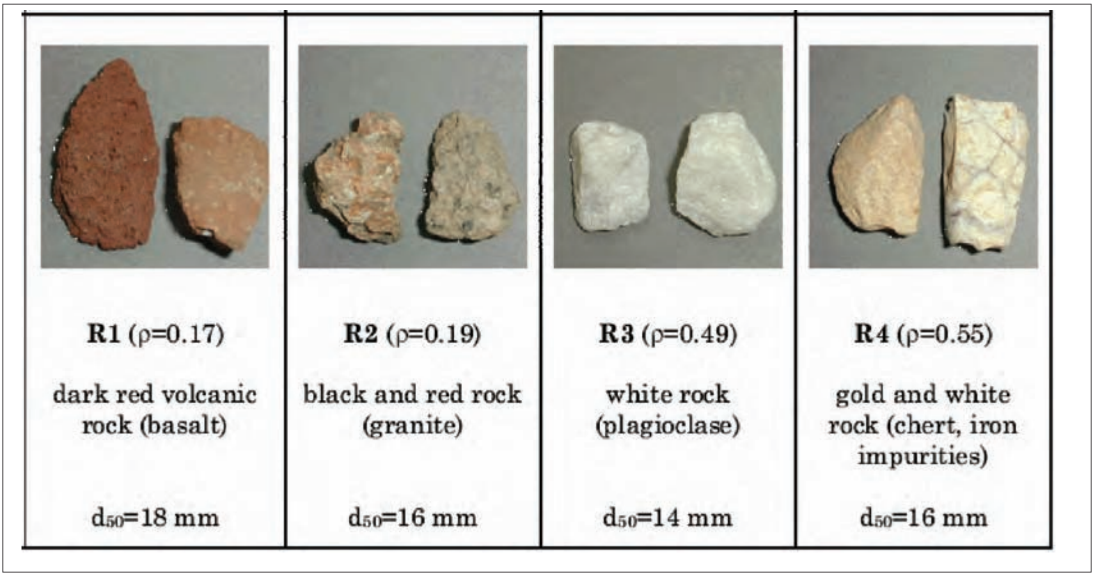
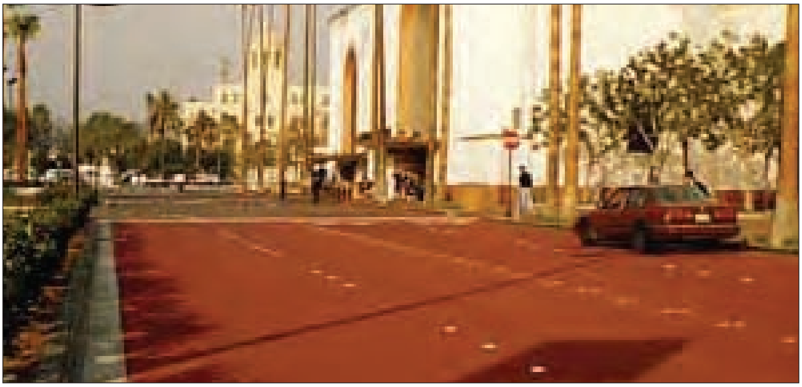


Plate 18 Solar reflectance of various types of aggregate used in pavements



Source: Asphacolor Corporation, www.asphacolour.com.

Plate 19 Roadway outside of Union Station in Los Angeles surfaced with a coloured asphalt emulsion sealcoat

Source: Integrated Paving Concepts, www.integratedpaving.com.

Plate 20 Asphalt pavement in a Hialeah, Florida, furniture store's parking lot, textured to resemble paving stones

Source: Soil Stabilization Products Company Inc., www.sspco.com.

Plate 21 Resin-based pavement used in the Land's End Coastal Trail alongside the San Francisco Bay