1 Introduction

1.1 Ecological climatology – concepts

1.1.1 Scientific origins

Ecology is the study of interactions of organisms among themselves and with their environment. It seeks to understand patterns in nature (e.g., the spatial and temporal distribution of organisms) and the processes governing those patterns. Climatology is the study of the physical state of the atmosphere – its instantaneous state or weather, its seasonal-to-interannual variability, its long-term average condition or climate, and how climate changes over time. These two fields of scientific study are distinctly different. Ecology is a discipline within the biological sciences and has as its core the principle of natural selection. Climatology is a discipline within the geophysical sciences based on applied physics and fluid dynamics. Both, however, share a common history.

The origin of these sciences is attributed to Aristotle (*circa* 350 BC) and Theophrastus (*circa* 300 BC) and their books *Meteorologica* and *Enquiry into Plants*, respectively, but their modern beginnings trace back to natural history and plant geography. Seventeenth, eighteenth, and nineteenth century naturalists and geographers saw changes in vegetation as they explored new regions and laid the foundation for the development of ecology and climatology as they sought explanations for these geographic patterns. Alexander von Humboldt, in the early 1800s, observed that widely separated regions have structurally and functionally similar vegetation if their climates are similar. Alphonse de Candolle hypothesized that latitudinal zones of tropical, temperate, and arctic vegetation are caused by temperature and in 1874 proposed formal vegetation zones with associated temperature limits. This provided an objective basis to map climatic regions, and in 1884 Wladimir Köppen used maps of vegetation geography to produce climate maps. His five primary climate zones shared similar temperature delimitations as de Candolle's vegetation (Table 1.1). The close correspondence between climate and vegetation is readily apparent, and many secondary climate zones such as tropical savanna, tropical rainforest, and tundra are named after vegetation. Although vegetation is no longer used to map the present climate, it is a principal means to reconstruct past climate from relationships of temperature and precipitation with tree-ring width, pollen abundance, and leaf form.

Despite shared origins, twentieth century advancement of ecology and climatology proceeded in the typical disciplinary framework of science into specialized fields of study. Ecology splintered into the study of animals or plants. Plant ecology further divided into topical studies of physiology, populations, communities, ecosystems, and landscapes. The study of weather and climate became organized around spatial scales of micrometeorology, mesoscale meteorology, and global climate and topical fields such as boundary layer meteorology, hydrometeorology, radiative transfer, and global dynamics.

With a lack of communication across disciplines, ecologists and climatologists can draw different insights to the same observations. Pieter Bruegel the Elder's painting "Hunters in the Snow" illustrates this (Fig. 1.1). H. H. Lamb, a prominent British climatologist, used this in his books to illustrate climate change (Lamb 1977, pp. 275–276; Lamb 1995, pp. 233–235). This scene was painted in the winter of 1565 and records, according to Lamb, Bruegel's impression of that severe winter. It was the beginning of prolonged artistic interest in Dutch winter landscapes that coincided with an extended period of colder than usual European winters. Richard Forman and Michel Godron similarly used this painting in their book on landscape ecology to illustrate the ecological concept of a landscape (Forman and Godron 1986, pp. 5–6). Instead of a visual record of an unusually cold winter, they saw the painting as an expression of the core tenets of landscape ecology: heterogeneity of landscape elements, spatial scale, and movement across the landscape.

The advent of global climate models in the 1970s and 1980s altered the disciplinary study of ecology and

TABLE 1.1. Relationship between de Candolle's plant types and Köppen's climate types

de Candolle plant type	Köppen climate type	Dominant vegetation
Megatherms	Humid tropical	Tropical rainforest Tropical savanna
Xerophiles	Dry	Desert Grassland
Mesotherms	Moist subtropical mid-latitude	Warm temperate deciduous forest Warm temperate coniferous forest Mediterranean
Microtherms	Moist continental	Cool temperate deciduous forest Cool temperate coniferous forest Boreal forest
Hekistotherms	Polar	Tundra

Source. Adapted from Colinvaux (1986, p. 326) and Oliver (1996).

climatology. These models require a mathematical representation of the exchanges of energy, water, and momentum between land and atmosphere. These processes are regulated in part by plants, which with their leaves, stomata, and numerous life forms do not conform to the mathematics of fluid dynamics. Atmospheric scientists developing climate models had to expand their geophysical framework to a biogeophysical framework (Deardorff 1978; Dickinson *et al*. 1986; Sellers *et al*. 1986). This development paralleled the trend by atmospheric scientists to recognize the planet as a climate system. Rather than delimiting Earth processes into separate academic disciplines of, for example, physical climatology, atmospheric chemistry, hydrology, ecology, geology, and oceanography, we now know these form a system of interacting physical, chemical, and biological components. It is now widely recognized that terrestrial ecosystems provide significant feedback to climate and that natural and human changes in land cover alter climate, the hydrologic cycle, and biogeochemical cycles.

The notion that vegetation affects climate is not new. Rapid and extensive clearing of forests for farmland and

FIGURE 1.1. "Hunters in the Snow" (Pieter Bruegel the Elder). Reproduced with permission of the Kunsthistorisches Museum (Vienna).

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towns during colonial settlement of North America prompted concern about how land clearing might change climate (Kittredge 1948; Landsberg 1970a; Thompson 1980; Feldman 1992). This culminated in the popular mid-nineteenth century notion "rain follows the plow," which attributed the increase in rainfall in the Great Plains at that time to cultivation and tree planting (Thompson 1980; Williams 1989). Similar concerns arose in Australia, where much of the native forest and woodland was cleared following European settlement in the early 1800s (Lawrence 2004). Today, it is seen in the concept of co-evolution of climate and life (Budyko 1974, 1986; Schneider and Mesirow 1976; Lovelock 1979, 1988; Schneider and Londer 1984; Schneider *et al.* 2004) and more recently in the recognition that climate change mitigation strategies must include an integrated assessment of terrestrial feedbacks on climate (Betts 2007).

1.1.2 Interdisciplinary framework

This book merges the relevant areas of ecology and climatology into an overlapping study of ecological climatology. Ecological climatology is an interdisciplinary framework to understand the functioning of terrestrial ecosystems in the climate system and the physical, chemical, and biological processes by which ecosystems affect climate. A central theme that emerges from this book is one of terrestrial ecosystems, through their cycling of energy, water, chemical elements, and trace gases, as a determinant of climate. Changes in terrestrial ecosystems through natural vegetation dynamics and through human land uses and land management are a significant feedback and forcing within the climate system.

Figure 1.2 illustrates five core areas: the *biogeophysical* and *biogeochemical* processes that regulate the exchanges of energy, water, momentum, and chemical materials with the atmosphere over periods of minutes to hours; *watersheds* and *ecosystems* and the hydrological and ecological processes that regulate these exchanges over periods of days to months; and *vegetation dynamics* and the ecological processes controlling the arrangement of plants into communities, the functioning of ecosystems, and temporal changes in response to disturbance over periods of years to centuries.

Biogeophysics is the study of physical interactions of the biosphere and geosphere with the atmosphere. It considers the transfers of heat, moisture, and momentum between land and atmosphere and the meteorological, hydrological, and ecological processes regulating these exchanges. Momentum is transferred when plants and other rough elements of the land surface interfere with the flow of air. Heat and moisture are exchanged when net radiation (R_n) at the surface is returned to the atmosphere as sensible heat (H), latent heat (λE), or stored in the ground (G). Biogeophysical feedbacks are understood through the surface energy balance:

$$R_n = S{\downarrow}\,(1 - r) + (\varepsilon L{\downarrow} - \varepsilon\sigma T_s^4) = H + \lambda E + G \qquad (1.1)$$

where $S{\downarrow}$ and $L{\downarrow}$ are downwelling solar radiation and longwave radiation, respectively, and r is surface albedo. The term $S{\downarrow}\,(1 - r)$ is the solar radiation absorbed by the land surface. The term $\varepsilon L{\downarrow}$ is the longwave radiation absorbed by the surface, and $\varepsilon\sigma T_s^4$ is the longwave radiation emitted by the surface with temperature T_s. Collectively, these three terms comprise net radiation.

The surface energy balance highlights two important land–atmosphere feedbacks. The first is related to surface albedo. An increase in surface albedo, which can occur with loss of vegetation cover, reduces the absorption of solar radiation at the surface and cools the surface climate. Less energy is returned to the atmosphere as sensible and latent heat, which promotes subsidence of air aloft and may reduce precipitation. Such albedo feedback on rainfall is particularly important in deserts. Vegetation masking of the high albedo of snow creates a warmer climate than in the absence of trees. A second feedback is related to latent heat flux, or evapotranspiration. High latent heat flux with wet soil creates a cool, moist atmospheric boundary layer – conditions that may feed back to increase precipitation. A decrease in vegetation cover that reduces latent heat flux warms surface climate and may reduce precipitation. This is particularly prominent in tropical deforestation.

Biogeochemistry is the study of element cycling among the biosphere, geosphere, and atmosphere. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are important greenhouse gases regulated in part by terrestrial ecosystems. The net storage of carbon in the biosphere in the absence of fire and other carbon losses, known as net ecosystem production (*NEP*) or net ecosystem exchange (*NEE*), is the balance among carbon uptake during gross primary production (*GPP*), carbon loss during plant respiration (R_a), and carbon loss during decomposition (R_h):

$$NEP = R_h - (GPP - R_a) = R_h - NPP \qquad (1.2)$$

The net carbon uptake by plants (i.e., $GPP - R_a$) is known as net primary production (*NPP*). The signature of terrestrial ecosystems is seen in the annual cycle of atmospheric CO_2, which has low concentration during the growing season when plants absorb CO_2 and high concentration during the dormant season (Fig. 3.5).

Biogeophysical and biogeochemical processes do not occur in isolation. In particular, stomata open to absorb

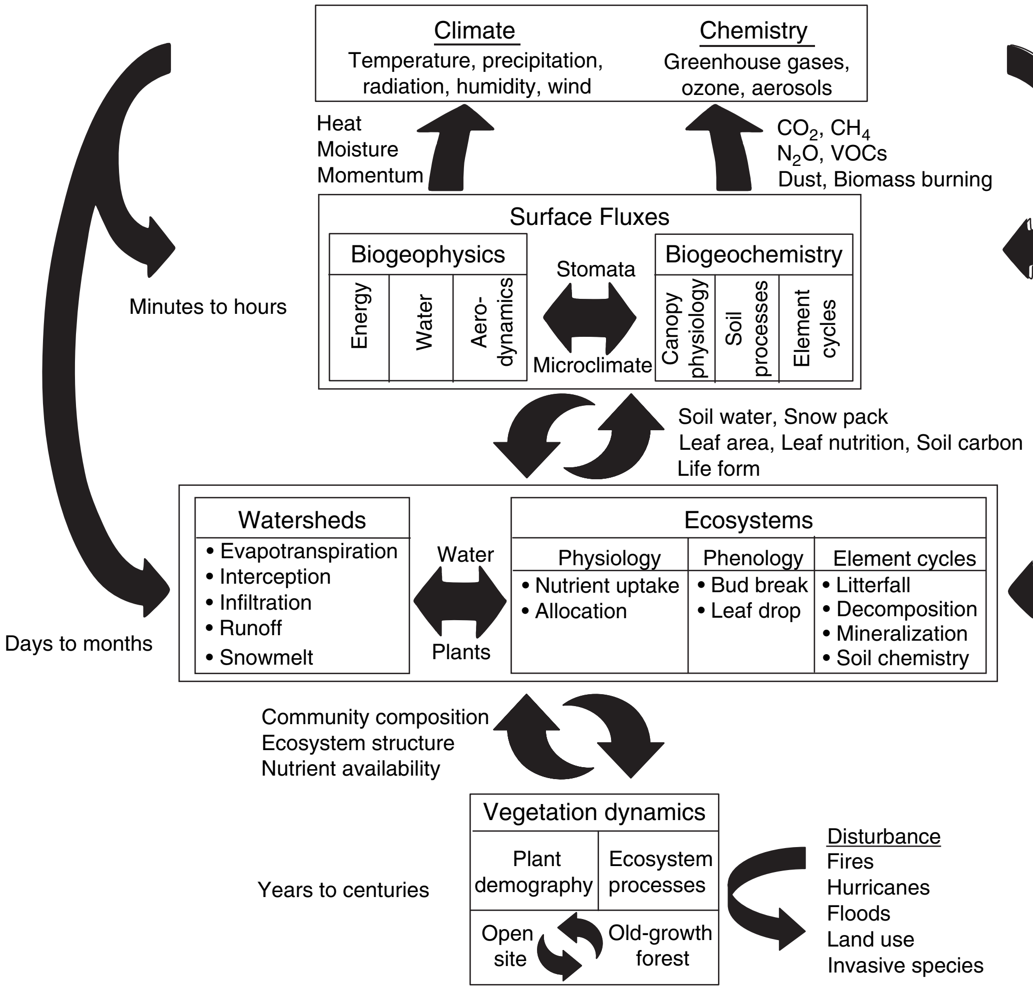

FIGURE 1.2. A generalized scope of ecological climatology showing the biogeophysical and biogeochemical processes by which terrestrial ecosystems affect weather and climate, the watershed and ecosystem processes that govern these, and the role of vegetation dynamics in initiating change.

CO_2 during photosynthesis, but in doing so water diffuses out of the leaf during transpiration. Consequently, water loss during transpiration is tied to carbon uptake during photosynthesis. This is seen in studies that relate leaf photosynthesis, transpiration, and stomatal conductance (Fig. 17.6). The physiology of stomata represents a balance between the conflicting goals of maximizing CO_2 uptake while minimizing water loss.

The exchange of energy, water, and other materials between biosphere and atmosphere depend on the hydrologic cycle. The fundamental system of study in hydrology is a watershed or catchment. Over long periods of time, it is commonly assumed that water entering a watershed as precipitation (P) is either returned to the atmosphere as evapotranspiration (E) or runs off into streams and rivers (R) so that the annual water balance is

$$P - E = R \tag{1.3}$$

A reduction in evapotranspiration, which occurs, for example, with deforestation, produces an increase in runoff (Fig. 12.3). Numerous topographic, edaphic, and ecological features control the hydrology of a watershed. Hydrologic processes such as evapotranspiration, interception of precipitation by plants, infiltration of water into soil, runoff into streams and rivers, and snowmelt determine soil water, snow pack, and saturated areas within the watershed – conditions that vary with a timescale of days to months and that influence surface fluxes.

Terrestrial ecosystems are an expression of an ecological system. All ecosystems have structure – the arrangement of materials in pools and reservoirs – and function – the flows and exchanges among these pools. In terms of carbon, the pools are typically foliage, stem, and root biomass and decomposing soil organic matter (Fig. 21.3). Functions include carbon uptake during photosynthesis and carbon loss during respiration (Fig. 1.2). A variety of ecological processes operating at timescales of days to months influence ecosystem function. The amount of leaf area is an important determinant of photosynthesis, absorption of solar radiation, heat and momentum fluxes, evapotranspiration, and interception. In many plant communities, the presence of leaves varies seasonally in relation to temperature or moisture stress. Other processes such as litterfall, decomposition, mineralization of organically bound nutrients, nutrient uptake, and the allocation of resources to growth influence carbon storage. Short-term functioning of terrestrial ecosystems seen in fluxes of photosynthesis and respiration is manifested in long-term relationships of climate with net primary production (Fig. 24.4) and soil carbon turnover (Fig. 24.10). Interannual variability in these functions is seen in interannual variability in atmospheric CO_2 (Fig. 29.4).

Ecosystems are not just static elements of the landscape; they are dynamic. The abundance and biomass of plant species change over periods of years to centuries. Disturbances such as floods, fires, and hurricanes initiate temporal change in ecosystems known as succession. The life history patterns of plants have evolved in part as a result of recurring disturbances. Many plant species are ephemeral members of the landscape, adapted to recently disturbed sites. Others dominate old-growth ecosystems in the late stages of succession. Climate change also alters ecosystems. Long-term changes in temperature, precipitation, atmospheric CO_2, and the chemistry of precipitation alter the conditions for vegetation growth. By altering species composition, ecosystem structure, and nutrient availability, vegetation change feeds back to affect climate. In particular, forest growth absorbs carbon from the atmosphere while deforestation releases carbon to the atmosphere. Human activities also alter ecosystems through clearing of land for agriculture, farm abandonment, and introduction of invasive species.

1.1.3 Climate–vegetation interactions

The coupling of ecosystems and climate occurs over a continuum of timescales from minutes to seasons to thousands of years (Table 1.2). At short timescales, the seasonal emergence and senescence of leaves alters the absorption of radiation, the dissipation of energy into latent and sensible heat, and CO_2 uptake. The effect of these changes can be seen in air temperature, humidity, and the seasonal drawdown of CO_2 in the atmosphere. Interannual variability in temperature and precipitation alter ecosystem metabolism, which is again evident in the concentration of CO_2 in the atmosphere. At longer timescales of decades to centuries, successional changes in response to recurring disturbances alter surface energy fluxes and carbon storage. Coupled climate–ecosystem dynamics are particularly evident over periods of centuries to millennia. Temperature, precipitation, and atmospheric CO_2 are the chief determinants of the biogeographic distribution of vegetation across the planet. In turn, biogeography affects climate and atmospheric CO_2 concentration. The outcome of climate–vegetation interactions can be seen in the evolutionary record. There is a close relationship between leaf shape and climate. Vascular plants introduced numerous biotic feedbacks on climate, primarily related to plant responses to CO_2 that affect stomatal conductance and leaf form. Over several decades, people greatly shape the landscape through clearing of land for agriculture, reforestation of abandoned farmland, and through urbanization. These land uses alter surface energy fluxes, biogeochemical cycles, and the hydrological cycle and produce a discernible signal in temperature, precipitation, and atmospheric CO_2 concentration.

1.2 Ecological climatology – applications

The scientific concepts of ecological climatology can be applied to design and manage the built landscape. There is a growing awareness of the goods and services provided by ecosystems and that they provide a natural solution to many environmental problems. Trees, parks, and greenbelts provide relief from the hot urban environment and for stormwater management. The restorative quality of gardens and parks is being recognized in medical studies. This represents a profound change in attitude towards vegetation, particularly forests. In the Colonial era of the United States, as land was being cleared for settlement, forests were viewed as both an unlimited source of resources needed for survival and a hostile wilderness that needed to be tamed and civilized (Williams 1989; Stegner 1990, pp. 9–21; Power 1996, pp. 131–148). In an increasingly technological world, it is ironic that the role of terrestrial and aquatic ecosystems – nature's technology – in improving the quality of the environment is becoming especially important.

1.2.1 Microclimatic landscape design

We frequently use technology to modify the prevailing climate for our needs. This is most evident in our homes, which are heated in winter and cooled by air conditioning in summer, and our residential yards, which may be irrigated to supplement rainfall. In our cities, vast drainage

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TABLE 1.2. Timescales of vegetation change and associated atmospheric impact

Vegetation change	Timescale	Ecological signal	Controlling processes	Atmospheric signal
Natural				
Leaf emergence	Seasonal to interannual	Leaf area index	Air temperature Soil water Life form	Cooler temperature Higher humidity CO_2 drawdown Lower albedo Greater latent heat Less sensible heat
Ecosystem metabolism	Seasonal to interannual	Leaf area index Carbon storage	Air temperature Soil water Humidity Solar radiation Atmospheric CO_2	CO_2 drawdown Albedo Latent heat Sensible heat
Succession	Decadal to century	Leaf area index Carbon storage Species composition Nutrient availability Ecosystem structure	Life history patterns Litterfall Soil water Soil nutrients Disturbance	CO_2 drawdown Surface fluxes
Biogeography	Century to millennial	Leaf area index Carbon storage Species composition Nutrient availability Ecosystem structure	Climate Succession Life history patterns	Temperature Precipitation Surface fluxes Atmospheric CO_2
Evolution	Millennial	Stomatal density Leaf form	Atmospheric CO_2	Leaf temperature Leaf energy fluxes
Human				
Agroecosystems Reforestation	Decadal	Leaf area index Carbon storage Species composition Nutrient availability Ecosystem structure	People Succession	Temperature Precipitation Surface fluxes Atmospheric CO_2
Urbanization	Decadal	Species composition Ecosystem structure Impervious area	People	Warm temperature Increased runoff Increased pollution

systems collect stormwater from impervious surfaces. Ski resorts make snow in winter to prolong the ski season. Farmers heat fruit orchards in springtime to prevent frost damage to emerging blossoms. In arid climates, clouds are seeded with dry ice or silver iodide to induce precipitation. We have developed a modern lifestyle independent of climate and the natural environment. Buildings, cities, and landscapes are often designed without regard to unique regional environments and ecosystems; we no longer know where in the world we live. This contrasts greatly with less technological eras. For example, colonists settling Virginia and Massachusetts during the 1600s quickly adapted English building design techniques to provide relief from the hot, humid Virginia summer and to accommodate the cold New England winter (Fitch 1948, 1966, 1972).

Topographic, edaphic, and ecological features of the landscape create large climate changes. Orographic precipitation creates a stark contrast between moist and arid climates on the windward and leeward slopes of mountains. Northeast slopes in the Northern Hemisphere are typically a few degrees cooler than southwest slopes, particularly during summer afternoons. Air temperature typically cools by 1°C with every 100 m gain in elevation. Cold air often collects at night in low-lying sites while a slightly higher location may bask in relative warmth. Oceans and large lakes moderate the seasonal variation in temperature. Sea breezes provide relief on a hot summer day while inland cities may suffer from a sweltering heat wave. One only has to stand under a tree on a hot summer day to realize the shaded environment under the canopy is cooler than open spaces. Windbreaks formed by trees conserve energy by reducing heat loss from strong winter winds.

By understanding the science of ecology and climatology, we can take advantage of natural landscape features and make climate work for us. This is a recurring theme within the landscape architecture and land-use-planning professions, which advocate understanding local environmental features as part of the site planning process (Lynch and Hack 1984; Steiner 1991; Simonds 1998) and creating designs that promote energy and water conservation (Robinette 1983, 1984; Moffat and Schiler 1994; Brown and Gillespie 1995). Use of vegetation to conserve energy and to create thermally pleasant environments by blocking cold winter winds, shading hot summer sun, and by evapotranspiration cooling is well documented (DeWalle *et al.* 1983; Parker 1983, 1987; Thayer *et al.* 1983; Enis 1984; Wagar 1984; Thayer and Maeda 1985; Heisler 1986; Wagar and Heisler 1986; Huang *et al.* 1987; Hoyano 1988; McPherson *et al.* 1988, 1989; Wilmers 1988). Precipitation can also be more effectively managed and stored by vegetated landscapes that promote infiltration in contrast to hard surfaces that promote runoff (Robinette 1984; Ferguson 1994, 1998).

1.2.2 Land-use planning

Cityscapes are quite different from rural landscapes. Consider the environmental changes as a parcel of land is developed. Albedo decreases and more solar radiation is absorbed at the surface. Tall, narrow urban canyons limit the loss of longwave radiation to the sky. Heat is generated from buildings and traffic. This energy is stored during the day in the steel, bricks, wood, asphalt, concrete, and other materials that form a city and slowly released at night. The hard, impervious urban fabric further alters the energy balance by limiting evapotranspiration. Air is polluted, which might alter rainfall. A greater portion of rainfall becomes runoff as the hard urban surface prevents infiltration and conveys surface water quickly to rivers. Constructed drainage systems of gutters, pipes, and treatment plants replace the networks of gullies, creeks, and wetlands that carry water across the landscape. Biogeochemical cycles are altered. Grass is cut, lawns are irrigated, fallen leaves are collected, and fertilizers, pesticides, and herbicides are applied in search of the perfect lawn. Native vegetation is removed and replaced with monolithic tracts of grass and scattered relic or introduced trees.

The conventional approach to landscape planning and design, especially at the scale of residential homes, office buildings, and parks, does not emphasize the environmental value of landscapes. This is particularly evident in the use of trees, which emphasizes the formal and visual aesthetics of landscapes (Arnold 1993; Thomas 1997). Cities are planned with regards to economic growth, social needs, and neighborhood concerns. Nature is typically perceived as separate from the city, and when it is considered it is more likely to be perceived as a constraint rather than as an opportunity.

Yet there is a strong ecological movement within the landscape planning and design professions (McHarg 1969; Hough 1984, 1995; Spirn 1984, 1988; Steiner *et al.* 1988; Bormann *et al.* 1993; Van der Ryn and Cowan 1996; Thompson and Steiner 1997). This movement recognizes that the landscape is not only where we live, but also regulates climate, air quality, water resources, and supports plants, animals, and other living creatures that sustain the healthy functioning of ecosystems. It emphasizes Earth as a system, with the biosphere as a regulator of planetary health through flows of energy, water, nutrients, and biomass. Ecological design advocates a new design aesthetic stemming from ecological functions and services rather than the traditional design principles of form, composition, color, and texture. The goods and services supplied by ecosystems provide a natural solution to urban environmental problems. Identity, form, and aesthetics arise from natural processes and features of the land.

There have been many topical treatments of the urban environment by designers and architects – its climate (Aronin 1953; Olgyay 1963; Givoni 1976, 1998; Robinette 1983; Lowry 1988; Crowther 1992; Brown and Gillespie 1995), hydrology (Robinette 1984; Ferguson 1994, 1998), and soils (Craul 1999) and how to incorporate these into urban planning and design. Perhaps because climate affects human health and comfort in many ways, consideration of climate in the built environment has received much attention. Microclimates must be considered in site selection and in the design itself. Cooling breezes and shade are needed during hot, overheated periods; the warmth of sunlight and protection from winds are needed during cold, underheated periods.

As architects and planners advocated design based on natural processes such as climate and ecology, scientists recognized urban climates as distinct from rural climates. The 1960s and 1970s saw a substantial scientific effort to characterize and understand these differences, culminating in a study of the climate of St. Louis, Missouri (Changnon 1981a). The development of Columbia, Maryland, from rural farmland to suburban city in the 1960s and 1970s provided an opportunity to examine changes in climate

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with urban development (Landsberg and Maisel 1972; Landsberg 1979). A similar interest in the urban climate continues today (Grimmond 2006).

The impact of the built environment on climate led to concern about a lack of communication among architects, planners, and scientists and the need to plan cities with respect to urban climates (Landsberg 1970b, 1973; Oke 1976, 1984, 1988; Changnon 1979, 1981b). The World Meteorological Organization held several symposia that addressed not only climate as it determines land-use practices but also the impact of urban development on climate (WMO 1970a,b, 1976). This interest continues, with a focus on developing countries and tropical climates (WMO 1986, 1994, 1996) and with increased interest on application to urban planning (Mills 2006; Oke 2006).

Ecologists, too, have recognized that the pristine ecosystem long favored for study is increasingly uncommon and have sought to apply ecological principles and methods of study to the urban ecosystem (Bormann *et al*. 1993; McDonnell and Pickett 1993; Platt *et al*. 1994; Dramstad *et al*. 1996; Flores *et al*. 1998; Zipperer *et al*. 2000). The United States National Science Foundation recognized urban settings as unique ecosystems, adding the cities of Phoenix, Arizona, and Baltimore, Maryland, as research sites in its long-term ecological research program.

Science, especially ecology, provides a useful framework to address land use, but cannot provide all the solutions. Ecology is both a science based on facts and an ideology based on values. Incorporation of ecological concepts into planning is often more in tune with environmentalism than ecological science (Daniels 1988; Flores *et al*. 1998). Landscape design, similarly, is both art and environmental stewardship – a schism that leads to heated debate about the ecological design movement (Mozingo 1997; Thompson and Steiner 1997). Improving the quality of the urban ecosystem and minimizing human impacts on nature requires a balance between the natural and cultural components of landscapes and between the facts of science and the values of design. Balancing these is essential to the application of science to landscape and urban planning (Oke 1984, 1988; Platt *et al*. 1994; Dramstad *et al*. 1996).

1.3 Overview of the book

The book is divided into seven sections on the Earth system, global physical climatology, soil processes, hydrometeorology, biometeorology, terrestrial plant ecology, and terrestrial forcings and feedbacks. The first section describes component spheres of the Earth system (Chapter 2) and the energy, water, and biogeochemical cycles that link these spheres (Chapter 3).

The second section reviews climates, climate variability, and climate change. The radiative balance of the atmosphere, especially solar radiation, its geographic variation, and its annual cycle, is an important determinant of climate (Chapter 4). Geographic and seasonal variation in the radiative balance drives the general circulation of the atmosphere (Chapter 5). This gives rise to Earth's macroclimates, and within which mountains, lakes, and vegetation create local climates (Chapter 6). The realized temperature and precipitation in any year can deviate markedly from the long-term climatology because of seasonal-to-interannual atmospheric variability such as the El Niño/Southern Oscillation and North Atlantic Oscillation (Chapter 7). Climate also changes over longer timescales of centuries and millennia in response to changes in insolation, greenhouse gases, and numerous feedbacks within the climate system (Chapter 8).

The third section reviews soil physics (Chapter 9) and biogeochemistry (Chapter 10). Soils store vast amounts of energy, which modulates the diurnal and annual cycle of temperature. They provide water for evapotranspiration and regulate the hydrologic cycle on land. The weathering of rocks and the decomposition of soil organic material are part of the biogeochemical cycling of carbon and provide nutrients to sustain plant growth.

The fourth section on hydrometeorology reviews the hydrologic cycle, surface energy fluxes, and the interactions between the hydrosphere and atmosphere. The hydrologic cycle on land is reviewed in terms of point processes (Chapter 11) and watersheds (Chapter 12). The hydrologic cycle regulates surface energy fluxes. The energy balance at Earth's land surface requires that energy gained from net radiation be balanced by the fluxes of sensible and latent heat to the atmosphere and the storage of heat in soil (Chapter 13). The fluxes of sensible and latent heat occur because the turbulent mixing of air transports heat and moisture, typically away from the surface (Chapter 14). Soil water exerts a strong control on the partitioning of net radiation in sensible and latent heat fluxes, and through this affects the atmospheric boundary layer (Chapter 15).

The fifth section reviews biometeorology. The exchanges of sensible heat, latent heat, and CO_2 between land and atmosphere are regulated by the physiology and micrometeorology of plant canopies. Individual leaves absorb radiation and exchange sensible heat and latent heat with the surrounding air (Chapter 16). The uptake of CO_2 during photosynthesis is tightly coupled to the loss of water during transpiration (Chapter 17). Both occur through stomatal openings on the leaf surface. The aggregate flux from vegetation is the integral of the individual leaf fluxes over the depth of the canopy (Chapter 18).

The sixth section reviews terrestrial plant ecology. It extends the discussion of plant physiology from the previous section to an overview of whole-plant allocation and plant strategies (Chapter 19), the arrangement of plant species into populations and communities (Chapter 20), and the functioning of ecosystems (Chapter 21). Vegetation changes over time in response to recurring disturbance (Chapter 22). Landscapes represent another level of ecological organization, merging the concepts of populations, communities, ecosystems, and plant dynamics. Spatial gradients in environment combine with recurring disturbance to create a mosaic of plant communities and ecosystems across the landscape (Chapter 23). The structure and composition of vegetation and the functioning of terrestrial ecosystems, which at a local scale are shaped by environmental factors such as temperature and moisture, are also influenced by global climate patterns. This is seen in the biogeography of vegetation and in the global carbon cycle, especially net primary production (Chapter 24).

The final section examines terrestrial forcings and feedbacks in the climate system, especially how natural and human changes in land cover and land use affect climate. Numerous global climate model experiments have demonstrated the role of land surface hydrology and terrestrial vegetation in determining regional and global climate. Chapter 25 reviews the representation of land surface processes in climate models. Soil water, snow, and vegetation contribute to climate variability (Chapter 26). Deforestation, reforestation, degradation of drylands, and cultivation of croplands are case studies of how human uses of land alter climate (Chapter 27). Vegetation dynamics in response to climate change also alters climate. The boreal forest–tundra ecotone and the Sahel of North Africa are prominent examples of coupled climate–vegetation dynamics (Chapter 28). In addition to biogeophysical feedbacks, terrestrial ecosystems are coupled to climate through various biogeochemical cycles. The carbon cycle is a prominent feedback on climate change, and many climate models now include terrestrial and oceanic carbon cycles (Chapter 29). Urbanization also alters climate and the hydrologic cycle (Chapter 30).

1.4 Review questions

1. Scientists have found fossilized remains of tree foliage in Antarctica that date to 100 million years ago. What does this indicate about the climate of that era?
2. The following data from Lovelock (1979) describes Earth with and without life. Which planet represents Earth with life? What does this suggest about relationships between the biosphere and climate?

	Planet A	Planet B
Atmospheric composition		
Carbon dioxide	98%	0.03%
Nitrogen	1.9%	79%
Oxygen	trace	21%
Argon	0.1%	1%
Surface temperature	290 ± 50 °C	13 °C
Surface pressure	60 000 hPa	1000 hPa

3. Describe changes in the ecosystem structure and function with reforestation that affect climate.
4. In a climate with cold winters and hot summers, an architect designs a house so that the main living space faces due east. Large windows along the east wall of the house promote winter solar heating. What can be done to mitigate excessive solar heating in summer?
5. In a climate with mild winters and hot summers, is it preferable to build a house on a north- or a south-facing slope to promote energy conservation? Which is preferable in a climate with cold winters and mild summers?
6. Discuss changes in climate faced by English settlers of Virginia and Massachusetts in the 1600s. How might these changes have affected building design?

	London	Boston	Norfolk
Average January temperature (°C)	4.4	−2.2	4.4
Days with minimum temperature <0 °C	41	98	54
Average July temperature (°C)	16.7	22.2	25.6
Days with maximum temperature >32 °C	1	13	32
Annual precipitation (mm)	584	1118	1143

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