Ecological Climatology

Concepts and applications

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Introduction

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1.1.1 Shared origins; disciplinary development

Ecology is the study of the 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 – ecology and climatology – can be considered as distinct as night and day. One is a discipline within the biological sciences: the other is a discipline within the geophysical sciences. One has as its core the principle of natural selection: the other applied physics and fluid dynamics. Both, however, share a common history.

The origin of these sciences is attributed to Aristotle (*circa* 350 B.C.) and Theophrastus (*circa* 300 B.C.) and their books *Meteorologica* (Lee 1962) and *Enquiry into Plants* (Hort 1968, 1980), respectively, but their modern beginnings trace back to natural history and plant geography. Naturalists and geographers exploring Earth in the 17th, 18th, and 19th centuries saw changes in vegetation as they explored new regions, and as they sought explanations for these geographic patterns they laid the foundations for the development of ecology and climatology (McIntosh 1985; Colinvaux 1986, pp. 323–327; Oliver 1996a,b; Shugart 1996). Alexander von Humboldt, in the early 1800s, recognized that the appearance and main characteristics of groups of plants were related to climate. He observed that widely separated regions have structurally and functionally similar vegetation if their climates are similar. Later, while studying maps of major plant formations, Alphonse de Candolle noticed the general latitudinal bands of tropical, temperate, and arctic vegetation. He hypothesized

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	Warm temperate deciduous forest
	Mid-Latitude	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 (1996a).

that this zonation was 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 distributions to produce climate maps. His five primary climate zones shared similar temperature delimitations as de Candolle's vegetation types (Table 1.1). The close correspondence between climate zones and major vegetation zones 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 present climate, it is a principal means to reconstruct past climates from relationships of temperature and precipitation with tree ring width (Jacoby and D'Arrigo 1989; Cook *et al.* 1991, 1998, 2000; D'Arrigo and Jacoby 1993, 1999; Cook 1995; D'Arrigo *et al.* 1996, 1998, 1999, 2000a,b, 2001; Jacoby *et al.* 1996, 2000; Villalba *et al.* 1998; Wiles *et al.* 1998; Pederson *et al.* 2001), pollen abundance (Prentice *et al.* 1991a, 1998; Huntley and Prentice 1993; Webb *et al.* 1993, 1998; Wright *et al.* 1993; Cheddadi *et al.* 1997; Bartlein *et al.* 1998), and leaf form (Wolfe 1995; Wilf 1997, 2000; Wolfe *et al.* 1998; Wilf *et al.* 1998). Past atmospheric CO_2 concentrations can be inferred from the decline in stomatal density with higher CO_2 (McElwain *et al.* 1999; Wagner *et al.* 1999; Royer *et al.* 2001). Vegetation geography is often used to interpret and test climate model simulations (Webb *et al.* 1993; Kutzbach *et al.* 1996, 1998; Ruddiman *et al.* 1997; Jolly *et al.* 1998a; Prentice *et al.* 1998; Kleidon *et al.* 2000).

Despite shared origins, the 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

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

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 atmospheric processes such as boundary layers, hydrometeorology, radiative transfer, clouds, and global dynamics.

Scientists, because of different methodologies and research interests, can draw different insights to nature even though they have the same information at hand. Pieter Bruegel the Elder's painting 'Hunters in the Snow' illustrates this point nicely (Figure 1.1). H.H. Lamb, a prominent British climatologist, used this in his books on climatology 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 winter, which was the severest experienced to date. Lamb notes that this was the beginning of a prolonged artistic interest in Dutch winter landscapes that coincided with an extended period of colder than usual European winters. On the other hand, Richard Forman and Michel Godron 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 seeing a visual record of an unusually cold winter, they see the painting as an expression of the core tenets of landscape ecology: heterogeneity of landscape elements, spatial scale, and movement across the landscape.

Disciplinary focus is evident in the way in which students of ecology and climatology learn about each other's science. The traditional ecological view is of climate as a controller of vegetation processes and geography (Begon *et al.* 1986; Colinvaux 1986; Barnes *et al.* 1998; Barbour *et al.* 1999; Smith and Smith 2001). In this biologically oriented view, climate is an exogenous forcing. The floristic composition of terrestrial ecosystems, the biomass of plants and decaying organic matter, and the rates of plant productivity and organic matter decomposition respond to changes in climate but do not themselves alter climate. Climatologists, on the other hand, have a geophysical view of the atmosphere, emphasizing heat and moisture transport (Peixoto and Oort 1991; Barry and Chorley 1992; Hartmann 1994). In this view, climate is understood in terms of the forcing of planetary energetics and atmospheric circulation by changes in greenhouse gases, aerosols, and solar radiation (Jones *et al.* 1996, 1999; Mann *et al.* 1998; Hansen *et al.* 1998b, 1999; Tett *et al.* 1999). Changes in the structure and function of terrestrial ecosystems as a result of climate change are seen as the impact of climate change rather than as feedbacks within the climate system.

The prominence of global environmental change research in the 1980s and 1990s altered the disciplinary study of ecology and climatology. In particular, the development of global climate models required a mathematical representation of the lower boundary of the atmosphere – the interface with terrestrial landscapes – and 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 or Earth system (Trenberth 1992a; Schneider 1997; Kump *et al.* 1999; Jacobson *et al.* 2000). 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. The inclusion in climate models of the exchanges of energy, water, and momentum between land and atmosphere has greatly altered our perception of the role of land in the climate system. It is now widely recognized that terrestrial ecosystems provide significant feedback to climate and that natural and human-mediated changes in land cover alter climate. One expression of this is in the concept of coevolution of climate and life, in which biological activity is regulated by climate and in turn, through the cycling of energy, water, and chemicals, regulates climate (Budyko 1974, 1986; Schneider and Mesirow 1976; Lovelock 1979, 1988; Schneider and Londer 1984).

The idea that changes in vegetation can alter climate is not new. Christopher Columbus is reported to have believed that heavy rainfall in the New World was caused by the luxuriant forests (Kittredge 1948, p. 6; Thompson 1980; Shukla and Mintz 1982). The rapid and extensive clearing of forests for farmland and townships during the colonial settlement of North America prompted concern about how land clearing might change climate (Kittredge 1948; Thompson 1980; Feldman 1992). In the Caribbean islands, as forests were being cleared to grow sugar cane, laws were enacted to preserve forests in an effort to promote rainfall (Anthes 1984; Feldman 1992). In the United States, Thomas Jefferson noted changes in climate as land was cleared and suggested repeated climate surveys to measure the change (Landsberg 1970c; Thompson 1980). Interest in how the changing landscape was altering climate 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, pp. 379–386).

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 landscapes in the climate system. It combines aspects of physical climatology, micrometeorology, hydrology, soil science, plant physiology, biogeochemistry, ecosystem ecology, biogeography, and vegetation dynamics to understand the physical, chemical, and biological processes by which landscapes affect and are affected by climate. It blurs the distinction between ecology and climatology so that the physiology of stomata are just as relevant to understanding climate as are clouds and convection. 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 within the climate system.

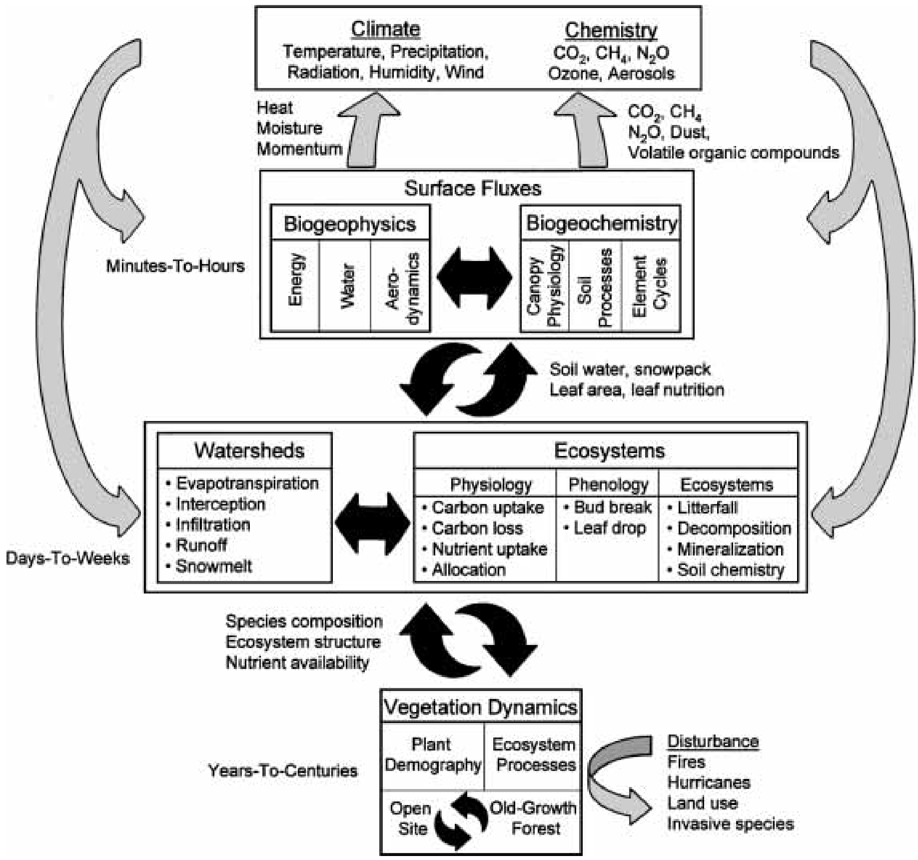

Figure 1.2. Generalized scope of ecological climatology showing the biogeophysical and biogeochemical processes by which terrestrial landscapes affect weather and climate, the ecological and hydrological processes that govern these, and the relationships among component processes. Updated from Sellers *et al.* (1995, 1997b).

Figure 1.2 provides a conceptual framework within which to organize traditional disciplinary studies. These are grouped into 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 the hydrologic processes that regulate these exchanges; *terrestrial ecosystems* and the ecological processes that control the abundance and distribution of plant species and their arrangement into communities and ecosystems; and *vegetation dynamics* and temporal changes in ecosystem structure and function. Each of these core areas exists as its own specialty of study, but they are linked by common physical, chemical, and biological processes.

Biogeophysics and biogeochemistry

Terrestrial ecosystems exchange heat, moisture, momentum, and a variety of chemical materials with the atmosphere. Heat and moisture are exchanged when the net radiation at the surface (R_n) is returned to the atmosphere as sensible heat (H), latent heat (λE, also known as evapotranspiration), or stored in the ground (G) so that the energy at the surface is balanced as

$$R_n = H + \lambda E + G$$

Momentum is transferred when plants and other rough elements of the land surface interfere with the flow of wind. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are important greenhouse gases regulated in part by terrestrial ecosystems. Other materials include dust, which affects the absorption, reflection, and transmission of solar radiation, and chemical reactants such as volatile organic compounds, which influence ozone near the surface. These surface fluxes occur on a near-instantaneous timescale, responding to changes in temperature, wind, humidity, and solar radiation over periods of minutes to hours. Biogeophysics is the study of the physical interactions of the biosphere and geosphere with the atmosphere (Gates 1980; Monteith and Unsworth 1990; Campbell and Norman 1998). It considers the transfers of heat, moisture, momentum, and gases between land and atmosphere and the meteorological processes regulating these exchanges. Biogeochemistry is the study of element cycling (e.g., carbon, nitrogen) among terrestrial plants, soil, rivers, oceans, and the atmosphere and the associated exchanges of gases and chemical reactants with the atmosphere (Schlesinger 1997; Jacobson *et al.* 2000). It links the biological cycling of elements with the geochemical cycling to understand the uptake, release, and transfer of chemical elements and gases among the biosphere, geosphere, hydrosphere, and atmosphere.

The exchanges of heat, momentum, moisture, and gases with the atmosphere regulate and are regulated by microclimate, the physiology of plants, and soil processes. In particular, stomata – microscopic pores on leaf surfaces – open to absorb CO_2 during photosynthesis, but in doing so water diffuses out of the leaf during transpiration. Consequently, water loss during transpiration (T) is tied to carbon uptake during photosynthesis (P) through stomatal conductance (g_s)

$$g_s \propto P \propto T$$

The physiology of stomata are regulated by the canopy microclimate, soil water, leaf nutrition, and the life history of plants. Thus, the study of biogeophysics and biogeochemistry are linked through canopy physics, soil physics, and plant physiology.

Watersheds

The cycling of water, energy, and chemical elements between biosphere and atmosphere depend on the hydrological and ecological status of landscapes. In hydrology, the fundamental system of study is a watershed or catchment. A watershed is topographically defined so that rain falling onto the watershed is collected and flows downhill into a stream or river. Over long periods of time (e.g., annually) it is commonly assumed that water entering a watershed as precipitation (P) is either returned to the atmosphere as evapotranspiration (ET) or runs off into streams and rivers (R) so that the long-term water balance is

$$P = ET + R$$

Numerous topographic, edaphic, and ecological features control the hydrology of a watershed. Important processes include evapotranspiration, which is part of the biogeophysical exchanges of energy and water with the atmosphere, snow melt, interception of precipitation by vegetation foliage and stems, infiltration of water into soil, and runoff of water along the ground surface into streams, rivers, and lakes. These processes determine the amount of water in soil, the amount of snow on the ground, and saturated areas within the watershed – conditions that vary with a time scale of days to weeks and that in turn influence surface fluxes.

Ecosystems

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 organic material in the soil. Functions include carbon uptake during photosynthesis (also known as gross primary production, GPP), carbon loss during plant respiration (R_a), and carbon loss during decomposition (R_h) so that the net storage of carbon in an ecosystem, known as net ecosystem production (NEP), is

$$NEP = (GPP - R_a) - R_h = NPP - R_h$$

The net carbon uptake by plants (i.e., $GPP - R_a$) is known as net primary production (NPP). A variety of ecological processes operating at timescales of days to weeks influence ecosystem function. Physiological processes such as carbon assimilation during photosynthesis, carbon loss during respiration, nutrient uptake, and the allocation of resources to growth determine short-term carbon gain. The amount of foliage present is an important determinant of processes such as photosynthesis, absorption of solar radiation, the exchanges of heat and momentum with the atmosphere, 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, and the mineralization of organically bound nutrients during decomposition influence carbon and nutrient storage, the distribution of carbon and nutrients within the ecosystem, and the rates of processes such as photosynthesis and transpiration.

Vegetation dynamics

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 are natural features of landscapes and initiate temporal changes 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 physiological processes such as photosynthesis and respiration, demographic processes such as reproduction, and ecosystem processes such as nutrient availability. By altering species composition and ecosystem structure, vegetation dynamics produces temporal changes in ecosystem functions and the biogeophysical and biogeochemical fluxes with 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 dynamics

The interrelationships between climate and vegetation can be seen at a variety of spatial and temporal scales. Consider, for example, the relationship between leaf shape and its microclimate (Parkhurst and Loucks 1972; Givnish and Vermeij 1976; Woodward 1993a). The temperature of a leaf is regulated by heat and moisture exchanges with the surrounding air. Under sunny conditions, high heat exchange cools the leaf surface; low heat exchange creates a warm leaf microclimate. Loss of water during transpiration can also cool a leaf because large amounts of energy are needed to change water from liquid to vapor. The ease with which heat and moisture are lost from a leaf is determined in part by leaf size and shape. A small leaf has a low resistance to heat and moisture transfer. Conditions at the leaf surface are closely coupled to the

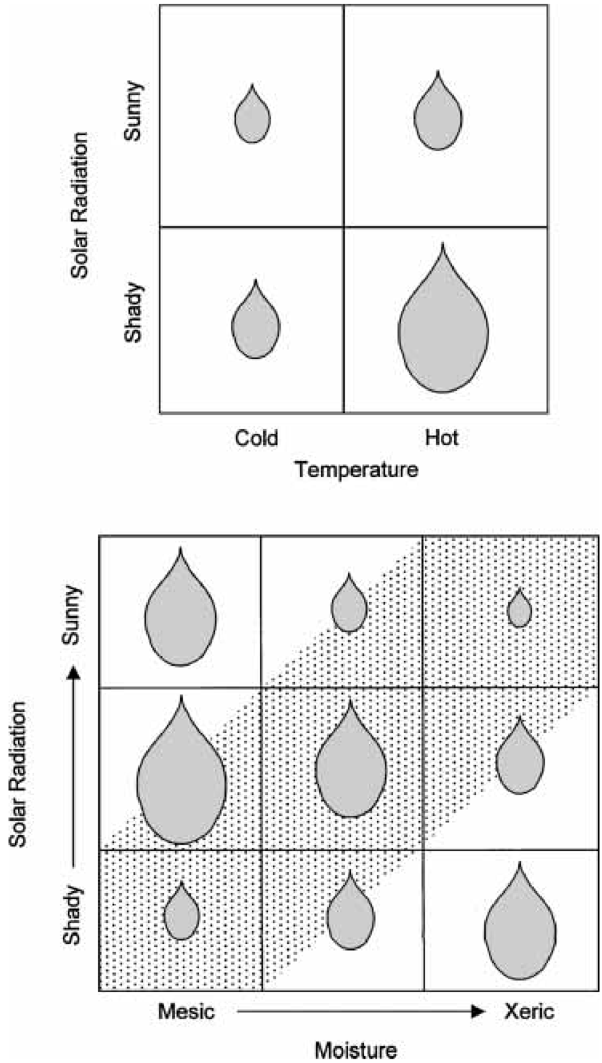

Figure 1.3. Optimal leaf size in relation to environment. Top: Leaf size in relation to solar radiation and temperature. Adapted from Parkhurst and Loucks (1972). Bottom: Leaf size in relation to solar radiation and moisture. The stippled area shows the habitats likely in nature and between the forest understory and overstory. Adapted from Givnish and Vermeij (1976).

air, and leaf temperature is similar to that of the surrounding air. A large leaf has a higher resistance to heat and moisture transfer. It is decoupled from the surrounding air so that leaf temperature is several degrees warmer than that of air. As a result, there is a relationship between environment and leaf size (Figure 1.3). Large leaves are favored in warm to hot climates with low light conditions and high humidity, such as might be found in the understory of

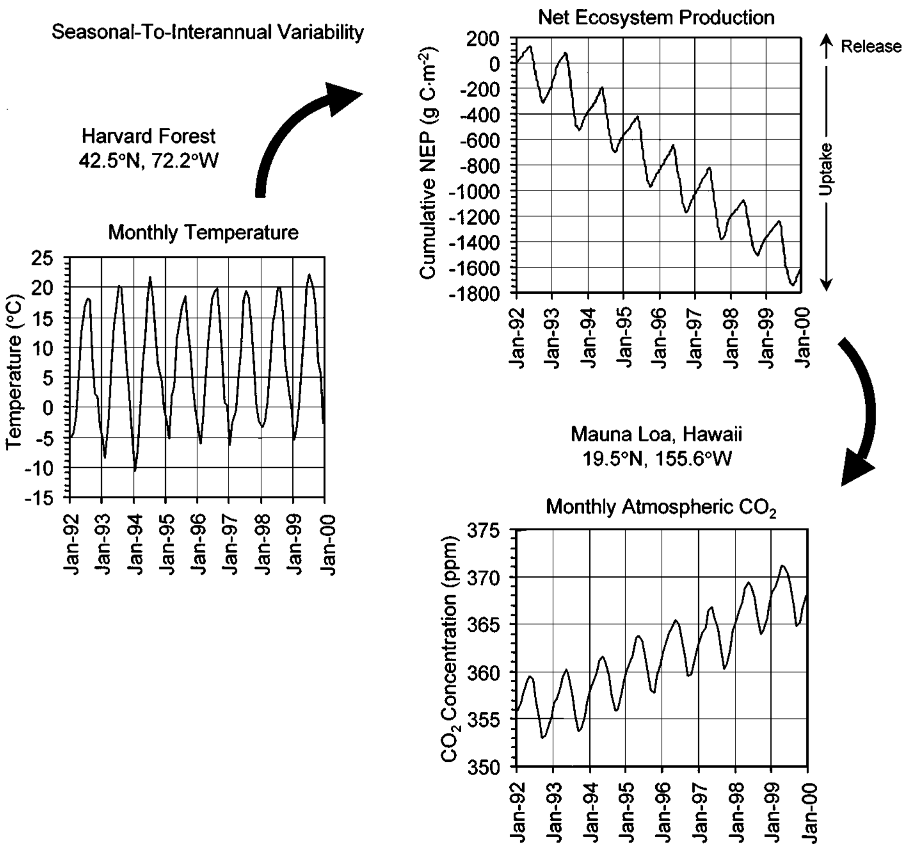

Figure 1.4. Climate–vegetation interactions at the seasonal to interannual timescale. Harvard Forest is a mixed deciduous–evergreen forest in central Massachusetts. Net ecosystem production is the cumulative daily uptake of carbon from 1992 through 1999 with negative values indicating uptake. Goulden *et al.* (1996a, 1996b) describes these measurements. Atmospheric carbon dioxide is monthly concentrations in parts per million by volume (ppm) measured at Mauna Loa, Hawaii, by C.D. Keeling and colleagues at the Scripps Institution of Oceanography (La Jolla, California). These data are archived at the Carbon Dioxide Information Analysis Center (Oak Ridge National Laboratory, Oak Ridge, Tennessee).

temperate and tropical forests. Small leaves are favored in sunny or dry environments (e.g., the forest overstory) and in cold climates.

Climate–vegetation dynamics can be seen in the seasonal growth and senescence of leaves in temperate climates, its effect on net ecosystem production, and resulting seasonal changes in atmospheric CO_2 concentration (Figure 1.4). In these climates, deciduous trees drop their foliage in autumn with the onset of short days and cold winters. In springtime, as temperatures warm and days become longer, buds break open and leaves emerge. This phenology is most pronounced for deciduous trees but also occurs in evergreen trees. The seasonal emergence and senescence of foliage in response to temperature drives a seasonal pattern of carbon uptake. Ecosystems have a net uptake of carbon during the growing season and net carbon loss during the dormant season. This annual cycle of carbon uptake and release drives an annual cycle of CO_2 concentration in the atmosphere. Carbon dioxide concentration is low during the growing season and increases during the non-growing season. Year-to-year variability in temperature and precipitation produce interannual variability in atmospheric CO_2.

The outcome of climate–vegetation dynamics is also seen at longer timescales of decades to centuries over which vegetation composition and structure change. Temperature and precipitation are the chief determinants of the broad biogeographic distribution of vegetation across the planet. In turn, the type of vegetation affects the exchanges of energy, moisture, and momentum with the atmosphere. Climate model studies for the height of the last ice age some 21 000 years ago illustrate the nature of these interactions (Figure 1.5, color plate). A simulation with the altered Earth–Sun geometry, lower atmospheric CO_2, and greater ice cover of this period shows a climate that is several degrees colder in the Northern Hemisphere than present. This climate change is large enough to alter the geographic distribution of terrestrial ecosystems. Another simulation with an interactive climate–vegetation model whereby vegetation both responds to and influences climate produces a different climate. Trees die back in the colder climate of the Northern Hemisphere and in the drier climate of the tropics. Tundra vegetation dominates much of the middle to high latitudes while grasslands cover the tropics and subtropics. As a result of these vegetation changes, temperatures cool over much of Eurasia where tree cover decreases and they warm in the tropics and subtropics where grasses replace trees. The reduction in forest cover at middle to high latitudes exposes the high albedo of the winter and spring snow cover, reducing the absorption of solar radiation. At low latitudes, loss of trees reduces evapotranspiration, warming climate and reducing precipitation.

1.2 Ecological climatology – applications

1.2.1 Land use and land cover change

Interest in the effects of vegetation on climate is part of a growing recognition of the goods and services provided by terrestrial ecosystems and how human uses of land alter these (Costanza *et al.* 1997; Daily 1997; Daily *et al.* 1997). Among these are services related to climate regulation, water resources,

Table 1.2. *Goods and services provided by terrestrial ecosystems*

Production of goods
Food
Timber
Fuel
Pharmaceutical products
Industrial products
Services
Waste treatment
Purification of water
Decomposition and recycling of wastes
Water resources
Storage and retention of water
Mitigation of floods and droughts
Soil resources
Generation and renewal of fertile soils
Erosion control and sediment retention
Biological resources
Maintenance of biodiversity
Pollination of crops
Pest control
Weather and climate
Regulation of chemical composition of atmosphere
Regulation of temperature and precipitation
Recreation
Aesthetic beauty

recycling wastes, maintenance of biodiversity, food production, pharmaceutical and industrial products, recreation, and cultural values (Table 1.2). Human activities have altered these services. The pristine landscape ecologists have long favored for study is increasingly rare, and there is growing ecological interest in people as agents of environmental change and our impacts on climate, biogeochemical cycles, the hydrologic cycle, and land cover (McDonnell and Pickett 1990, 1993; Turner *et al.* 1990; Lubchenco *et al.* 1991; Meyer and Turner 1992; Vitousek 1994; Meyer 1996; Vitousek *et al.* 1997a,b).

The rise of agriculture has led to significant destruction of forest cover and appropriation of ecosystem functions. It is estimated that between 1700 and 1980 global forest and woodland area decreased by 17%, from 61 to 51 million km^2 (Figure 1.6). Cropland area increased almost sixfold, from 2.6 million km^2 in 1700 to 15 million km^2 in 1980. Croplands now cover significant portions of central North America, Europe, Asia, and South America (Figure 1.7, color plate). Human-mediated changes in land use and land cover

Table 1.3. *Human appropriation of net primary production (NPP) and evapotranspiration (ET) due to land use.*

Land use	NPP (10^{15} g yr^{-1})	ET (km^3 yr^{-1})
Cultivation	15.0	5 500
Grazing	11.6	5 800
Forest	13.6	6 800
Urban	0.4	100
Total co-opted	40.6	18 200
Global total	135.0	69 600
Percent co-opted	30%	26%

Note: Units are grams of biomass (NPP) and cubic km of water (ET).
Source: Data from Vitousek *et al.* (1986) and Postel *et al.* (1996).

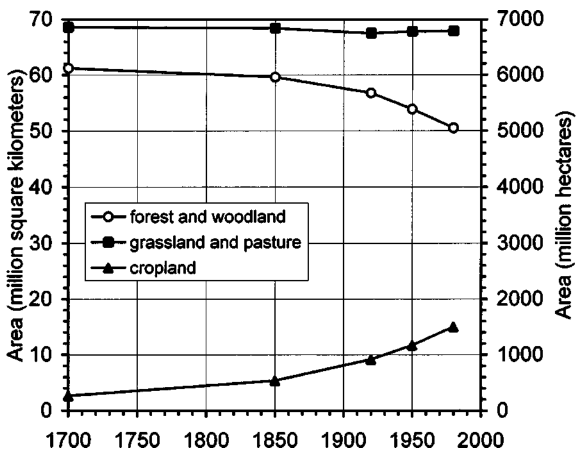

Figure 1.6. Global area of forest, grassland, and cropland from 1700 to 1980. Data from Richards (1990).

have a significant impact on climate that is noticeable on the planetary scale and comparable in magnitude to other climate forcings such as increases in greenhouse gases (Hansen *et al.* 1998b; Brovkin *et al.* 1999; Chase *et al.* 2000; Pitman and Zhao 2000; Govindasamy *et al.* 2001; Zhao *et al.* 2001). In addition, the cycling of carbon, nitrogen, and water among atmosphere, ocean, and land has been altered. Some 30% of the net primary production of terrestrial ecosystems is now managed by humans in farmland, rangeland, and commercial forests (Table 1.3). Clearing of forests for agricultural land releases much of the carbon stored in trees and soils to the atmosphere (Houghton *et al.* 1983; Houghton 1995, 1999, 2000a,b). It is estimated that from 1850 to 1990 an amount of

Table 1.4. *Human appropriation of accessible runoff for various uses*

Sector	Water use ($km^3\ yr^{-1}$)	Consumption ($km^3\ yr^{-1}$)
Offstream uses		
Agriculture	2 880	1 870
Industry	975	90
Urban	300	50
Reservoir loss	275	275
Instream needs	2 350	0
Total co-opted	6 780	2 285
Accessible runoff	12 500	12 500
Percent co-opted	54%	18%

Note: Only a portion of offstream water use is actually consumed in the production of goods and the rest is returned. Reservoir loss is evaporation of water in large reservoirs intended for human uses. Instream use is the water flow needed to maintain navigation, water quality, recreation, and wildlife habitats.
Source: Data from Postel *et al.* (1996). Postel *et al.* (1996), WMO (1997b), and Postel (1998, 2000) review global water use.

carbon equal to one-half that emitted during the combustion of fossil fuels over the same period was released to the atmosphere as a result of changes in land use (Houghton 1999). The production of nitrogen fertilizers, the cultivation of legumes and other nitrogen-fixing plants, and to a lesser extent the combustion of fossil fuels have doubled the rate of nitrogen input on land (Vitousek 1994; Galloway *et al.* 1995; Vitousek *et al.* 1997a). The increased availability of nitrogen in terrestrial and aquatic ecosystems is thought to have contributed to the acidification of soils, rivers, and lakes, accelerated the loss of biodiversity, and caused changes in the composition and functioning of these ecosystems (Vitousek 1994; Vitousek *et al.* 1997a; Moffat 1998). In particular, the amount of nitrogen transported to oceans by rivers has increased greatly with the advent of intensive agriculture (Turner and Rabalais 1991, 1994; Howarth *et al.* 1996; Alexander *et al.* 2000). Some 26% of the annual evapotranspiration by terrestrial ecosystems has been appropriated by managed lands (Table 1.3). Globally, human activities appropriate about 54% of the available renewable freshwater – a total of 6780 km^3 of water each year – for a variety of agricultural, industrial, municipal, and other uses (Table 1.4). Some of this withdrawn water is returned, but still 18% of the available water is consumed in the production of

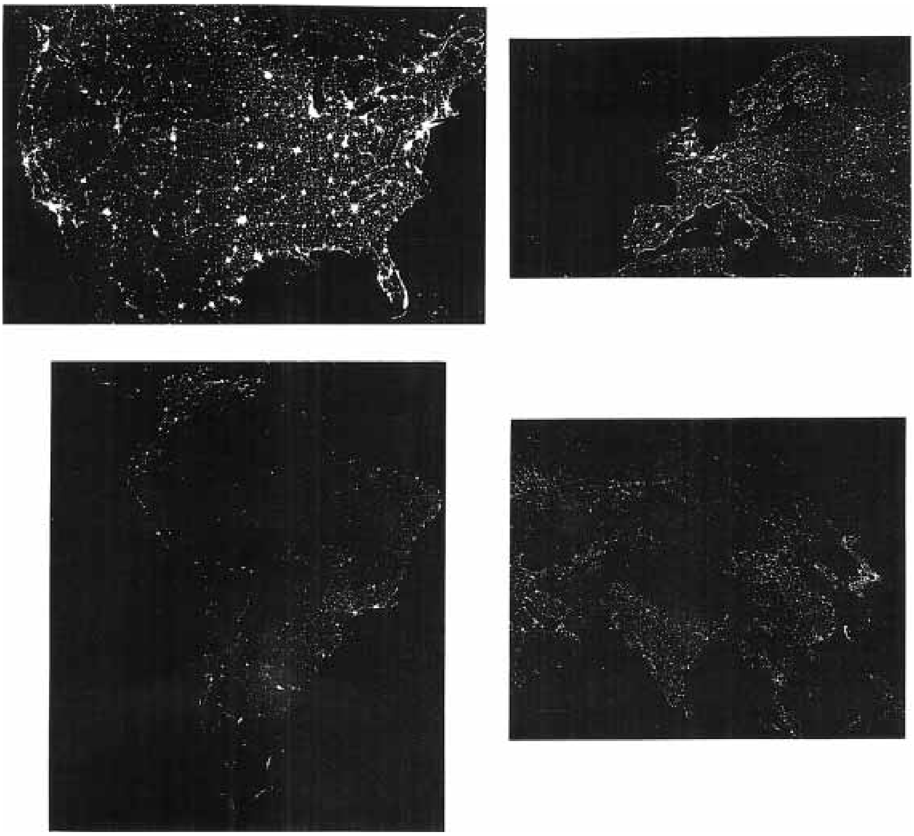

Figure 1.8. Urban areas as seen by satellite in nighttime lights of the world. Top left: United States. Top right: Europe. Bottom left: South America. Bottom right: Asia. Images from the Defense Meteorological Satellite Program and provided by the National Geophysical Data Center (National Oceanic and Atmospheric Administration, Boulder, Colorado). These data have been used to assess the environmental impacts of urbanization (e.g., Elvidge *et al.* 1997; Imhoff *et al.* 1997).

materials. Appropriation of water is seen in the flow of rivers. Some 77% of the annual discharge of 139 large river systems in the northern third of the world has been affected by dams, water regulation, interbasin diversion, and irrigation (Dynesius and Nilsson 1994). Only 39% of these river systems remain free flowing.

Regionally, large tracts of land have been urbanized, as seen in the nighttime lights of the world (Figure 1.8). The cycling of energy and water between land and atmosphere is altered. Urban areas are generally several degrees warmer than rural areas. The impervious urban fabric blocks water from infiltrating into the soil, generating more runoff than natural landscapes and

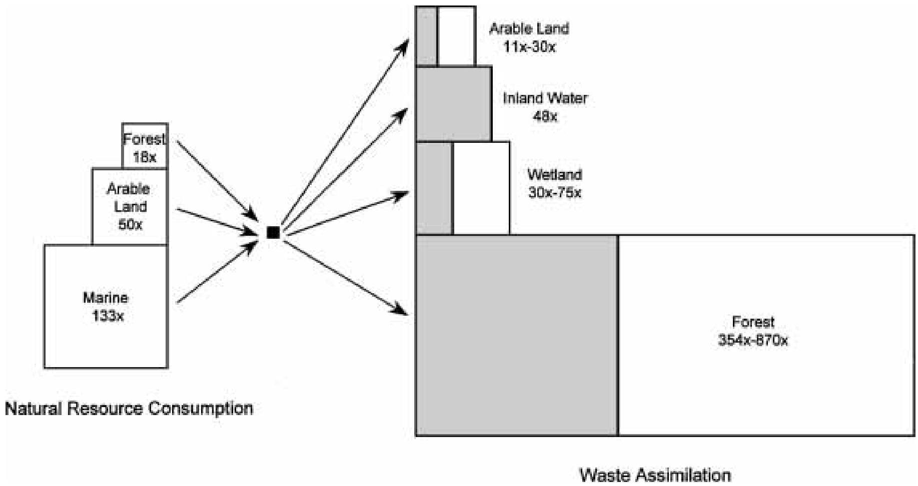

Figure 1.9. Ecological footprint of 29 large cities in Baltic countries of Europe. Left: Area of forest, arable land, and ocean utilized during resource consumption. Right: Area of arable land, inland water, wetland, and forest needed to assimilate urban wastes. Numbers show the required area per unit urban area. Data from Folke *et al.* (1997).

reducing the cooling effect of evapotranspiration. Biogeochemical cycles are altered as the natural cycling of carbon and nutrients between vegetation and soil is interrupted, fertilizers are applied, and soils are degraded. Forest, prairie, desert, chaparral, and other ecosystems, with their supporting cast of native flora and fauna, are replaced by monolithic tracts of suburban lawns.

The appropriation of ecosystem functions by humans is seen in the concept of 'ecological footprints', or the land needed to support human activities (Waggoner 1994; Wackernagel and Rees 1996). For example, one study estimated the ecological footprint of 29 cities in the Baltic region of Europe with a population of 250 000 or more people (Figure 1.9). The consumption of wood, paper, fibers, and food were related to the area of agricultural, forest, and marine ecosystems needed to provide these resources. The 22 million inhabitants of these 29 cities require an area of forest, agricultural, and marine ecosystems that is 201 times greater than the area of the cities themselves. Wastes are produced by these cities and land must be appropriated to absorb this waste. In particular, nitrogen, phosphorus, and CO_2 are produced by human activities. If there is to be no net release of these materials, forest, wetland, and agricultural lands must be appropriated to absorb the cities' emissions. It is estimated that between 443 to 1023 km^2 of land must be set aside for each square kilometer of city area to sequester carbon and retain nitrogen and phosphorus. The total appropriation of ecosystems for consumption and waste assimilation is thought to be 60 000 to 115 000 m^2 for every person.

1.2.2 Land use planning

Changing land use, like global climate change, is a grand unplanned experiment of unknown social and environmental consequences. Unlike global change, land use occurs locally in our communities. It gives substance to abstract global environmental issues at space and timescales to which people can see and respond. We see these changes happen in our communities over our lifetime, and in many cases over a period as little as several years. People, through the way communities are designed and built and landscapes are managed, have an enormous impact on the physical and biological environment – a bigger impact, in fact, than is expected from global climate change (McDonnell and Pickett 1990; Changnon 1992).

The conventional approach to landscape planning and design, particularly at the scale of residential homes, office buildings, and parks, emphasizes the formal and visual aesthetics of landscapes not their environmental value. This is particularly evident in the use of trees in the landscape (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 perceived as a constraint rather than as an opportunity. The growing interest in ecological goods and services provides an alternative view to the role of landscapes in the environment. The landscape is not only where we live, but also regulates climate, atmospheric chemistry, water resources, and supports plants, animals, and other living creatures that sustain the healthy functioning of ecosystems.

There is a strong ecological movement within the landscape planning and design professions (McHarg 1969; Spirn 1984, 1988; Hough 1984, 1995; Koh 1988; Olin 1988; Steiner *et al.* 1988; Bormann *et al.* 1993; Lyle 1994; P. Lewis 1996; Van der Ryn and Cowan 1996; Thompson and Steiner 1997). This movement, too, emphasizes Earth as a system, with the biosphere as a central 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. In addition, ecological design recognizes that different bioclimatic ecoregions have different environmental problems and require different environmental solutions (McHarg 1969; Berg 1994; Bailey 1996, 1998).

1.2.3 Ecosystem functions

People have long tried to intentionally modify weather for their own particular purposes through a variety of spiritual and physical means (Cotton and Pielke 1995). In the sixteenth century, it was believed that gunfire and loud noises inhibited rainfall, but by the nineteenth century this had changed to the belief that explosions stimulated rainfall (Lindgrén and Neumann 1981). Coating large areas in coastal arid climates with asphalt has been proposed as a means to induce more rainfall (Black and Tarmy 1963; Black 1963), as has introduction of irrigated crops in dry climates (Anthes 1984). With concern over global climate change, there are now examples of geoengineering climate and weather through purposeful manipulation of geophysical processes (Marland 1996, and accompanying articles). For example, iron fertilization has been proposed as a means of increasing carbon uptake by marine organisms, thereby reducing the buildup of CO_2 in the atmosphere. Such open ocean iron fertilizations have been conducted in the equatorial Pacific (Coale *et al.* 1996; Behrenfeld *et al.* 1996; Cooper *et al.* 1996) and in the Southern Ocean off Antarctica (Boyd *et al.* 2000; Abraham *et al.* 2000).

Technology can, of course, be used to fix problems, but these fixes often have unintended consequences that introduce new problems (Tenner 1996). In an increasingly technological world it is perhaps ironic that the role of terrestrial and aquatic ecosystems – nature's technology – in improving the quality of the environment is becoming especially important. There is a growing awareness of the goods and services provided by ecosystems (Table 1.2) and that vegetation provides a more natural solution to environmental problems. Greenbelts and trees are increasingly recognized for the recreational, spiritual, and aesthetic qualities of vegetation, for shade and relief from the warm urban climate, for stormwater management, and for habitat preservation (Smardon 1988; Moll and Ebenreck 1989; Givoni 1991; Platt *et al.* 1994; Rosenfeld *et al.* 1995, 1998; Fabos and Ahern 1996; Ferguson 1998). Forests and wetlands are being used to naturally filter excessive nutrients, pollutants, and sediments from sewage and urban runoff (DeLaney 1995; Dickey 1997). Certain plants absorb and tolerate toxic metals such as zinc, cadmium, and lead, giving rise to restoration of contaminated lands in a procedure known as phytoremediation (Comis 1996; Dobson *et al.* 1997a; Thompson 1998b; Raskin and Ensley 2000). The restorative quality of gardens and parks is being recognized. Outdoor gardens in medical settings provide therapy and emotional healing, leading to better health and faster recovery from illness (Marcus and Barnes 1995; C. Lewis 1996; Tyson 1998; Thompson 1998a). This represents a profound change in attitudes towards vegetation, particularly forests. In the colonial era of the United States,

Table 1.5. *Climates of London, Boston (Massachusetts), and Norfolk (Virginia)*

	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

Note: Fitch (1947, pp. 10–11) used the contrast between England and America to introduce the influence of climate on building design. Ludlum (1984) describes some of the hardships faced by early colonists. Prolonged drought may have contributed to the failure of the Jamestown settlement (Stahle *et al.* 1998).

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 (Stegner 1990; Williams 1989, pp. 9–21; Power 1996, pp. 131–148). Now, parks and forests are promoted as means to escape the stress and hostility of modern life, store carbon, and improve the environment.

1.2.4 Bioclimatic ecoregions

Imagine you live in a region where climate is relatively moderate, without extremely cold winters or hot summers. Snow is rare. In January, the coldest month of the year, temperature averages 4.4 °C (40 °F). In July, the warmest month, temperature averages 16.7 °C (62 °F). Days with high temperatures above 32.2 °C (90 °F) are rare. Now you move to a place where winters are much more severe. Heavy snow and long freezes are common in winter. The average January temperature is below freezing, and 98 days of the year have a low temperature below freezing. Summers are hot, with July temperature of 22.2 °C (72 °F). Almost twice as much precipitation falls each year compared with your native land. Such was the case facing the Pilgrims as they migrated from England to Plymouth, Massachusetts (Table 1.5). Settlers in Jamestown, Virginia, faced less severe winters, but oppressive heat and humidity. Concepts formed and lessons learned in England did not work in Massachusetts and Virginia. The colonists quickly adapted English building design techniques to accommodate the cold New England winter and provide relief from the hot, humid Virginia summer (Fitch 1947, 1966, 1972).

The history of the United States has been shaped by mass movements of people. This was particularly true during the colonial period and through the 1800s, but it is also true in more recent times as the Depression, the decline

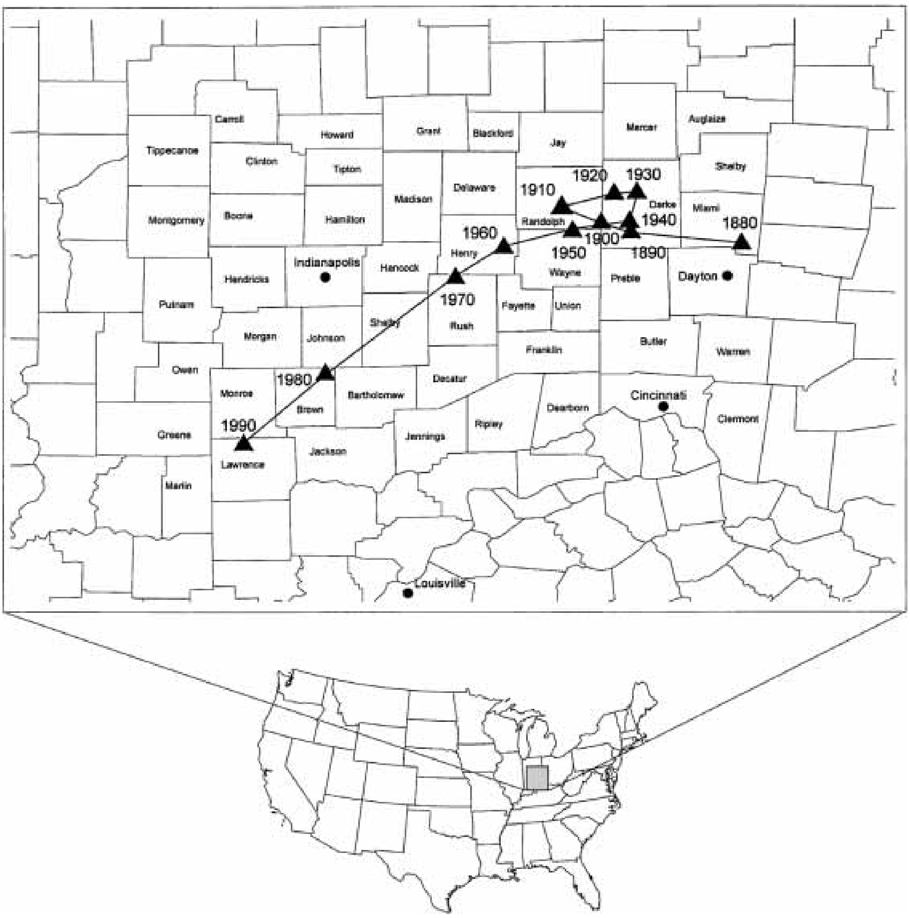

Figure 1.10. Median population center of the United States from 1880 to 1990. This is the geographic location where one-half of the population lives to the north and one-half to the south and where one-half of the population resides to the east and one-half resides to the west. Adapted from U.S. Census Bureau (1999, p. 27).

of agriculture in the South, and other social processes led to large-scale migrations (Figure 1.10). These movements continue today, especially in the interior western region between the Rocky Mountains and the Cascade and Sierra Nevada Mountains, where the population has grown faster than the rest of the United States during the 1990s (Riebsame and Robb 1997). As part of this migration, people bring with them their own aesthetics and intrinsic values. For example, the species of trees planted in urban landscapes often reflects a desire to recreate the childhood environment (Worthen 1975). As with the colonial settlers at Plymouth and Jamestown, our views of nature are shaped by our geographical history. But does this match the ecological functioning? In many respects, we have developed a modern lifestyle that is 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.

The close correspondence between climate and vegetation is one of the core tenets of bioclimatic ecoregions, which provide a more natural context to address environmental problems rather than political or administrative boundaries. The political units – cities, counties, states, countries – upon which socioeconomic decisions are made too often do not coincide with natural environmental units such as soil type, climate zone, ecosystem, and watershed. Bioregionalism, which integrates people, commerce, and land into a regional context, has long been a focus of land use planning. In the early-1900s there was a strong movement by planners in Europe and the United States to link land use with the regional environment (Hall 1988). These planners recognized that different regions, because of their individual climate, vegetation, and soil, develop different industries and cultures. Social, cultural, and economic settings are linked to the physical landscape by natural resources and human responses to these resources. These planners – Patrick Geddes from Scotland and Lewis Mumford from the United States were the most prominent – advocated regional land use planning based on ecological balance and renewal (Geddes 1915; Mumford 1940). They envisioned regions defined as geographic areas that possess a unity of climate, soil, vegetation, industry, and culture. These regions would be self-sufficient, with agriculture, industry, commerce, and housing in harmony with the environment. Today, there is renewed interest in bioregionalism, with regions defined based on ecosystems or watersheds rather than political boundaries, as a means to conserve natural resources, protect ecosystems, and develop more environmentally sound growth management strategies (McHarg 1969; Berg 1994; Bailey 1996, 1998).

1.3 Overview of the book

Several themes guide this book. First, the concept of ecological functions provides an overarching structure to the book. The climatic, hydrologic, geomorphologic, and ecological processes that determine landscape structure and function are reviewed. The recurring theme is the functioning of landscapes in terms of flows of energy, water, and chemical elements. These cycles affect climate, atmospheric chemistry, water resources, and plant abundance and geographic distribution, which in turn alter the ecological functioning of landscapes. A second theme is natural and human-mediated changes in land cover and ecosystem functions and how these changes affect climate, water resources, and biogeochemical cycles. Finally, ecological functions vary geographically in relation to climate, hydrology, soils, and vegetation. As a result, the impacts of land use and land cover change on climate, water resources, and biogeochemical cycles vary in different regions.

The book is divided into three parts. Part I introduces the principles of climatology. Chapters 2, 3, and 4 review the physical processes controlling global climate, climate variability at seasonal to interannual timescales, and climate change over periods of centuries to millennia. The traditional view is one in which climate determines the broad geographic distribution of vegetation. Terrestrial ecosystems are seen as passive components of the climate system, responding to climate change but not altering climate change. We now know this is not correct. Many of the feedbacks in the climate system are related to physical and biological processes that occur on land. Changes in snow cover, soil water, and the timing of leaf emergence are important determinants of seasonal to interannual climate variability. Natural and human-induced changes in land use and land cover alter climate.

Part II examines the hydrological, meteorological, and ecological processes by which landscapes affect and are affected by climate. The hydrologic cycle is reviewed first (Chapter 5), then soils and geologic processes (Chapter 6). The basic principles of micrometeorology are introduced to show how different environments, from an individual leaf to plants to landscapes, create their own microclimate. Chapter 7 introduces the basic scientific concepts of the surface energy budget – net radiation, sensible heat, latent heat, and ground heat storage. Chapter 8 shows how specific landscape features (e.g., forest clearings) create microclimates. Chapters 9 and 10 show how plants are organized into populations, communities, and ecosystems. Physiological processes are scaled from leaf level to whole plants (Chapter 9) and then to communities and ecosystems (Chapter 10) to show how landscapes are organized in space. Landscapes change over time. Chapter 11 reviews the timescales at which vegetation changes and the ecological processes controlling vegetation dynamics.

Part III combines this knowledge of climatology, hydrology, geology, and ecology to show how natural and human-mediated changes in land use and land cover affect climate. First, natural vegetation change is considered in coupled climate–ecosystem dynamics (Chapter 12). This dynamics occurs at a variety of spatial scales from leaf stomata to changing biogeography. The timescales of this dynamics are near instantaneous, seasonal, annual, decadal, centuries, and millennia as determined by a variety of ecological processes such as plant physiology, allocation, succession, and migration. The boreal forest–tundra ecotone and the Sahel region of North Africa are important examples of climate–ecosystem dynamics at the biogeographical spatial and temporal scale. Human land uses also alter the flows of energy, water, and nutrients. Tropical deforestation, temperate deforestation, desertification of drylands, cultivation of grasslands, and reforestation following farm abandonment are case studies of how agricultural uses of land alter climate (Chapter 13). Urbanization also alters climate, hydrology, and ecological functions (Chapter 14).