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FIFTH EDITION

THE GLOBAL CASINO

AN INTRODUCTION TO ENVIRONMENTAL ISSUES

NICK MIDDLETON

ROUTLEDGE

The Global Casino

The Global Casino is an introduction to environmental issues which deals both with the workings of the physical environment and the political, economic and social frameworks in which the issues occur. Using examples from all over the world, the book highlights the underlying causes behind environmental problems, the human actions which have made them issues, and the hopes for solutions. It is a book about the human impact on the environment and the ways in which the natural environment impacts human society.

The fifth edition has been fully revised and updated throughout, with new case studies, figures, and online resources such as downloadable figures and tables from the text and multiple choice questions for students. New topics covered in extended boxed case studies include payment for environmental services, ocean acidification, biofuels in Brazil, waste reduction through industrial symbiosis, and the long-term impact of natural disasters on vulnerable groups. Other approaches and concepts covered for the first time in this new edition include traditional ecological knowledge, environmental justice, the 'resource curse', and urban biodiversity. Eighteen chapters on key issues follow three initial chapters which outline the background contexts of the physical and human environments and the concept of sustainable development. Each chapter provides historical context for key issues, outlines why they have arisen, and highlights areas of controversy and uncertainty to appraise how issues can be resolved both technically and in political and economic frameworks. Each chapter also contains an updated critical guide to further reading and websites, as well as discussion points and essay questions. The text can be read in its entirety or individual chapters adopted as standalone reading.

This book is an essential resource for students of the environment, geography, earth sciences and development studies. It provides comprehensive and inspirational coverage of all the major global environmental issues of the day in a style that is clear and critical.

Nick Middleton is a Fellow and Lecturer in Physical Geography at St Anne's College, Oxford University. He also works as an environmental consultant and freelance author having written more than 250 articles in journals, magazines and newspapers, and 19 books.

Companion Website

A companion website accompanies this book at www.routledge.com/cw/middleton which contains additional resources for both students and lecturers, including:

- A glossary of terms used throughout the text
- A test bank of multiple choice questions for each chapter for students to test their understanding
- Downloadable figures and tables from the book

The Global Casino

An introduction to environmental issues

Fifth edition

Nick Middleton

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Contents

List of figures

List of tables

Preface

This book is about environmental issues: concerns that have arisen as a result of the human impact on the environment and the ways in which the natural environment affects human society. The book deals with both the workings of the physical environment and the political, economic and social frameworks in which the issues occur. Using examples from all over the world, I aim to highlight the underlying causes behind environmental problems, the human actions which have made them issues, and the hopes for solutions.

Eighteen chapters on key issues follow the three initial chapters that outline the background contexts of the physical and human environments and introduce the concept of sustainable development. The conclusion complements the book's thematic approach by looking at the issues and efforts towards sustainable development in a regional context. The organization of the book allows it to be read in its entirety or dipped into for any particular topic, since each chapter stands on its own. Each chapter sets the issue in a historical context, outlines why the issue has arisen, highlights areas of controversy and uncertainty, and appraises how problems are being, and can be, resolved, both technically and in political and economic frameworks. Information in every chapter has been expanded and updated to keep pace with the rapid increase in research and understanding of the issues. The chapters are followed by expanded critical guides to further reading on the subjects – including some sources freely available online – guides to relevant sites on the Web and sets of questions that can be used to spark discussion or as essay questions.

I decided on the title *The Global Casino* because there are many parallels between the issues discussed in this book and the workings of a gambling joint. Money and economics underlie many of the 18 issues covered here, which can be thought of as different games in the global casino, separate yet interrelated. Just like a casino, environmental issues involve winners and losers. The casino's chance element and the players' imperfect knowledge of the outcomes of their actions are relevant in that our understanding of how the Earth works is far from perfect. The casino metaphor also works on a socio-economic level, since some individuals and groups of individuals can afford actively to take part in the games while others are less able. Some groups are more responsible for certain issues than others, yet those who have little influence are still affected by the consequences. Different individuals and groups of people also choose to play the different games in different ways, reflecting their cultural, economic and political backgrounds and the information available to them.

The stakes are high: some observers believe that the global scale on which many of the issues occur represents humankind gambling with the very future of the planet itself. Everyone who reads this book has some part to play in the 'Global Casino'. I hope that the information presented here will allow those players to participate with a reasonable knowledge of how the games work, the consequences of losing, and the benefits that can be derived from winning.

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CHAPTER ONE

The physical environment

1

TOPICS COVERED

Classifying the natural world, Natural cycles, Timescales, Spatial scales, Time and space scales, The state of our knowledge

The term environment is used in many ways. This book is about issues that arise from the physical environment, which is made up of the living (biotic) and non-living (abiotic) things and conditions that characterize the world around us. While this is the central theme, the main reason for the topicality of the issues covered here is the way in which people interact with the physical environment. Hence, it is pertinent also to refer to the social, economic and political environments to describe those human conditions characteristic of certain places at particular times, and to explain why conflict has arisen between human activity and the natural world. This chapter looks at some of the basic features of the physical environment, while Chapter 2 is concerned with the human factors that affect the ways in which the human race interacts with the physical world.

CLASSIFYING THE NATURAL WORLD

Geography, like other academic disciplines, classifies things in its attempt to understand how they work. The physical environment can be classified in numerous ways, but one of the most commonly used classifications is that which breaks it down into four interrelated spheres: the lithosphere, the atmosphere, the biosphere and the hydrosphere. These four basic elements of the natural world can be further subdivided. The lithosphere, for example, is made up of rocks that are typically classified according to their modes of formation (igneous, metamorphic and sedimentary); these rock types are further subdivided according to the processes that formed them and other factors such as their chemical composition. Similarly, the workings of the atmosphere are manifested at the Earth's surface by a typical distribution of climates; the biosphere is made up of many types of flora and fauna, and the hydrosphere can be subdivided according to its chemical constituents (fresh water and saline, for example), or the condition or phase of the water: solid ice, liquid water or gaseous vapour.

These aspects of the natural world overlap and interact in many different ways. The nature of the soil in a particular place, for example, reflects the underlying rock type, the climatic conditions of the area, the plant and animal matter typical of the region, and the quantity and quality of water available. Suites of characteristics are combined in particular areas called ecosystems. These ecosystems can also be classified in many ways. One approach uses the amount of organic matter or biomass produced per year – the net production – which is simply the solar energy fixed in the biomass minus the energy used in producing it by respiration (see below). The annual net primary production of carbon, a basic component of all living organisms, by major world ecosystem types is shown in Table 1.1. Clear differences are immediately discernible between highly productive ecosystems such as forests, marshes, estuaries and reefs, and less productive places such as deserts, tundras and the open ocean. All of the data are averaged and variability around the mean is perhaps greatest for agricultural ecosystems which, where intensively managed, can reach productivities as high as any natural ecosystem. One of the main reasons for agriculture's low average is the fact that fields are typically bare of vegetation for significant periods between harvest and sowing.

Table 1.1 Annual net primary production of carbon by major world ecosystem types

Ecosystem type	Mean net primary productivity (g C/m²/year)	Total net primary production (billion tonnes/C/year)
Tropical rain forest	900	15.3
Tropical seasonal forest	675	5.1
Temperate evergreen forest	585	2.9
Temperate deciduous forest	540	3.8
Boreal forest	360	4.3
Woodland and shrubland	270	2.2
Savanna	315	4.7
Temperate grassland	225	2.0
Tundra and alpine	65	0.5
Desert scrub	32	0.6
Rock, ice and sand	1.5	0.04
Agricultural land	290	4.1
Swamp and marsh	1125	2.2
Lake and stream	225	0.6
Total land	324*	48.3
Open ocean	57	18.9
Upwelling zones	225	0.1
Continental shelf	162	4.3
Algal bed and reef	900	0.5
Estuaries	810	1.1
Total oceans	69*	24.9
Total for biosphere	144*	73.2

Note: *The means for land, oceans and biosphere are weighted according to the areas covered by specific ecosystem types.
Source: after Whittaker and Likens (1973).

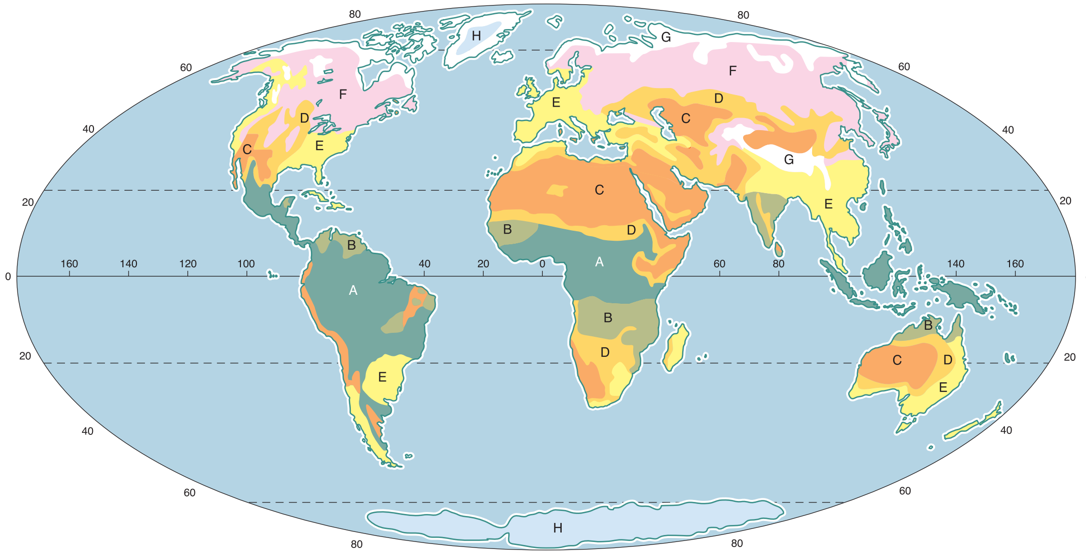
One of the main factors determining productivity is the availability of nutrients, key substances for life on Earth: a lack of nutrients is often put forward to explain the low productivity in the open oceans, for example. Climate is another important factor. Warm, wet climates promote higher productivity than cold, dry ones. Differences in productivity may also go some way towards explaining the general trend of increasing diversity of plant and animal species from the poles to the equatorial regions. Despite many regional exceptions such as mountain tops and deserts, this latitudinal gradient of diversity is a striking characteristic of nature that fossil evidence suggests has been present in all geological epochs. The relationship with productivity is not straightforward, however, and many other hypotheses have been advanced, such as the suggestion that minor disturbances promote diversity by preventing a few species from dominating and excluding others (Connell, 1978).

The relationships between climate and the biosphere are also reflected on the global scale in maps of vegetation and climate, the one reflecting the other. Figure 1.1 shows the world's morphoclimatic regions, which are a combination of both factors. Despite wide internal variations, immense continental areas clearly support distinctive forms of vegetation that are adapted to a broad climatic type. Such great living systems, which also support distinctive animals and to a lesser extent distinctive soils, are called biomes, a concept seldom applied to aquatic zones. Different ecologists produce various lists of biomes and the following eight-fold classification may be considered conservative (Colinvaux, 1993):

1. tundra
2. coniferous forest (also known as boreal forest or taiga)
3. temperate forest
4. tropical rain forest
5. tropical savanna
6. temperate grassland
7. desert
8. maquis (also known as chaparral).

A striking aspect of the tundra biome is the absence of trees. Vegetation consists largely of grasses and other herbs, mosses, lichens and some small woody plants which are adapted to a short summer growing season. The tundra is also notable for receiving relatively little precipitation and being generally poor in nutrients. The cold climate ensures that the rate of biological processes is generally slow and the shallow soils are deeply frozen (permafrost) for all or much of the year, a condition which underlies about 20 per cent of the Earth's land surface. Many animals hibernate or migrate in the colder season, while others such as lemmings live beneath the snow.

The main tundra region is located in the circumpolar lands north of the Arctic Circle, which are bordered to the south by the evergreen, needle-leaved boreal or taiga forests (Figure 1.2). Here, winters are very cold, as in the tundra, but summers are longer. Most of the trees are conifers such as pine, fir and spruce. They are tall and have a narrow, pointy shape which means that the snow tends to slide off their branches, while their needles also shed snow more easily than broad leaves. These adaptations reduce the likelihood of heavy snow breaking branches. Boreal forests are subject to periodic fires, and a burn–regeneration cycle is an important characteristic to which populations of deer, bears and insects, as well as the vegetation, are adapted. Much of the boreal forest is underlain by acid soils.



- A — Tropical Humid – Rainforest. Rainy climate with no winter. Either constantly moist or with monsoon rains.
- B — Tropical Humid – Savanna. Rainy climate with either a dry summer or winter season.
- C — Dry – Desert or Arid climate.
- D — Dry – Steppe or Semi-Arid climate.
- E — Warmer Humid – Rainy climate with mild winters. (Includes Mediterranean, Humid Subtropical and Marine West Coast climates).
- F — Cooler Humid – Rainy climate with severe winters. (Includes Continental Warm and Cool Summer, and Subarctic climates).
- G — Polar – Tundra climate.
- H — Polar – Ice Cap. Perpetual frost.

Figure 1.1 Present-day morphoclimatic regions of the world's land surface (Williams *et al.*, 1993).

Figure 1.2 Coniferous forest in Finland, the eastern end of a broad region of boreal or taiga forest that stretches to the Russian Far East.

The temperate forests, by contrast, are typically deciduous, shedding their leaves each year. They are, however, like the boreal forests in that they are found almost exclusively in the northern hemisphere. This biome is characteristic of northern Europe, eastern China and eastern and Midwest USA, with small stands in the southern hemisphere in South America and New Zealand. Tall broadleaf trees dominate, the climate is seasonal but water is always abundant during the growing season, and this biome is less homogeneous than tundra or boreal forest. Amphibians, such as salamanders and frogs, are present, while they are almost totally absent from the higher-latitude biomes.

The tropical rain forest climate has copious rainfall and warm temperatures in all months of the year. The trees are always green, typically broad-leaved, and most are pollinated by animals (trees in temperate and boreal forests, by contrast, are largely pollinated by wind). Many kinds of vines (llianas) and epiphytes, such as ferns and orchids, are characteristic. Most of the nutrients are stored in the biomass and the soils contain little organic matter. These forests typically display a multi-layered canopy (Figure 1.3), while, at ground level, vegetation is often sparse because of low levels of light. Above all, tropical rain forests are characterized by a large number of species of both plants and animals.

Savanna belts flank the tropical rain forests to the north and south in the African and South American tropics, a biome known as cerrado in Brazil. The trees of tropical savannas are stunted and widely spaced, which allows grass to grow between them. Herds of grazing mammals typify the savanna landscape, along with large carnivores such as lions and other big cats, jackals and hyenas. These mammals, in turn, provide a food source for large scavengers such as vultures. The climate is warm all year, but has a dry season several months long when fires are a common feature. These fires maintain the openness of the savanna ecosystem and are important in mineral cycling.

Figure 1.3 An area of primary tropical rain forest, an evergreen biome with great biodiversity, in Panama, Central America.

The greatest expanses of the temperate grassland biome are located in Eurasia (where they are commonly known as steppe, Figure 1.4), North America (prairie) and South America (pampa), with smaller expanses in South Africa (veldt). There are certain similarities with savannas in terms of fauna and the occurrence of fire, but unlike savannas, trees are absent in temperate grasslands. The vegetation is dominated by herbaceous (i.e. not woody) plants, of which the most abundant are grasses. The climate in this biome is temperate, seasonal and dry. Typical soils tend to be deep and rich in organic matter.

In many parts of the world, where climates become drier, temperate grasslands fade into the desert biome. Hyper-arid desert supports very little plant life and is characterized by bare rock or sand dunes, but some species of flora and fauna are adapted to the high and variable temperatures – the diurnal temperature range is typically high in deserts – and the general lack of moisture. Some water is usually available via precipitation in one of its forms: most commonly

Figure 1.4 Temperate grassland in central Mongolia is still predominantly used for grazing. In many other parts of the world such grasslands have been ploughed up for cultivation.

Figure 1.5 This strange-looking plant, the welwitschia, is found only in the Namib Desert. Its adaptations to the dry conditions include long roots to take up any moisture in the gravelly soil and the ability to take in moisture from fog through its leaves. The welwitschia's exact position in the plant kingdom is controversial, but it is grouped with the pine trees.

rainfall or dew, but fog is important in some coastal deserts (Figure 1.5). Sporadic, sometimes intense, rain promotes rapid growth of annual plants and animals such as locusts, which otherwise lie dormant for several years as seeds or eggs.

A very distinctive form of vegetation is commonly associated with Mediterranean climates in which summers are hot and dry and winters are cool and moist. It is found around much of the Mediterranean Basin (where it is known as maquis), in California (chaparral), southern Australia (mallee), Chile (mattöral) and South Africa (fynbos). Low evergreen trees (forming woodland) and shrubs (forming scrub) have thick bark and small, hard leaves that make them tolerant to the stresses of climatic extremes and soils that are often low in nutrients. During the arid summer period this biome is frequently exposed to fire, which is important to its development and regeneration.

All these natural biomes have been affected to a greater or lesser extent by human action. Much of the maquis, for example, may represent a landscape where forests have been degraded by people, through cutting, grazing and the use of fire. The human use of fire may also be an important factor in maintaining, and possibly forming, savannas and temperate grasslands. The temperate forests have been severely altered over long histories with high population densities as people have cleared trees for farming and urban development (Figure 1.6). Conversely, biomes considered

Figure 1.6 The US city of New York, part of one of the world's most extensive areas of urban development. Only a few of the original temperate forest trees survive in parks and gardens. Urban areas are now so widespread that they are often treated as a type of physical environment in their own right (see Chapter 10).

by people to be harsh, such as the tundra and deserts, show less human impact. The anthropogenic influence is but one factor that promotes change in terrestrial as well as oceanic and freshwater ecosystems, because the interactions between the four global spheres have never been static. Better understanding of the dynamism of the natural world can be gained through a complementary way of studying the natural environment. Study of the processes that occur in natural cycles also takes us beyond description, to enable explanation.

NATURAL CYCLES

A good means of understanding the way the natural world works is through the recognition of cycles of matter in which molecules are formed and reformed by chemical and biological reactions and are manifested as physical changes in the material concerned. The major stores and flows of water in the global hydrological cycle are shown in Figure 1.7. Most of the Earth's water (about 97 per cent) is stored in liquid form in the oceans. Of the 3 per cent fresh water, most is locked as ice in the ice caps and glaciers, and as a liquid in rocks as groundwater. Only a tiny fraction is present at any time in lakes and rivers. Water is continually exchanged between the Earth's surface and the atmosphere – where it can be present in gaseous, liquid or solid form – through evaporation, transpiration from plants and animals, and precipitation. The largest flows are directly between the ocean and the atmosphere. Smaller amounts are exchanged between the land and the atmosphere, with the difference accounted for by flows in rivers and groundwater to the oceans. Fresh water on the land is most directly useful to human society (see Chapter 8), since water is an essential prerequisite of life, but the oceans and ice caps play a key role in the workings of climate.

Similar cycles, commonly referred to as biogeochemical cycles, can be identified for other forms of matter. Nutrients such as nitrogen, phosphorus and sulphur are similarly distributed among the four major environmental spheres and are continually cycled between them. Carbon is another key element for life on Earth, and the stores and flows of the carbon cycle are shown in Figure 1.8. The major stores of carbon are the oceans and rocks, particularly carbonate sedimentary rocks such as limestones, and the hydrocarbons (coal, oil and natural gas), plus 'clathrates', or gas hydrates, found mainly in high latitudes and in the oceans along continental margins. Much smaller proportions are present in the atmosphere and biosphere. The length of time carbon spends in particular stores also varies widely. Under natural circumstances, fossil carbon locked in rocks remains in these stores for millions of years. Carbon reaches these stores by the processes of sedimentation and evaporation, and is released from rocks by weathering, vulcanism and sea-floor spreading. In recent times, however, the rate of flow of carbon from some of the lithospheric stores – the hydrocarbons or fossil fuels – has been greatly increased by human action: the burning of fossil fuels, which liberates carbon by oxidation. Hence, a significant new flow of carbon between the lithosphere and the atmosphere has been introduced by human society and the natural atmospheric carbon store is being increased as a consequence (see Chapter 11).

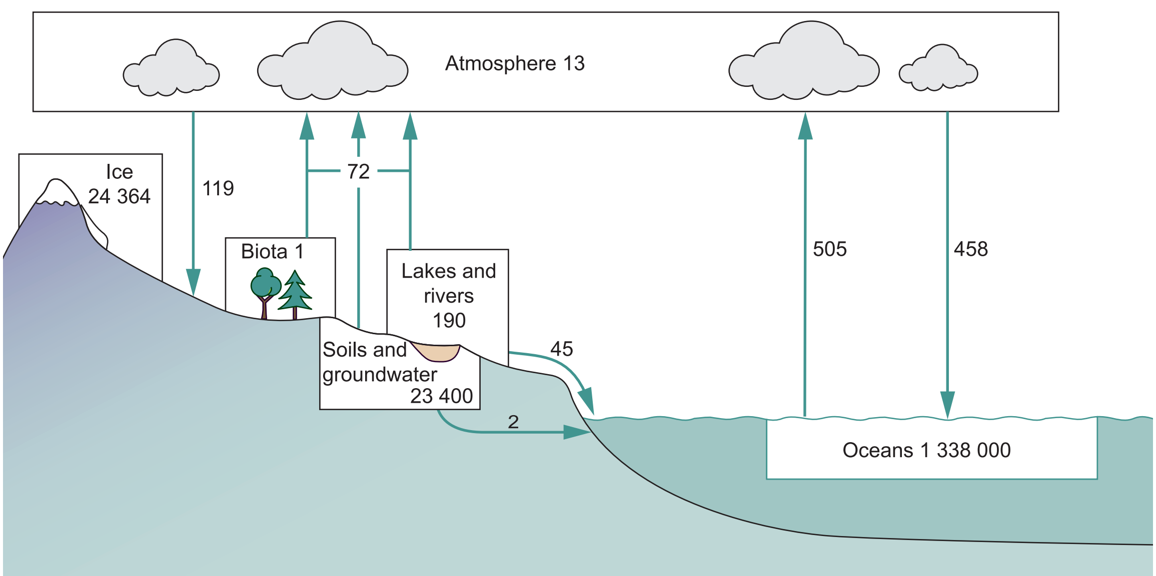


Figure 1.7 Global hydrological cycle showing major stores and flows (data from Shiklomanov, 1993). The values in stores are in thousand km³, values of flows in thousand km³ per year.

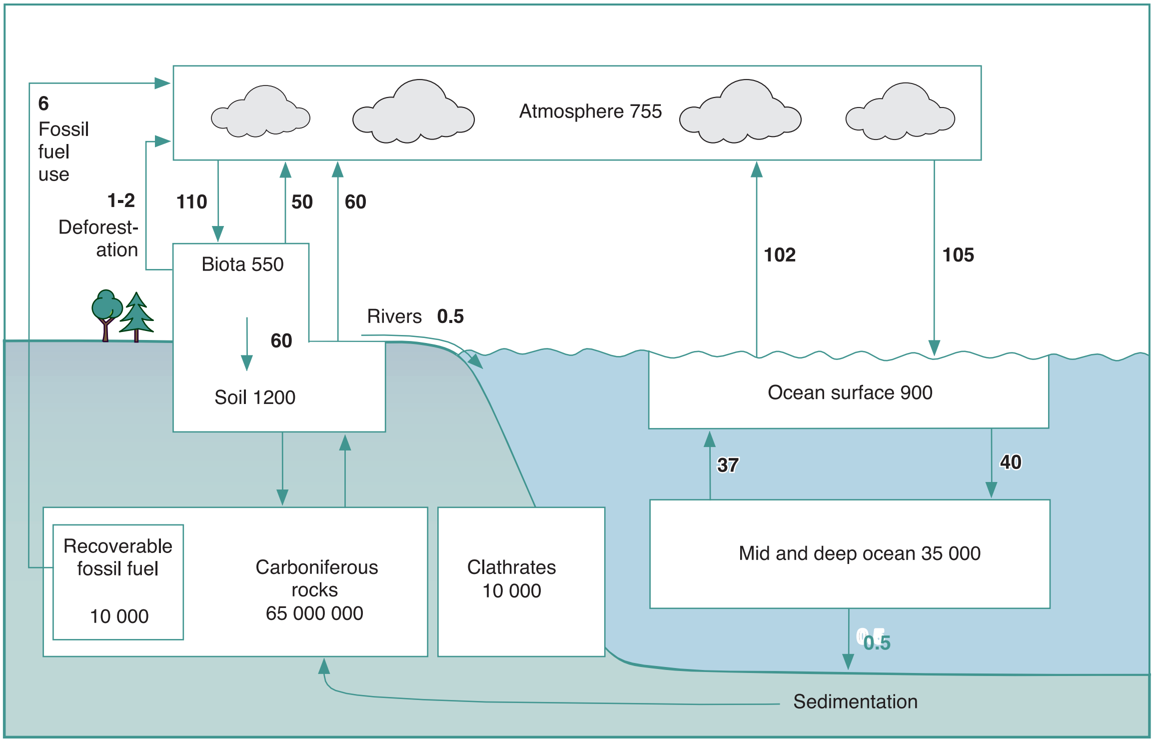


Figure 1.8 Global carbon cycle showing major stores and flows (after Schlesinger, 1991 and Grace, 2004). The values in stores are in units of Pg C, values of flows in Pg C per year. 1 Pg C = 10^{15}g C = 1 billion tonnes of carbon as CO_2.

Carbon also reaches the atmosphere through the respiration of plants and animals, which in green plants, blue-green algae and phytoplankton is part of the two-way process of photosynthesis. Photosynthesis is the chemical reaction by which these organisms convert carbon from the atmosphere, with water, to produce complex sugar compounds (which are either stored as organic matter or used by the organism) and oxygen. The reaction is written as follows:

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

This equation shows that six molecules of carbon dioxide and six molecules of water yield one molecule of organic matter and six molecules of oxygen. The reaction requires an input of energy from the sun, some of which is stored in chemical form in the organic matter formed.

The process of respiration is written as the opposite of the equation for photosynthesis. It is the process by which the chemical energy in organic matter is liberated by combining it with oxygen to produce carbon dioxide and water. All living things respire to produce energy for growth and the other processes of life. The chemical reaction for respiration is, in fact, exactly the same as that for combustion. Humans, for example, derive energy for their life needs from organic matter by eating (just as other animals do) and also by burning plant matter in a number of forms, such as fuelwood and fossil fuels.

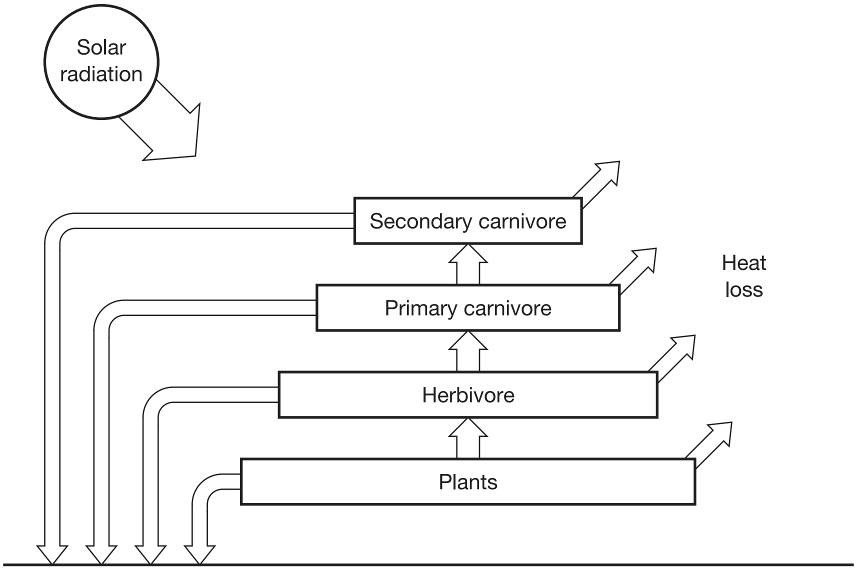


Figure 1.9 Energy flow through a food chain.

The flow of converted solar energy through living organisms can be traced up a hierarchy of life-forms known as a food chain. Figure 1.9 shows a simple food chain in which solar energy is converted into chemical energy in plants (so-called producers), which are eaten by herbivores (so-called first-order consumers), which, in turn, are eaten by other consumers (primary carnivores), which are themselves eaten by secondary carnivores. An example of such a food chain on land is:

grass → cricket → frog → heron

Each stage in the chain is known as a trophic level. In practice, there are usually many, often interlinked, food chains that together form a food web, but the principles are the same. At each trophic level some energy is lost by respiration, through excretory products and when dead organisms decay, so that available energy declines along the food chain away from the plant. In general terms, animals also tend to be bigger at each sequential trophic level, enabling them to eat their prey safely. This model helps us to explain the basic structures of natural communities: with each trophic level, less energy is available to successively larger individuals and thus the number of individuals decreases. Hence, while plants are very numerous because they receive their energy directly from the sun, they can support only successively fewer larger animals. With the exception of humans, predators at the top of food chains are therefore always rare.

Food chains, the carbon cycle and the hydrological cycle are all examples of 'systems' in which the individual components are all related to each other. Most of the energy that drives these systems comes from the sun, although energy from the Earth also contributes. All the cycles of energy and matter referred to in this section are affected by human action, deliberately manipulating natural cycles to human advantage. One of the human impacts on the carbon cycle has been mentioned, but humans also affect other cycles. The cycle of minerals in the rock cycle is affected by the construction industry, for example. Human activity affects the hydrological cycle by diverting natural flows: the damming of rivers (see Chapter 9) or extracting groundwater for human use (see Chapter 10). The nitrogen cycle is affected by concentrating nitrogen in particular places such as by spreading fertilizers on fields. Food chains are widely affected: human populations manipulate plants and animals to produce food (see Chapter 13).

However, since all parts of these cycles are interrelated, human intervention in one part of a cycle also affects other parts of the same and other cycles. These knock-on effects are the source of many environmental changes that are undesirable from human society's viewpoint. Our manipulation of the nitrogen cycle by using fertilizers also increases the concentration of nitrogen in rivers and lakes when excess fertilizer is washed away from farmers' fields. This can have deleterious effects on aquatic ecosystems (see Chapters 7 and 8). Excess nitrogen can also enter the atmosphere to become a precursor of acid rain (see Chapter 12). One of the effects of acid rain is to accelerate the rate of weathering of some building stones. A better appreciation of these types of changes can be gained by looking at the various scales of time and space through which they occur.

TIMESCALES

Changes in the natural environment occur on a wide range of timescales. Geologists believe that the Earth is about 4600 million years old, while fossil evidence suggests that modern humans (*Homo sapiens*) appeared between 100,000 and 200,000 years before present (BP), developing from the hominids whose earliest remains, found in Africa, date to around 3.75 million BP (Table 1.2). The very long timescales over which many changes in the natural world take place may seem at first to have little relevance for today's human society other than to have created the world we know. It is difficult for us to appreciate the age of the Earth and the thought that the present distribution of the continents dates from the break-up of the supercontinent Pangaea, which began during the Cretaceous period. Indeed, relative to the forces and changes due to tectonic movements, the human impact on the planet is very minor and short-lived. However, such Earth processes do have relevance on the timescale of a human lifetime. Tectonic movements cause volcanic eruptions that can affect human society as natural disasters at the time of the event. Some volcanic eruptions also affect day-to-day human activities on slightly longer timescales, by injecting dust into the atmosphere, which affects climate, for example, and by providing raw materials from which soils are formed. This example also illustrates the fact that the same event may be interpreted as bad from a human viewpoint on one timescale (a volcanic disaster) and good on another timescale (fertile volcanic soils).

It is important to realize that the timescale we adopt for the study of natural systems can affect our understanding as well as our perception of them. Many such systems are thought to be in 'dynamic equilibrium', in which the input and output of matter and energy are balanced. This is a state or regime organized around a set of processes that maintain equilibrium by being mutually reinforcing. However, recognition of dynamic equilibrium in natural systems depends upon the timescale over which the system is studied. To take the Earth as a whole, for example, the idea of dynamic equilibrium has been proposed to explain why the temperature of the Earth has remained relatively constant for the past 4 billion years, despite the fact that the sun's heat has increased by about 25 per cent over that period. The Gaia hypothesis suggests that life on the planet has played

Table 1.2 Geological timescale classifying the history of the Earth

Era	Period		Start (million years BP)	Important events
		Holocene	0.01	Early civilizations
	Quaternary	Pleistocene	2.6	First humans
		Pliocene	5	First hominids
		Miocene	23	
		Oligocene	34	
		Eocene	56	
Cenozoic	Tertiary	Palaeocene	66	Extinction of dinosaurs
	Cretaceous		146	Main fragmentation of Pangaea
	Jurassic		200	
Mesozoic	Triassic		251	First birds
	Permian		299	Formation of Pangaea
		Pennsylvanian	318	
	Carboniferous	Mississippian	359	
	Devonian		416	
	Silurian		444	First land plants and animals
	Ordovician		488	First vertebrates
Palaeozoic	Cambrian		542	
Precambrian			4600	Formation of Earth

Source: after Goudie (1993a); Colinvaux (1993); Williams *et al*. (1993).

a key role in regulating the Earth's conditions to keep it amenable to life (Lovelock, 1989). The theory is not without its critics, but even if we accept it, the dynamic equilibrium holds only for the few billion years of the Earth's existence. Astronomers predict that eventually the sun will destroy the Earth, so that over a longer timescale, dynamic equilibrium does not apply. This example applies over a very long timescale, and from our perspective the destruction of the Earth by the sun is not imminent, but the principle is relevant to all other natural systems. Adoption of different timescales of analysis dictates which aspects of a system we see and understand because the importance of different factors changes with different timescales. Indeed, even within the lifespan of the Earth, dramatic changes are known to have occurred, such as the progression of glacial and interglacial periods. The longer the timeframe, the coarser the resolution and vice versa. In a simple example, a human being who contracts a cold might feel miserable for a few days, but in terms of that person's lifetime career the cold is a very minor influence. This principle is depicted for measurements of mean annual air temperature at Oxford in England in Figure 1.10.

One of the key components of natural cycles and dynamic systems is the operation of feedbacks. Feedbacks may be negative, which tend to dampen down the original effect and thereby maintain

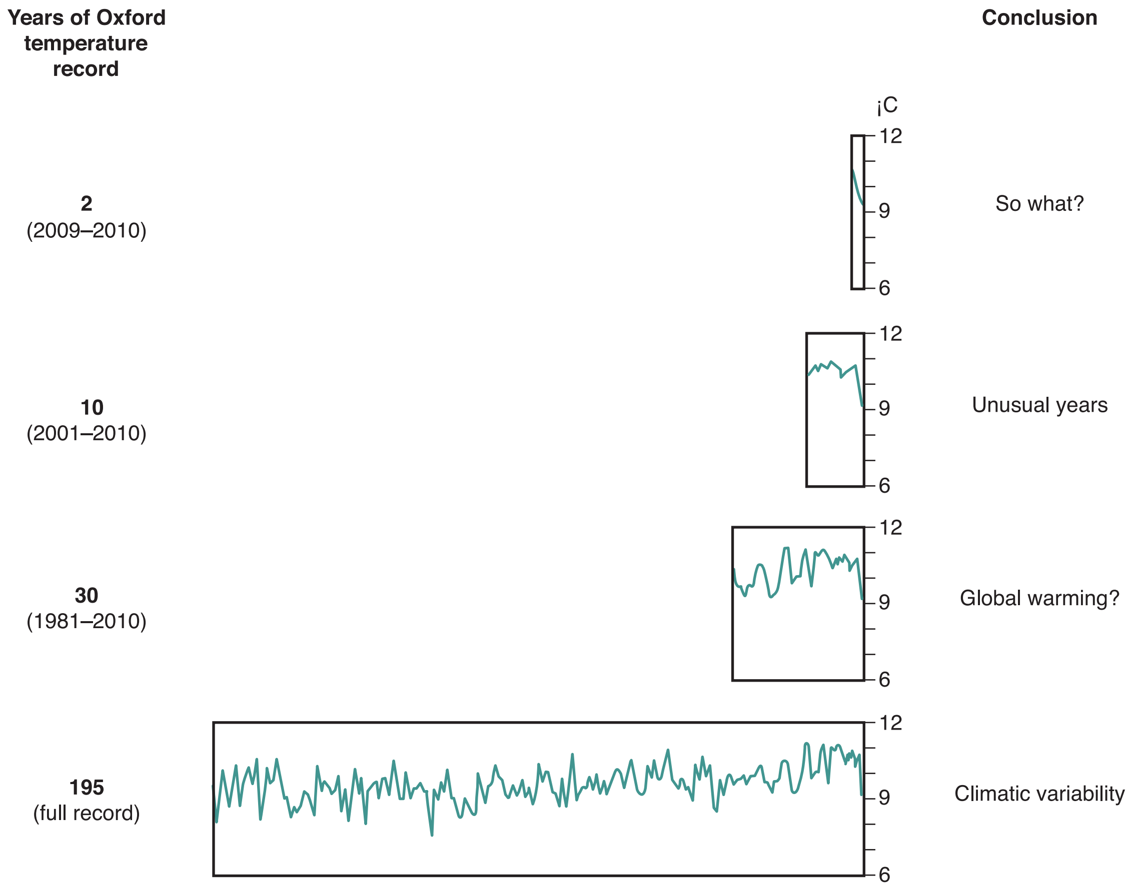


Figure 1.10 Demonstration of how the length of data record (here annual mean air temperature at Oxford, England) can influence conclusions about environmental variability (using data 1815–2010 at www.geog.ox.ac.uk/research/climate/rms/meanair.html).

dynamic equilibrium, or they may be positive and hence tend to enhance the original effect. An example of negative feedback can be seen in the operation of the global climate system: more solar energy is received at the tropics than at the poles, but the movement of the atmosphere and oceans continually redistributes heat over the Earth's surface to redress the imbalance. Positive feedbacks can result in a change from one dynamic equilibrium to another: a change often termed a regime shift. If a forest is cleared by human action, for example, the soil may be eroded to the extent that recolonization by trees is impossible.

This last example illustrates another important aspect of natural cycles: the existence of thresholds. A change in a system may not occur until a threshold is reached: snow will remain on the ground, for example, until the air temperature rises above a threshold at which the snow melts. Crossing a threshold may be a function of the frequency or intensity of the force for change: a palm tree may be able to withstand, or be 'resilient' to, winds up to a certain speed, but will be blown out of the soil by a hurricane-force wind that is above the tree's threshold of resilience. Conversely, thresholds may be reached by the cumulative impacts of numerous small-scale events:

regular rainfall inputs of moisture to a slope may build up to a point at which the slope fails, or in the erosion example, the gradual loss of soil reaches the point at which there is not enough soil left for trees to take root and grow.

These two illustrations of how thresholds can be crossed also embody two important ideas on the way change occurs in the physical environment. The hurricane represents a high-magnitude, low-frequency event, for which some use the term 'catastrophe'. An opposing view ascribes change in the environment to small-scale, commonly occurring processes. Of course, most environments are affected by both catastrophic and gradual changes.

To complicate things further, there may be a lag in time between the onset of the force for change and the change itself: the response time of the system. An animal seldom dies immediately upon contracting a fatal disease, for example; its body ceases to function only after a period of time. Likewise in the erosion example, trees are unable to colonize only after a certain amount of soil has been lost. Consideration of feedbacks, thresholds and lags leads to some other characteristics of natural systems – their sensitivity to forces for change, which dictates their ability to maintain or return to an original condition following a disturbance: their 'stability'. A natural system's ability to maintain its original condition with the same functions and processes is dictated by its 'resistance' to disturbance, while the ability to return to an original condition is commonly referred to as 'resilience' (see Box 8.1).

The variability in natural disturbances affecting some environments means that assuming them to be in a more or less stable dynamic equilibrium is not reasonable, however. These are commonly referred to as 'non-equilibrium' environments, of which drylands are a good example. Drylands are highly dynamic and are currently thought of as being in a constant state of change, driven by disturbances such as the variability of fire and insect attack and, perhaps most importantly, the variability of moisture from rainfall. Amounts vary widely, from one intense rainy day in a dry month through seasonal variations to longer periods such as droughts. Many aspects of the physical environment respond accordingly. Perennial plants and small animals respond particularly quickly, so that a different level of their populations can be expected at each particular time. Larger animals respond to such a dynamic environment by moving, sometimes over very large distances, to take advantage of the spatial changes in water and food availability. The dynamism of drylands makes it difficult to assess degradation in these areas (see Chapter 5).

All these considerations on changes in natural ecosystems through time can be assembled into some typical patterns that are illustrated hypothetically in Figure 1.11. The parameters represented on the y axis of the graphs could be a measurement of any physical thing, such as soil organic matter content, species diversity, carbon dioxide concentration in the atmosphere, or the volume of water flowing along a river channel. Figure 1.11a might represent a mature forest with small variations in biomass with the seasons, and as individual trees grow and die. This constant system could equally be described as stable or as one that is in dynamic equilibrium. It contrasts with the cyclical pattern in Figure 1.11b, which could represent natural cycles of heather burning and regeneration. Figure 1.11c could illustrate natural succession of vegetation in an area with a long-term directional trend. The pattern induced by episodes such as drought, which allow recovery in systems with sufficient resilience (Figure 1.11d), contrasts with a catastrophic disturbance that exceeds resilience, so that the system crosses a threshold resulting in long-term change from one state to another – a regime shift (Figure 1.11e) – such as when soil erosion proceeds to a level where certain types of vegetation can no longer survive in the area.

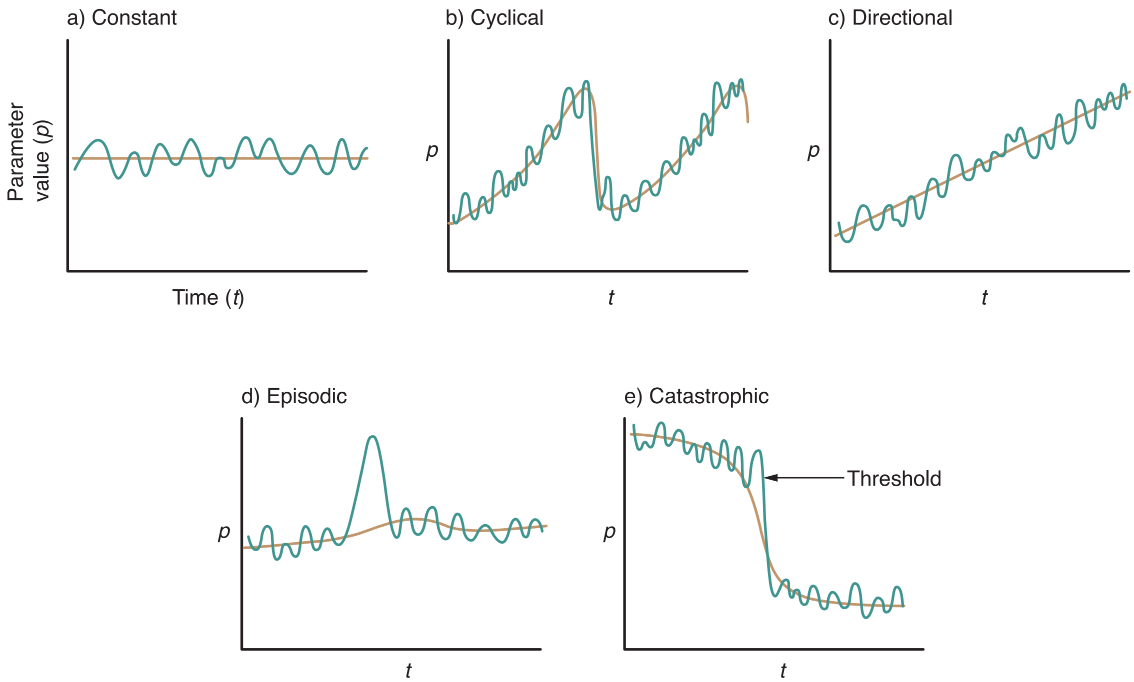


Figure 1.11 Main types of long-term trends in ecosystems, with shorter-term fluctuations superimposed (after Burt, 1994).

The graphs shown in Figure 1.11c and Figure 1.11e also illustrate two different forms of change over time. The trend shown in Figure 1.11c is linear, while that shown in Figure 1.11e is non-linear. Abrupt, sometimes unexpected, changes are typical of such non-linear systems. Such regime shifts are often difficult to reverse, thus presenting a substantial challenge to ecosystem management and development goals. In some cases, mismanagement may accelerate or exacerbate regime shifts (see Box 6.1).

SPATIAL SCALES

Just as the choice of timescales is important to our understanding of the natural environment, so too is the spatial scale of analysis. Studies can be undertaken at scales that range from the microscopic – the effects of salt weathering on a sand grain, for example – through an erosion plot measured in square metres, to drainage basin studies that can reach subcontinental scales in the largest cases, to the globe itself. As with time, the resolution of analysis becomes coarser with increasing spatial scale. We draw a line on a world map to divide one biome from another, but on the ground there is usually no line, more a zone of transition, which may itself vary over different timescales.

Similarly, the types of influence that are important differ according to spatial scale. To use another example involving humans, a landslide that results in the loss of a farmer's field may have a significant impact on the farmer's ability to earn a living, but the same landslide has a minimal impact on national food production.

Figure 1.12 Tundra in northern Canada, part of a biome that may be particularly sensitive to a human-induced warming of global climate and that could create a positive feedback by releasing large amounts of methane, a greenhouse gas (see Chapter 11).

Thresholds and feedbacks also have relevance on the spatial scale. Certain areas may be more sensitive to change than others and if a threshold is crossed in these more sensitive areas, wider-scale changes may be triggered. Soil particles entrained by wind erosion from one small part of a field, for example, can initiate erosion over the whole field. On a larger scale, sensitive areas such as the Labrador–Ungava plateau of northern Canada appear to have played a key role in triggering global glaciations during the Quaternary because they were particularly susceptible to ice-sheet growth. A contemporary large-scale example can be seen in the tundra biome (Figure 1.12), which could release large amounts of methane locked in the permafrost if the global climate warms due to human-induced pollution of the atmosphere. Methane is a greenhouse gas, so positive feedback could result, enhancing the warming effect worldwide.

TIME AND SPACE SCALES

The key factors influencing natural events also vary at different combined spatial and temporal scales. Individual waves breaking on a beach constantly modify the beach profile, which is also affected by the daily pattern of tides dictating where on the beach the waves break. Individual storms alter the beach too, as do the types of weather associated with the seasons. However, all these influences are superimposed upon the effects of factors that operate over longer timescales and larger spatial scales, such as sediment supply and the sea level itself (Clayton, 1991).

The range of temporal and spatial scales is illustrated for some biological and climatic processes in Figure 1.13. This emphasizes the fact that various processes in the natural environment

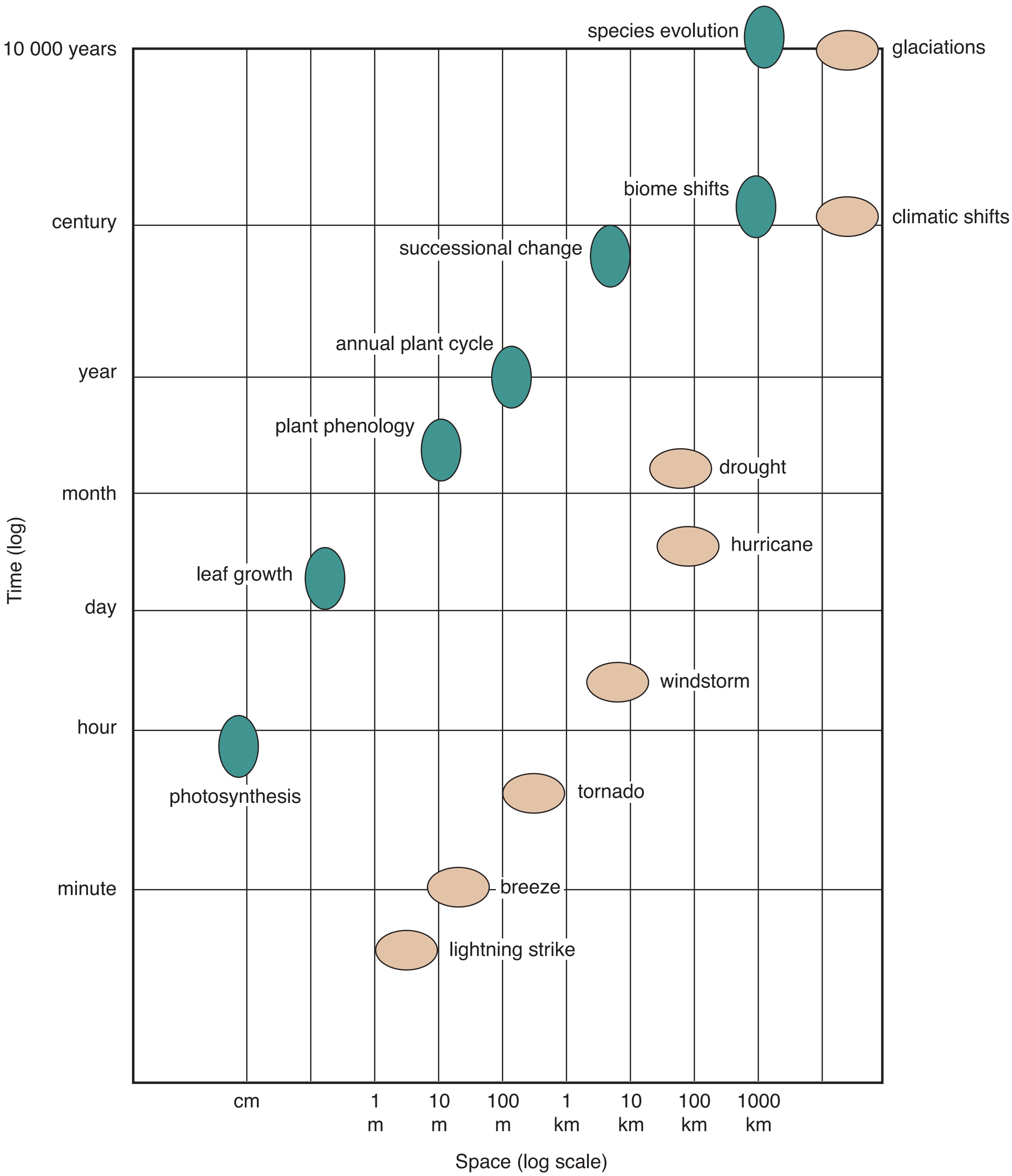


Figure 1.13 The range of temporal and spatial scales at which ecosystem processes exist and operate (after Holling, 1995).

(e.g. climatic changes, tornadoes) exist at specific scales, as do its elements (e.g. species, biomes). It is also important to note that no part of the physical environment is a closed self-supporting system; all are a part of larger interacting systems.

The environmental issues in this book have arisen as a consequence of human activity conflicting with environmental systems. Resolution of such conflicts can only be based on an understanding of how natural systems work. For issues that stem from human impact upon the physical environment, as most do, we need to be able to rank the temporal and spatial scale of human impact in the natural hierarchy of influences on the natural system in question. Inevitably, we tend to focus on scales directly relevant to people, but we should not forget other scales, which may have less direct but no less significant effects. Indeed, successful management of environmental issues relies on the successful identification of appropriate scales and their linkages.

THE STATE OF OUR KNOWLEDGE

We already know a great deal about how the natural world works, but there remains a lot more to learn. We have some good ideas about the sorts of ways natural systems operate, but we remain ignorant of many of the details. Some of the difficulties involved in ascertaining these details include a lack of data and our own short period of residence on the Earth. Direct measurements using instruments are used in the contemporary era to monitor environmental processes. Historical archives, sometimes of direct measurements, otherwise of more anecdotal evidence, can extend these data back over decades and centuries. Good records of high and low water levels for the River Nile at Cairo extend from AD 641 to 1451, although they are intermittent thereafter until the nineteenth century, and continuous monthly mean temperature and precipitation records have been kept at several European weather stations since the early eighteenth century. We have a reasonable global coverage of meteorological stations measuring temperature in a systematic manner for the period from 1850 to the present. Other types of written historical evidence date back to ancient Chinese and Mesopotamian civilizations as early as 5000 BP. The further back in time we go, however, the patchier the records become, and in some parts of the world historical records begin only in the last century.

These data gaps for historical time, and for longer time periods of thousands, tens of thousands and millions of years, can be filled in using natural archives. The geological timescale given in Table 1.2 is based on fossil evidence. Such 'proxy' methods are based on our knowledge of the current interrelationships between the different environmental spheres. Particular plants and animals thrive in particular climatic zones, for example, so that fossils can indicate former climates. The variability of climate during an organism's lifetime can also be inferred in some cases. Study of the width of the annual growth rings of trees gives an insight into specific ecological events that changed the tree's ability to photosynthesize and fix carbon. Essentially similar methods can be used to infer environmental variability from changes in the rate of growth of coral reefs. Other proxy 'palaeoenvironmental indicators' include pollen types found in cores of sediment taken from lake or ocean beds, and the rate of sediment accumulation in such cores can tell us something about erosion rates on the surrounding land. Landforms, too, become fossilized in landscapes to provide clues about past environmental conditions. Examples include glacial and periglacial forms in central and northern Europe, indicating colder conditions during previous glaciations, and fossilized sand dunes in the Orinoco Basin of South America, also dating from periods of high-latitude glaciation, which indicate an environment much drier than that of today.

As with instrumental data and historical archives, natural archives used as proxy variables are patchy in both their spatial and temporal extent. Warm-water coral reefs grow only in tropical waters, ice accumulates only under certain conditions and not many trees live longer than 1000 years. Even instrumental data may not be perfectly reliable over long periods of time because methods and instrumentation can change, monitoring sites can be moved and external factors may alter the nature of the reading. The availability and limitations through time and space of some of the variables used to indicate temperature, a key palaeoenvironmental variable, in the Holocene period are shown in Table 1.3.

Given these gaps in our data and understanding of environmental change through time and across space, some academics have explored other kinds of knowledge about how our planet works. One additional source of information about ecosystems and resources is the traditional ecological knowledge (TEK) of indigenous people that a number of research projects has shown can complement science (see Box 11.1). Constant interaction with the physical environment enables many indigenous people to build a knowledge base of the land and develop the sensitivity to recognize critical signs and signals that something unusual is happening. Berkes (2012) points out that systems of TEK build holistic pictures of the environment by considering a large number of variables qualitatively, while science tends to concentrate on a small number of variables quantitatively. Both are important. Quantification has its limits because there is an inverse relationship between the complexity of a system and the degree of precision that can be used meaningfully to describe it. Hence, indigenous ways of knowing show us an alternative approach that can complement science. There are several other ways in which the two kinds of knowledge are complementary, as Table 1.4 shows with regard to monitoring wildlife populations.

It is clear that our understanding of how environments change can be built up only slowly in a patchwork fashion, but the understanding gained from all these lines of evidence can then be used to predict environmental changes, incorporating any human impact, using models that simulate environmental processes. The accuracy of a model can be assessed by comparing its output with any monitored record, records reconstructed from proxy variables, and the understanding provided by TEK, these sources of information allowing us to develop the model as discrepancies are identified. The human impact may still provide further complications, however, because in many instances through prehistory, history and indeed in the present era, it can be difficult to distinguish between purely natural events and those that owe something to human activities (temperature readings at a town that becomes a city are an obvious example because urbanization affects temperature). It is the interrelationships between human activities and natural functions that form the subject matter of this book.

Table 1.3 Spatial and temporal availability and limitations of instrumental data and some proxy variables for temperature in the Holocene

Variable	Spatial extent	Timescale		
		Interannual	Decades to centuries	Centennial and longer
Instrumental data	Europe from early 1700s, most other coastal regions during nineteenth century. Continental interiors by 1920s, Antarctica by late 1950s	Should be 'perfect' if properly maintained – changes assessable on daily, monthly and seasonal timescales	Site moves, observation time changes and urbanization influences present problems – changing frequency of extremes assessable	As previous, but rates of change to site, instrumentation and urbanization mean absolute levels increasingly difficult to maintain
Proxy indicators Contemporary written historical records (annals, diaries, etc.)	Europe, China, Japan, Korea, eastern North America. Some potential in Middle East, Turkey and South Asia and Latin America (since 1500s)	Depends on function of diary information (freeze dates, harvest dates and amounts, snowlines, etc.). Very difficult to compare with instrumental data	Depends on diary length and observer age. Lower frequencies increasingly likely to be lost due to human lifespan	Only a few indicators are objective and might provide comparable information (e.g. snowlines, rain days)
Tree-ring widths	Trees growing poleward of 30° or at high elevations in regions where cool season suspends growth	Generally dependent upon growing season months. Exact calendar dates determined by cross-dating	Standardization method potentially compromises interpretation on longer timescales	Highly dependent on standardization method. Likely to have lost variability, but difficult to assess
Ice-core melt layers	Coastal Greenland and high-latitude and high-altitude ice caps, where temperatures rise above freezing for a few days each summer	Depends on summer warmth. Unable to distinguish cold years that cause no melt. Rarely compared with instrumental records. Dating depends on layer counting – increasingly difficult with depth	May not respond to full range of temperature variability. Whole layer may melt if too warm; no melt layers if too cold	Increasingly depends on any flow model and layer compaction. Veracity can be assessed using other cores
Coral growth and isotopes	Tropics (between 30° N and S) where shallow seas promote coral growth	Response to annual and seasonal water temperature and salinity. Dating depends on counting. Rarely cross-dated	As coral head grows, low-frequency aspects may be affected by amount of sunlight, water depth, nutrient supply, etc.	Only achieved in a few cases. Veracity can be assessed by comparison with other corals

Source: after Jones *et al.* (1998: Tables 1 and 2).

Table 1.4 Areas where science and traditional ecological knowledge (TEK) can be complementary for population monitoring

Principle	Explanation
Long and short time series	Science is good at collecting data over short time periods over a large area, whereas TEK tends to focus on long time periods, often in small areas, as needed to establish a baseline. Using both together provides more complete information on both time and space scales
Averages and extremes	Much of science collects numerical data, emphasizing statistical analysis of averages. Holders of TEK are very good at observing extreme events, variations, and unusual patterns and remembering them through oral history and social memory
Quantitative and qualitative information	Science demands quantitative data on parts of the system, whereas TEK strives for qualitative understanding of the whole. Understanding of complex systems requires both, so the two are complementary. Qualitative measures can be more rapid and inexpensive, but at the expense of precision
TEK for better hypotheses, science for a better test of mechanisms	TEK provides a short cut to more relevant hypotheses for problem solving but does not usually address mechanisms (the 'why' question). Science has powerful tools for testing the 'why' but can waste time and effort on trivial hypotheses. Using both approaches together benefits from their relative strengths
Objectivity and subjectivity	Science strives to be objective, excluding people and feelings. TEK explicitly includes people, feelings, relationships and sacredness. Science is good at monitoring populations from a distance, but the incorporation of traditional monitoring allows a stronger link between science and community, producing 'science with a heart'

Source: after Moller *et al*. (2004).

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WEBSITES

gcmd.gsfc.nasa.gov/ a wide range of data on the earth sciences is available through the Global Change Master Directory.

www.fao.org/gtos/ the Global Terrestrial Observing System is a programme for observations, modelling and analysis of terrestrial ecosystems to support sustainable development.

www.igbp.net/ the International Geosphere-Biosphere Programme's mission is to deliver scientific knowledge to help human societies develop in harmony with the Earth's environment.

www.inqua.org/ the International Union for Quaternary Research oversees scientific research on environmental change during the Quaternary.

www.lternet.edu/ the Long Term Ecological Research Network supports research on long-term ecological phenomena in the USA and the Antarctic.

www.pages-igbp.org/ PAGES (Past Global Changes) supports research aimed at understanding the Earth's past environment to enable predictions for the future.

POINTS FOR DISCUSSION

- How and why can we recognize large-scale ecosystem types called biomes?
- It is a biological fact that predators at the top of food chains are always rare. The only exception is humans and this is why we face so many environmental issues. How far do you agree?
- Prepare a report for a national agency outlining the arguments for and against the funding of long-term environmental monitoring.
- Explain why studies of the physical environment should be carried out at a range of temporal and spatial scales.

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