Ecology and Environmental Health

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Chapter 1
Ecology and Environmental Health
Bruce Wilcox and Holly Jessop
(Howard Frumkin. 2012. Environmental Health: From Global to Local. Princeton U. Press)

This chapter introduces the science of ecology, its general principles, and their relevance to environmental health. **Ecology** is defined as the study of the interactions between organisms and their environment, including both the living (biological) and non-living (physical) components.

Ecology involves subject matter that is often readily observable and evident all around us. From the moment of birth, each of us interacts with the environment. Life's journey begins by developing relationships both with other humans and non-human organisms, and by engaging in interactions with our physical surroundings.

Most ecologists study wildlife, wetlands, forests, fisheries, or parts of these and other natural systems. The concepts and principles that make up the ecological sciences deal with how nature works. Nearly everybody at one time or another actively observes and even ponders nature, making almost anyone an ecologist of sorts. This is true even for someone who has lived entirely in an urban environment. Ecology is also a broad scientific discipline. In fact, the development of ecological thought historically involved numerous ideas from other sciences including geology, physics, sociology, and economics.

In spite of our intimate connections with the environment and awareness of nature, the scientific concepts of ecology are not necessarily always intuitive – just as is true for physics and economics! Every organism interacts with a multitude of other organisms, contributes to the flow of energy and materials (the currency of ecological systems), and responds to the physical environment in myriad subtle ways. We humans, the most conscious species today, are actually unconscious of most of the "invisible" ways in which we influence and are influenced by our environment. For example, most people know little of the organisms and processes that underlie the ecological systems responsible for the oxygen we breathe, the water we use, the food we eat, and the infectious illnesses we contract.

It would take a book at least as big as this one to describe thoroughly the ecological basis of human health and well-being. This chapter focuses on the ecological concepts and principles most relevant to human health and how these help us to understand specific environmental health problems. Before proceeding, let us briefly consider the purpose, approaches, and perspectives encompassed by the field of ecology.

THE FIELD OF ECOLOGY

Ecology aims to understand how natural systems such as plant and animal communities are organized and function. This includes investigating subsystems and parts of natural systems, the relationships among them, and the processes at and above the level of the individual organism that allow biological systems to persist and evolve as dynamic entities. Modern ecology emerged from **natural history**, which primarily focused on descriptions and catalogues of plants and animals, and generally considered biological systems (including species) to be static entities. After Charles Darwin's publication of *On The Origin of Species* (1859) the fact that living organisms undergo change through the process of **natural selection** began to be incorporated into ecological study of the dynamics of natural systems. Thus ecology and **evolutionary biology** are closely allied and are considered one field by many biologists.

In fact, Ernst Haeckel, the German zoologist and Darwin contemporary who coined the term “ecology” in 1866 was an interpreter of Darwin’s work. Haeckel created the new term to draw attention to the study of organisms in their environments, in contrast to their study only in the laboratory: The “eco” in ecology (from the Greek *oikos*) means home or place of dwelling (Keller and Golley, 2000).

While ecology developed as a natural science during the 19th and 20th centuries, many of its concepts and principles were applied to other fields, ranging from human social development (Bronfenbrenner, 1979), to social and cultural systems (Park, 1952; Bennett, 1993), and to epidemiology (Last, 1998). Also, the traditional focus on the study of natural systems such as forests, grasslands, wetlands, rivers, lakes, and the ocean has increasingly been extended beyond purely “natural” systems. For example, the application of ecological thinking began expanding by the mid-20th century to encompass human-built or “hybrid” human-natural systems such as cities and cultivated landscapes (Nevah and Lieberman, 1994). Recently, the **social ecological systems perspective** (Berkes *et al.*, 2003) and the **resilience theory** (Gunderson and Holling, 2002) have developed within the field of ecology to explicitly deal with humans and nature as a single, integrated, and complex system. This integrative approach to understanding living systems has been found necessary to meaningfully address issues such as sustainability; a concept that implies the dependence of human health and well-being on “healthy ecosystems. As such, ecology has become as much a worldview as it is a scientific discipline (Keller and Golley 2000).

Ecology is mainly built on three different but complementary perspectives often considered its major subdisciplines: ecosystem ecology, community ecology, and population ecology (Begon *et al.*, 1986). In addition, the linking of these concepts across different scales is often aided by landscape ecology, which tends to act as a bridge linking these disciplines, especially in applied contexts. The fundamentals of three main sub-disciplines of ecology are summarized immediately below. These and other lines of ecological research will then be further discussed in this chapter in the context of specific environmental health challenges.

Ecosystems, Communities and Populations

Ecosystem ecology stresses energy flows and material cycles, including how energy and materials are modified by human activities. It aims to understand how energy and materials (such as water, carbon, nitrogen, phosphorus, and other elements) essential to growth and metabolism—from the organism level to the entire ecosystem—flow in, out, through, and are compartmentalized and transformed.

The **ecosystem** is in many ways the most important concept and functional entity in ecology, much as the cell is in physiology. An ecosystem is formed by the interactions of living organisms with their physical environment. Much as particular kinds of cells make up tissues and organ systems, different kinds of ecosystems make up Earth’s living environmental systems. Collectively, these constitute the entire **biosphere**, often viewed as the largest ecosystem of all and also a central concept in ecology. The biosphere is the largest known ecosystem, in which all other ecosystems are embedded; It consists of all the Earth’s living organisms interacting with the physical environment.

The idea of the biosphere and its development is fundamental to understanding life on

Earth, and the dependence of our health and well-being on natural systems (see Box 1.1). Therefore, the biosphere concept is critically important to understanding environmental health issues such as global climate change. Remarkably, its original conception a century ago included many insights relevant to environmental health today. These include recognition of the risks as well as benefits of an economy based on fossil fuels (such as coal, petroleum, and natural gas) and associated synthetic compounds (such as plastics, pharmaceuticals, and pesticides). The biosphere concept and its development also pointed the discovery of the predominance and ubiquitous character of life in the form of microorganisms, occurring everywhere and within every living thing. This included the observation that microorganisms constitute most of the free-living total biomass on Earth, which drive or regulate the biogeochemical cycles that make the biosphere possible, and which are an integral part of the ecology of every single living organism including humans. For example, every human supports hundreds of species of known microorganisms (mainly bacteria and viruses), ranging from the beneficial bacterial “flora” of our gastrointestinal tracts (without which we could not live) to the harmful influenza viruses that can cause disease.

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Box 1.1 - The Biosphere

The term biosphere was coined by the pioneering 19th century earth scientist Eduard Suess (1885). The idea was expanded and elaborated by Vladimir Vernadsky in an extraordinary two volume essay, *Biosphera* (1925). Vernadsky presented a number of the key ideas that make up modern ecology as well as the earth sciences, such as the idea that balanced carbon exchange between the Earth’s surface and atmosphere contributes to our planet’s habitability. His idea lead to the discovery that this balance is changing, due primarily to anthropogenic burning of fossil fuels and deforestation, which in turn is contributing to changes in the Earth’s climate system (Smil, 2002). The myriad direct and indirect affects of global climate change on health are discussed in Chapter X.

What is the biosphere and its relationship to ecological understanding? The biosphere is the layer of living matter—microbes, plants, and animals—that has been described as a “film” on the surface of the planet. It is sandwiched between the relatively thick lithosphere (the outer rocky layer of Earth) and the troposphere (the lowermost portion of the Earth’s atmosphere). Life penetrates rocks, as well as the ocean depths and the highest mountain peaks where only tiny microorganisms adapted to extreme environmental conditions can exist. However, it is only a relatively narrow zone within the biosphere where the transformation of solar energy through photosynthesis is possible.

Organisms have not only developed and adapted to conditions within the Earth’s biosphere: Living organisms have themselves also created the biological and physical conditions of the biosphere. For example, the original environment on the Earth’s surface would have been completely uninhabitable and even fatal to most organisms living on the Earth today. However, the evolution of photosynthetic organisms, which generate oxygen, ultimately led to today’s atmosphere. Such modifications to the biosphere have allowed subsequent life forms to evolve, survive, and even flourish. Indeed, many contemporary life forms, including ourselves, now depend on the oxygen generated by photosynthesis. And, without today’s protective tropospheric shield, very few kinds of organisms could survive the intense ultraviolet radiation and temperature extremes that would otherwise exist on the Earth’s surface.

As a central paradigm in ecology, the biosphere provides us with a way of thinking about life framed in a large view, along with an understanding of the processes that make it possible for life to have evolved and survive on Earth. Today we call this a systems view, with the Earth seen as a single unit of interacting living and non-living parts and related processes. The idea of the biosphere provides the framework that allows us to begin to make sense of the complexity of human-nature interactions. The idea of the biosphere also links directly to the ecosystem concept, which is central to understanding the ecological basis of environmental health.

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The other two major branches of ecology view nature from the perspective of component "parts", above the level of species that make up ecosystems. **Community ecology** deals with ecological communities, which are defined as assemblages of interacting plants, animals, and microbes co-existing in a particular location. Its aim is to understand the factors and mechanisms that determine the composition and diversity of species found in a particular place. Community and ecosystem ecology overlap. However, community ecology focuses less on energy and material transfers and more on processes and factors that determine species' composition and diversity.

Population ecology attempts to explain the dynamics of species' populations, and interactions among species, as well as relationships between species and their physical environment. The overlap of community ecology and population ecology becomes apparent when we consider that inter-species interactions—competition, predation, and parasitism—are some of the key determinants by which species co-exist in a particular place (that is, make up a community).

In sum, ecosystem ecologists are mainly interested in how ecosystems are organized and function; community ecologists in why communities have the number and assortment of species that they do; and population ecologists in what determines the abundance and distribution of a species. The perspectives and research foci of the major sub-disciplines of ecology are summarized in Table 1.1.

TABLE 1.1: THE MAJOR SUB-DISCIPLINES OF ECOLOGY

Sub-Discipline of Ecology	**Focus**
Ecosystem Ecology	Whole systems view. Ecosystem as unit of study. Emphasis on energy and material cycles.
Community Ecology	Interactions of species. Emphasis on species' composition and diversity.
Population Ecology	Population-level processes. Emphasis on population dynamics, regulation, and inter-species interactions.

Core questions of ecology

The sub-disciplines of ecology are complementary. All address an overarching question that has motivated natural historians and ecologists from the beginning: what determines why and how ecological systems form, species assemblages develop, and populations survive in the environments that they do? Scientists began focusing on this question in earnest beginning with Alfred Russell Wallace, Darwin's contemporary and co-discoverer of the principle of evolution by natural selection. Wallace (1876) was the first to map the world's "Zoogeographic Realms"—comprehensive distributions of known animal species. This in turn led generations of ecologists to investigate what determines the geographic distribution of major types of ecosystems and communities. In addition, countless ecologists have studied individual species' interactions with each other and with the physical environment.

Certain critical features determine the character of ecosystems. Prime among them are the amount of precipitation, the temperature, and the availability of soil nutrients. These features, in turn, predict the kind of vegetation that grows, defining the major ecological zones or biomes (see Figures 1.1 and 1.2). **Biomes** are basically the world's major geographic regions defined by characteristic ecosystem type. Major biome types include tundra, boreal forest, temperate forest, tropical forest, scrubland, grassland and savannah, and desert (Table 1.2); these are divided into subtypes such as coniferous or deciduous forest, semi-arid or tropical scrubland, and so on. Importantly, the traits of the organisms that make up a biome or ecosystem type, and the physical structure of the vegetation including its height and density, are the response to evolutionary and ecological constraints and opportunities posed largely by climate.

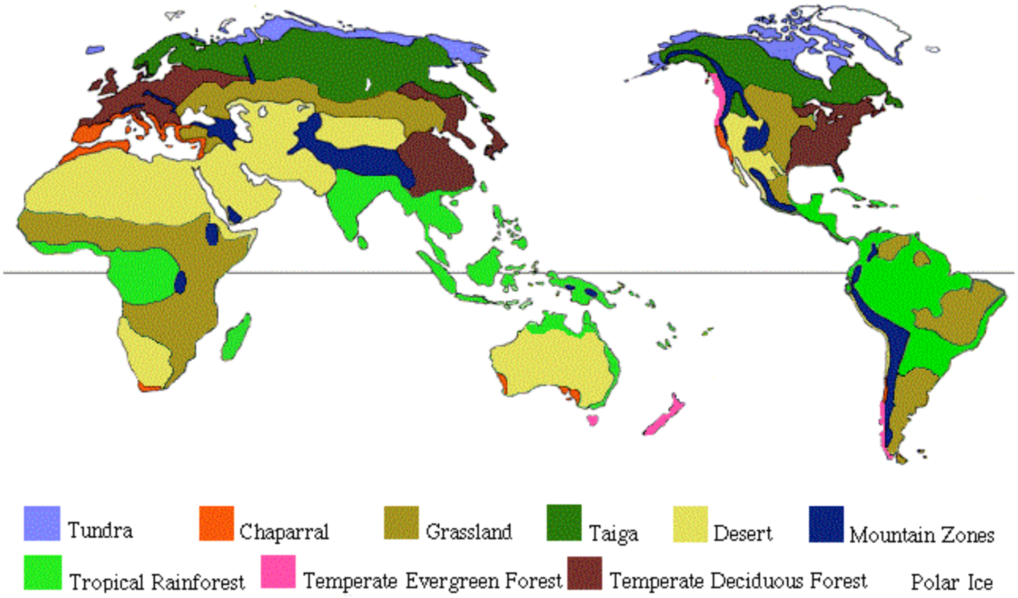

Figure 1.1 – Map of world biomes, from http://www.digitalpencil.org/projects_Allgrades/aroundtheworld/biomes/Images/BiomeOfWorldMap.gif**.**

Figure 1.2 – "Cloud" diagram of the major terrestrial biomes plotted by mean annual temperature and precipitation, from Odum (1993).

Local circumstances such as the geology and landscape topography can also have a strong influence on the ecosystem type that develops in an area. But even these **abiotic** factors are ultimately shaped or determined in part by biological, or **biotic** factors. For example, the reshaping of rocks and landforms, or **geomorphology**, is partly a consequence of the interaction of vegetation cover and rainfall. Vegetation influences not only rainfall but also the rates of erosion in uplands and sedimentation in lowlands, including deposition of sediments and soil "downstream" in river systems.

TABLE 1.2: MAJOR ECOSYSTEM TYPES & BIOMES, adapted from Odum (1993)
MARINE ECOSYSTEMS
Open ocean (pelagic)
Continental shelf water (inshore water)

Upwelling regions (fertile areas with productive fisheries)
Deep sea (hydrothermal vents)
Estuaries (coastal bays, sounds, river mouths, salt marshes)
FRESHWATER ECOSYSTEMS
Lentic (standing water): lakes and ponds
Lotic (running water): rivers and streams
Wetlands: marshes and swamp forests
TERRESTRIAL BIOMES
Tundra: arctic and alpine
Boreal coniferous forests
Temperate deciduous forests
Temperate grassland
Tropical grassland and savanna
Chaparral: winter rain-summer drought regions
Desert: herbaceous and shrub
Semi-evergreen tropical forest: pronounced wet and dry seasons
Evergreen tropical rain forest
DOMESTICATED ECOSYSTEMS
Rural techno-ecosystems (transportation corridors, small towns, industries)
Agro-ecosystems
Urban-industrial techno-ecosystems (metropolitan districts)

Understanding the internal workings of ecosystems related to these observed biogeographic patterns has provided critical insights into the mechanisms underlying a number of important environmental health problems. For example, not the least of these is how changing human land use and industrial activity has altered the natural cycling, storage, and release of carbon in its different forms (solid and gaseous). The net decrease in carbon stored in ecosystems like tropical forests and increase in carbon dioxide in the Earth's atmosphere is a key contributor to global warming and its associated health impacts (discussed further in Chapter X).

Observing how different biomes and ecosystems vary in their organization, functioning, and types of organisms that make them up has helped reveal mechanisms underlying other environmental health challenges. For example, studies of how energy and matter is transferred from lower to higher levels in the food chains of aquatic ecosystems explains such phenomena as biomagnification. As will be described below, this can result in unsafe levels of toxins in seafood. Similarly, studies of ecosystem "physiology" and discovery of factors that control biomass production in aquatic ecosystems has helped to explain how nutrient pollution can cause toxic algal blooms. Other research on the regulatory functions of forest ecosystems has helped to explain how deforestation releases vectors and pathogens from natural controls leading to emerging infectious diseases.

ECOSYSTEM PROCESSES AND FUNCTIONING

Naturally mediated and regulated ecological processes, such as the breakdown of organic waste and the recycling of chemical elements, are all part of what is called **ecosystem functioning**. For example, key processes involving the back and forth movement of materials between the living and non-living components of the biosphere are the **hydrological cycle** (Figure 1.3) and **biogeochemical cycles**. The latter include the **carbon cycle** and **nitrogen**

cycle (Figures 1.4–1.5).

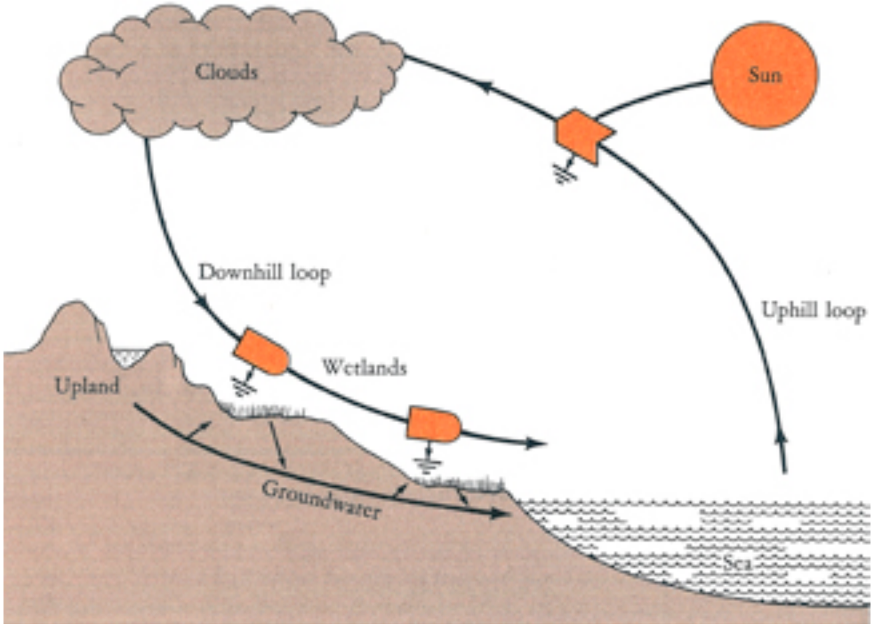

Figure 1.3 – Hydrological cycle, from Odum (1993).

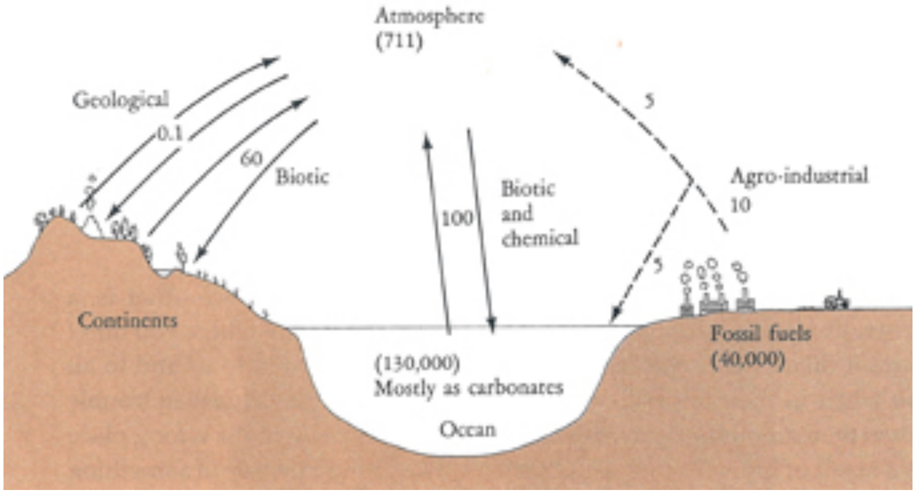

Figure 1.4 – Carbon cycle, from Odum (1993).

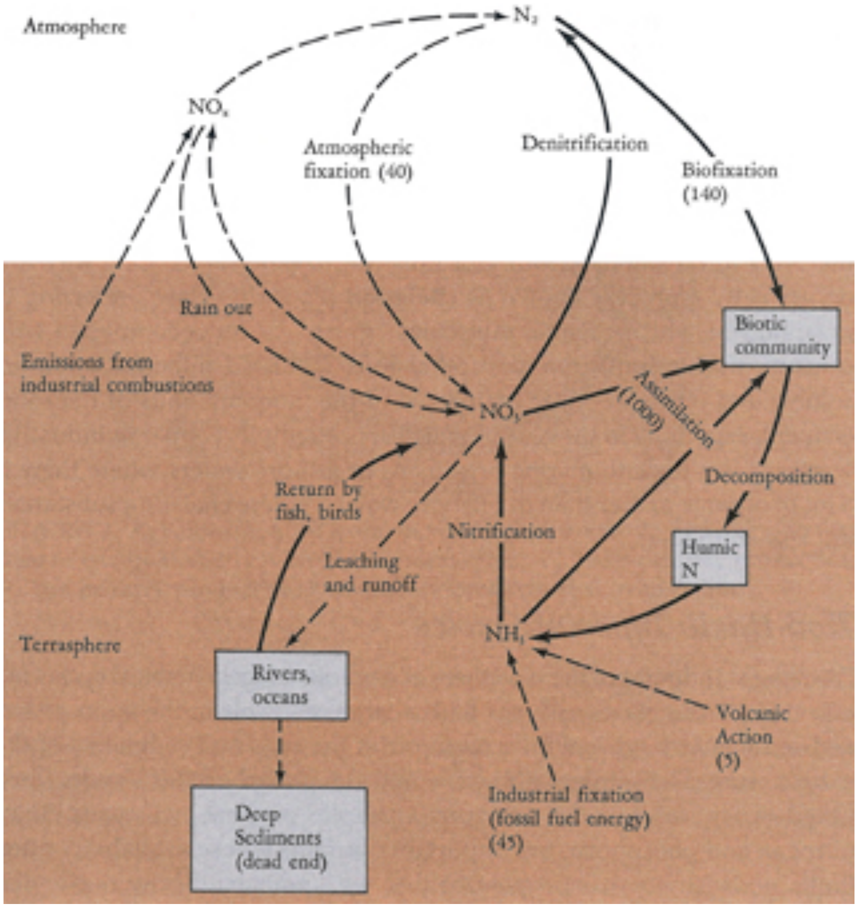

Figure 1.5 – Nitrogen cycle, from Odum (1993).

Such recycling of water and elements are central to the functioning of ecosystems and the biosphere. Indeed, these processes are the basis of Earth's life support system, and thus are essential to human health. For example, they make possible the existence of wetlands, marshes, and mangrove forests that provide key **ecosystem services (see Box 1.2)** such as natural waste recycling, water filtration, barriers against storm surges and saltwater intrusion, and nurseries for fish and shellfish. The degradation of ecosystems and the alteration of their functioning can have severe health consequences. This relationship of ecological functioning to human health is a recurrent theme in this chapter and is discussed further in the context of other processes and properties of ecosystems, communities, and populations.

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Box 1.2 – Ecosystem Services

As described in the Millenium Ecosystem Assessment Report (2005), the benefits obtained from ecosystems are indispensable to the well-being of people throughout the world. These include food, natural fibres, a steady supply of clean water, regulation of some pests and diseases, medicinal substances, recreation, and protection from natural hazards such as storms and floods. Yet, because of the complexity of ecosystems, the innumerable ways human well-being is linked to their own productivity, and the limitations of economic methods and data, it is not yet possible to accurately measure the economic value of goods and services provided by ecosystems (Daily *et al.,* 2003). The Millenium Ecosystem Assessment Report categorizes ecosystem services as: provisioning services, regulating services, supporting services, and cultural services. Of the functional characteristics of ecosystems most beneficial to human populations, those particularly relevant to environmental health are the regulating and purifying functions: provision and purification of water, recycling of wastes, and regulation of climate and of infectious diseases (as summarized below from the Report).

Provision of clean water: Ecosystems, especially forests, act both as reservoirs and pumps, holding water much like a giant sponge. Through the process of evapotranspiration, forest vegetation draws water from the ground and releases it into the atmosphere. These functions, that contribute to much of the hydrological cycle, effectively recycle used as well as unused surface water, remove impurities, and deliver fresh water to where it can be harvested. Fresh water is a key resource for human health for growing food, drinking, washing, cooking, and the dilution and recycling of wastes. Unfortunately, over a billion people in the world do not have access to clean water as a result of ecosystem degradation, population growth, and inadequate water treatment and distribution infrastructure. Overall, the burden of disease from inadequate water, sanitation, and hygiene totals 1.7 million deaths and the loss of more than 54 million healthy life years.

Waste recycling (nutrients, pathogens, and breakdown of toxins): As suggested above, ecosystem processes involved in the breakdown of organic wastes, and even filtering of suspended material including pathogens, provide effective mechanisms for cleansing the environment of wastes. Natural ecosystems can be so effective at purifying and detoxifying wastewater that some municipalities have restored wetlands in order to use them as a means of tertiary sewage treatment. The filtering and microbial degradation properties of wetlands, which include marshes, swamps, and streamside or riparian zones consisting of soil perennially saturated with water, are capable of physically removing or breaking down even the most toxic chemicals and heavy metals as well as human pathogens. Despite their value, wetlands are among the world’s most endangered ecosystems, as coastal wetlands and their upstream tributary rivers and streams are often filled and paved over for urban development, or are otherwise functionally destroyed by misdirected flood management programs. The loss of this waste recycling capacity has now led to local and sometimes global waste accumulation, as the ecosystems that remain are unable absorb and remove the onslaught of contaminants. For example this of recycling capacity, along with fertilizer-laden runoff in the Mississippi River Basin, is responsible for the eutrophic “dead zone” in the Gulf of Mexico.

Regulation of infectious disease: An ecosystem’s characteristics, particularly its landscape ecology, strongly influences the incidence of zoonotic and vector-borne diseases in local human populations and the potential for the emergence of new, epidemiologically significant diseases. Intact ecosystems, with their innumerable interspecies relationships and heterogeneous landscape structures, tend to moderate population dynamics and prevent any particular species (including host, vector, or pathogen species) from dispersing widely, becoming super-abundant, or both. This moderating function tends to break down with the clearing or fragmentation of natural ecosystems, such as logged forests and the expansion of cropland and pastureland. Artificial changes in the distribution and availability of surface waters, such as through dam construction, irrigation, and stream diversion have a similar effect. Changes in animal husbandry and livestock production systems, toward more intensive methods that involve the increased concentration, movement, and novel mixing of animal species, animal products and waste effectively provides conditions for the cultivation and maintenance of new pathogens strains, as evidenced with avian influenza (H5N1).

Climate regulation. Natural ecosystems regulate the global climate system by acting as sinks for greenhouse gases. In particular, the clearing and burning of tropical forests around the world

has been major contributor to the accelerated increase in carbon dioxide in the Earth's atmosphere and global warming in recent decades. At the regional and local levels, natural and managed ecosystems strongly influence climate due to physical properties that affect the flows of energy and rainfall. For example, the conversion of vegetated land cover to hardened surfaces associated with urbanization produces the "urban heat island" effect, elevating the temperature of a city and the surrounding region. In this way ecosystems tend to moderate extreme weather events (thought to be increasing due to anthropogenic global climate change) such as heat waves, freezing weather, storms, or the frequency and magnitude of associated floods and coastal storm surges. Thus ecosystems limit the degree and extent of the impacts of adverse weather events on public health, directly through reductions in deaths and injuries, and indirectly through economic disruption, infrastructure damage, and population displacement. Ecosystems, and how they are managed, also can have a strong negative or positive impact on air quality and the associated health risks.
<END BOX 1.2>

Ecosystem Organization

The preceding discussion alluded to the distinction of "ecosystem" as a theoretical idea or paradigm on the one hand, and a particular entity on the other: a lake, a forest patch, or a coral reef. Realizing this distinction, the great ecologist Eugene Odum pointed to organizational integrity as the defining criterion for an ecosystem (Odum, 1971); He defined an **ecosystem** as "any unit that includes all of the organisms (*i.e.* the 'community') in a given area interacting with the physical environment so that a flow of energy leads to clearly defined trophic structure, biotic diversity, and material cycles (*i.e.* exchange of materials between living and nonliving parts) within the system."

The two most significant organizational aspects of any ecosystem, to which ecosystem functioning is tied, are trophic structure and the associated material cycles of nutrients (such as carbon, nitrogen, phosphorus, and potassium), trace essential minerals (such as iron, sulfur, zinc, and selenium), and water. **Trophic structure** refers to the organization of ecosystems by feeding levels, often conveniently conceptualized as a pyramid. A **trophic level**, is the position that an organism occupies in a food chain—what it eats, and what eats it ("trophic" derives from *trophe*, the Greek word for feeding). As shown in Figure 1.6, organisms such as plants and algae that utilize photosynthesis to convert solar energy into stored chemical energy (in the form of carbohydrates) can be represented as **primary producers** (or **autotrophs)** because they make their own energy. These kinds of organisms constitute the base of the trophic pyramid, and at the same time, the bottom of the food chain.

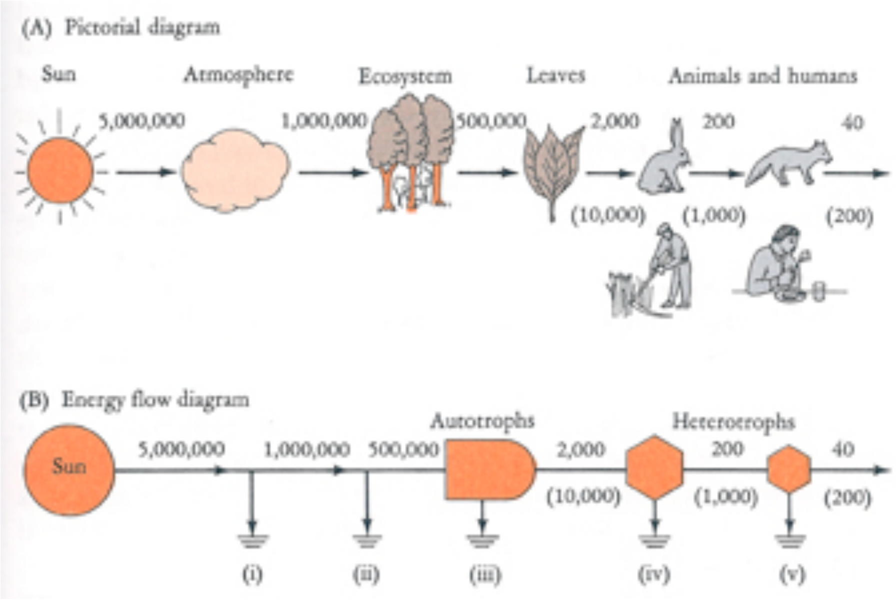

Figure 1.6 – Solar energy flow through a biological food chain, from Odum (1993).

Producers are fed upon by **primary consumers** (species of herbivores) that in turn are fed upon by **secondary consumers**, and so on. Secondary consumers are called **heterotrophs** because they get their energy from feeding on other organisms (both plants and animals). The amount of biomass found at a trophic level (*i.e.* the mass of all the individual organisms of all the species at a particular trophic level added up) decreases by roughly an order of magnitude with each step up the pyramid. This is because, as energy is transferred from one trophic level to the next (producers→herbivores→carnivores), a portion of the energy is lost as heat (as a consequence of the Second Law of Thermodynamics). In fact, the amount of energy gathered from solar radiation and stored in plant biomass is relatively small, compared to the total solar energy reaching Earth. Thus, we can easily understand why top predators such as sharks or tigers tend to have relatively small population sizes even under the best of circumstances. The naturally small population sizes of top predators are why these types of animals can so easily become endangered through overharvesting or habitat loss.

The relationships of trophic structure, **nutrient cycles**, and **energy flow** are shown in Figure 1.7, which shows how the one-way flow of energy, entering the ecosystem as sunlight, drives the cycling of nutrients such as nitrogen. The compartments in Figure 1.7 represent pools of nutrients and the biomass of organisms (autotrophs and herterotrophs). In a healthy ecosystem, the energy flow, nutrient cycles, and biomass are relatively stable. These compartments represent the “stocks” of energy and materials, while the pathways are their “flows.” As we will see later in the chapter, human activities can dramatically alter these quantities and processes, resulting in serious imbalances that can lead to severe environmental health consequences.

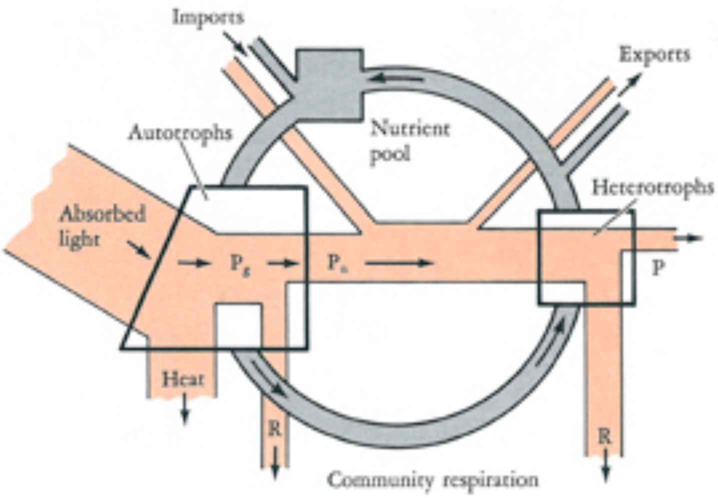

Figure 1.7 – Nutrient cycling and energy flow through an ecosystem, from Odum (1993).

One important consequence of trophic structure is the ability of some pollutants to become concentrated at higher trophic levels, such as in predator species. Examples of this phenomenon are discussed in Box 1.3.

<START BOX 1.3>

Box 1.3: Toxins and Biomagnification: Mercury and POPs

Contrary to the behavior of energy in ecosystems, a significant portion of which is lost as waste heat as it is transferred from one trophic level to the next, some substances instead actually increase in concentration as they are transferred up a food chain. This phenomenon is called **biomagnification**. For example, biomagnification and the associated process of bioaccumulation, are responsible for the potentially harmful levels of toxic substances often found in some species of fish. Similarly, terrestrial predators feeding at the tops of food pyramids may suffer greater harms from environmental toxins that have become increasingly concentrated in prey organisms. Such chemical hazards arise from natural as well as "unnatural" human disturbances and inputs into fresh water, marine, and/or terrestrial environments.

Biomagnification is the sequence of processes that results in greater concentrations of a substance in organisms at higher levels in the food chain. These processes include **bioaccumulation**, which is the uptake by organisms (including humans) of contaminants more rapidly than their bodies can eliminate them. Of course, over time an organism consumes a vastly greater amount of biomass than that represented by its own body, thus effectively integrating the exposures of many organisms in its food chain. An organism can thus potentially assimilate and concentrate a toxic substance at much greater levels than occur in its environment. Moreover, the higher an organism's trophic level, the greater is the concentration of a bioaccumulated substance.

Mercury provides a key example of biomagnification of a toxic substance. Mercury is well known as an environmental pollutant with serious human health consequences. Fish and other wildlife in various ecosystems commonly have concentrations of mercury of toxicological concern when eaten by humans. Mercury enters ecosystems as a result of both natural processes and human activities (especially coal mining and combustion, since coal may be contaminated with mercury) and is converted to various forms, including that most toxic to humans, methylmercury. Many of the details of how mercury compounds form and circulate in an ecosystem remain unknown. However, what is known is that mercury has the potential to be a serous health hazard and that human-derived emissions are increasing.

Persistent organic pollutants (POPs) provide other examples of toxic chemical substances that can dangerously biomagnify. With slow or no degradation, such substances persist in the environment and can undergo easy transport by wind or water forces. Like mercury, POPs can have negative impacts on both wildlife and human health. For example, many widely-used pesticides (*e.g.* DDT), industrial solvents, and pharmaceuticals are POPs that have been demonstrated to cause health problems even at very low levels of exposure. Also like mercury, the mechanism driving biomagnification of POPs is bioaccumulation combined with the trophic pyramid of ecosystems: autotrophs and primary consumers accumulate POPs in their tissues, resulting in concentrations greater than that in the surrounding environment. When these organisms are themselves consumed by heterotrophs, POPs become even more concentrated. Thus, POPs in small amounts in the environment can quickly become hazardously concentrated in organisms who feed at higher trophic levels. Unfortunately, POPs are becoming ubiquitous in the biosphere, deriving almost solely from human-generated effluents into the Earth's hydrological cycle.

<END BOX 1.3>

Hierarchy and Scale

Ecosystems, and biological systems in general, have been found to exhibit properties consistent with all so-called complex systems. The most obvious of these properties is hierarchical organization. As illustrated in Table 1.3, ecological systems, like sociopolitical systems, self-organize in a nested manner, in which larger entities (or subsystems) that exist at one scale contain subsystems that exist at a smaller scale (and which operate on shorter time or spatial scales).

Table 1.3: LEVELS OF ORGANIZATIONAL HIERARCHIES

SOCIOPOLITICAL	ECOLOGICAL
World	Biosphere
Nation (or region)	Biome (or biogeographic province)
State or Province	Landscape
Country or District	Ecosystem
Municipality	Biotic community
Household	Population (species)
Individual	Organism

This hierarchical property of complex systems—the scaled, nested arrangement of parts—has functional implications. The function of the whole system—the biosphere in the case of ecological systems—both constrains the behavior of the parts (or subsystems) and is a consequence of them. For example, carbon dioxide uptake and oxygen release by the autotrophic organisms that make up communities and ecosystems help to determine the atmospheric concentrations of these gases, which in turn drive weather patterns globally. As illustrated in Figure 1.2, the average precipitation and temperature of different weather patterns themselves influence ecological processes to the extent of determining biomes and the types of primary producers present in a regional ecosystem.

Complex systems are replete with these kinds of circular feedback mechanisms, leading to non-linear responses to natural and human ecosystem perturbations. Because the outcomes are extremely difficult to predict accurately, they can also be easy to ignore or deny. This is often the case with climate change: The massive conversion of the world's natural ecosystems to urban ecosystems over the past three centuries, along with fossil fuel burning, is known to be causing a dramatic change in the atmospheric concentration of greenhouse gases—just one of many ecological consequences of the transformation of the biosphere through human activities (Smil, 2002) also see Chapter X). The gradual nature of this change, and the inability of science to provide precise predictions, has frequently resulted in policy makers and the public being taken by "surprise" by events related to the consequences of climate change. However, experts knowledgeable about ecological systems often are anything but surprised.

Crawford Holling and colleagues have shown how this pattern of denial and surprise apply to many environmental crises and failures of environmental management, ranging from sustainable management of forests and fisheries, to pest and vector-borne disease control efforts: Building on earlier research on ecosystem organization, behavior, and management, Holling and colleagues have developed a useful ideological framework based on complexity theory and case studies (Holling, 1978; Holling, 198?; Gunderson, *et. al*, 1995; Gunderson and Holling, 2002; Berkes, *et al.*, 2003). A central feature of this framework is a model called the **adaptive renewal cycle** (Figure 1.8). This model describes the repeated cycles of change exhibited by ecological, economic, and institutional systems—as coupled human-natural systems—through four distinct phases: exploitation, conservation, release, and re-organization.

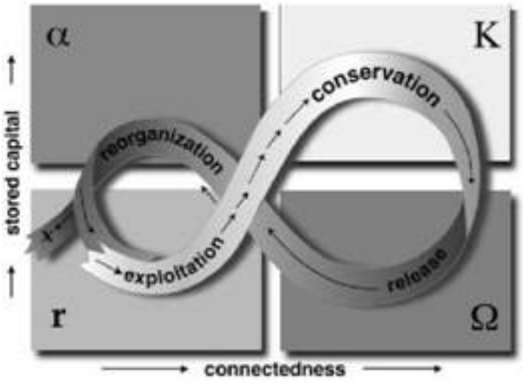

Figure 1.8: The adaptive renewal cycle, from Gunderson and Holling (2002).

Unlike traditional ecosystem models that treat humans as external components, the adaptive renewal cycle model acknowledges the reality of what has been called the **total human ecosystem** (Nevah and Lieberman, 1994)—the idea that humans and their environment form a single entity to be studied in its totality. This model incorporates feedback relationships within and between the human and natural system components. This includes those that link the institutional and natural parts of the system, involving "signals" that provide feedback (information) about the status of the stocks and flows of energy and materials.

A classic example of such a feedback is the information gathered by fishery biologists on the status of target fish population(s) being harvested. This information typically is gathered and provided to decision makers who then decide how to adjust harvesting rates, through such approaches as limiting the number of permits issued, constraints on fishing gear, and other measures. Ideally, the feedback mechanism thus triggers institutional behavior that results in a sustainable harvesting regime, with functionally intact fish populations, healthy ecosystems, and economically productive fishing industries.

This system of cyclical monitoring and adjusting was named **adaptive management** (Holling, 1978; Walters, 1986). It is the central idea of **ecosystem management** and involves monitoring key indicators of the health of the ecosystem, such as measures of nutrient flow and animal stocks—and adjusting human actions accordingly. The idea of adaptive management has more recently been extended to environmental health risk management (Carpenter, 1997).

The Chesapeake Bay offers one of the best cases of adaptive management in this regard. This ecosystem has long been one of Eastern North America's most important ecosystems for its environmental resources including its fisheries, recreational uses, and other values. So its health, and the implications of pollutant discharges into the Bay and its upstream drainages had long been a concern. Beginning in the 1970's, when most of the major Federal and State environmental protection laws where put in place in the United States, government agencies monitored with increasing technical sophistication the state of this aquatic ecosystem using various ecological indicators, and indicators of environmental health risk. These indicators included, for example, concentrations of toxic metals and organic compounds in waters, sediments, fish, or shellfish.

An adaptive management system came about though a dynamic relationship between science and governance that has evolved since the 1970's (Hennessey, 1994). This ultimately led to a comprehensive set of measures indicating the state of health of the Bay ecosystem and its resources, and the risks to human health. These risks include exposure to toxic chemicals, risks of infection by pathogens, and frequency and intensity of production of biotoxins by harmful algae (Boesch, 2000). The Chesapeake Bay Program has become a model for large-scale environmental restoration and management that involves stakeholders' participation at all levels of government, and an extensive research community. The evolving suite of ecosystem health indicators has at times numbered more than 82 separate metrics adapted to different management needs: condition indicators, evaluation indicators, diagnostic indicators, communication indicators, and futures indicators (Hershner *et al*., 2007).

Biological Diversity and Ecosystem Functioning

The concept of biodiversity is closely intertwined with the organizational hierarchy of biological systems and complex ecosystem functioning, including some ecological processes that affect human health. Biological diversity, or **biodiversity** as it often called, refers to the organismal variety at different levels of the organizational hierarchy, as well as **genetic diversity** among individual organisms (Grifo and Rosenthal, 1997; Chivian and Bernstein, 2008). Ecosystems with greater numbers of different species, and/or species populations harboring greater differences in their genetic makeup, are said to have greater biodiversity.

Ecosystems that retain higher levels of biological diversity (that is, that are more ecologically intact) often retain superior air, water, and soil quality, and regulate pathogens more effectively. Moreover, greater biological diversity makes ecosystems more resilient and better able to assimilate environmental stressors, such as physical restructuring, invasive species, extreme weather events, over-harvesting, or pollution (Folke et al., 2004). Overall, such consequences of greater biodiversity offer numerous benefits for human health.

Biodiversity is unfortunately eroding at unprecedented and alarming rates, largely through the degradation of ecosystems (especially tropical forests), species extinctions, and the reduction of genetic diversity within species. Ecologists have documented that among higher groups of organisms (such as birds, mammals, reptiles, and amphibian species), whose status can be relatively well monitored (in contrast to the millions upon millions of invertebrate species), species are now being extinguished due to human activities at a rate at least a thousand times faster than new species are being created.

COMMUNITIES AND SPECIES

Community ecology focuses on the determinants of the number and composition of species in an ecological community. These determinants include resources, space, species-specific characteristics, and inter-species interactions.

Assembling communities

The amount of space in a habitat plays a key role in determining the number of species present. This is described as the **species-area relationship** (Figure 1.9). According to **Darlington's Rule**, a ten-fold increase in the size of a habitat approximately doubles the number of species (Rosenzweig, 1995). This relationship helps explain why shrinking habitat reduces the number of species, which then alters species composition and threatens biodiversity. As biodiversity in a community declines, so too does resilience and the ecosystem's functional capacity.

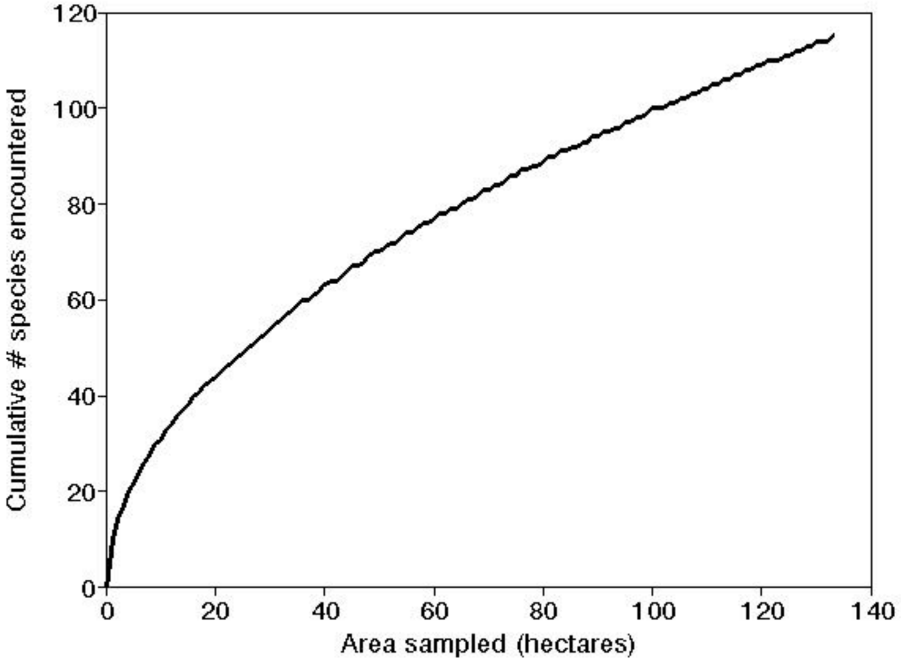

Figure 1.9 – Species-area curve.

As the total amount of space available to an ecological community changes, so do two other important environmental variables. One is the amount of resources available to support a viable population (*i.e.* one whose demographic and genetic assets ensure long-term persistence). The second is the variety of such resources, or **habitat diversity**. Clearly, since larger areas are likely to incorporate greater quantities of any resource, they can support bigger populations. A large and geographically dispersed population ensures against any number of natural and human threats to species survival. Greater resource diversity translates into a greater number of species that a habitat can support.

The notion of the particular needs of a species, which are the unique set of conditions to which it is adapted, as well as its role in the community, is termed **niche**. Metaphorically speaking, a niche is like the occupation of a species, while its habitat is like its address. The concept of niche is central in ecology: This notion links community ecology and population ecology, and is also critical to evolutionary biology. A species niche is molded through natural selection over evolutionary time, and dynamically adjusted through physiological and/or behavioral adaptations. The driving forces for evolutionary change are abiotic factors, along with biotic factors including competition, predation, parasitism, and disease.

The biotic circumstance of a species is a particularly important aspect of niche theory, in which the **competitive exclusion principle** comes into play. This principle states that no two species can occupy the same niche. In a classic example, ecologist Robert MacArthur found that five species of wood warblers—insect-eating birds that live in coniferous forests—occupied distinct niches within the same trees (Figure 1.10). Ecologists have found that in nature, as well as in the laboratory, when the populations of two species are forced to exploit the same resource, one species eventually eliminates the other through direct interference, more efficient resource use, or both.

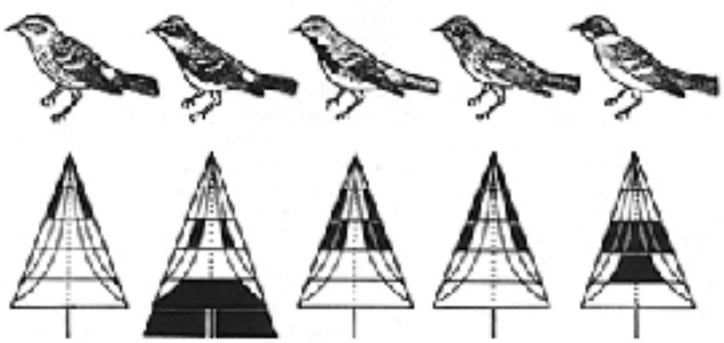

Figure 1.10 – MacArthurs warblers, from Ehrlich *et al.* (1988). MacArthur found that different warbler species tended to allocate their time to different parts of the tree—one toward the outside of the top, another mostly around the middle interior, and so on. In this diagram, the zones that accounted for 50 percent of the birds' feeding activity are blackened.

Predators, parasites, and disease all play important roles in determining the presence or absence of a species in a community. Competition is an especially powerful factor in determining the composition of communities when the extent of available habitat is limited. This helps explain why large islands can support more species than small islands (Figure 1.11); The greater the options for dividing up the available space and resources (such as food, shelter, and breeding sites), the larger the number of species that can be supported. Also, structural diversity is generally a good surrogate for habitat diversity. Thus, tropical forests and coral reefs, with their intricate architectures, tend to have very high numbers of species.

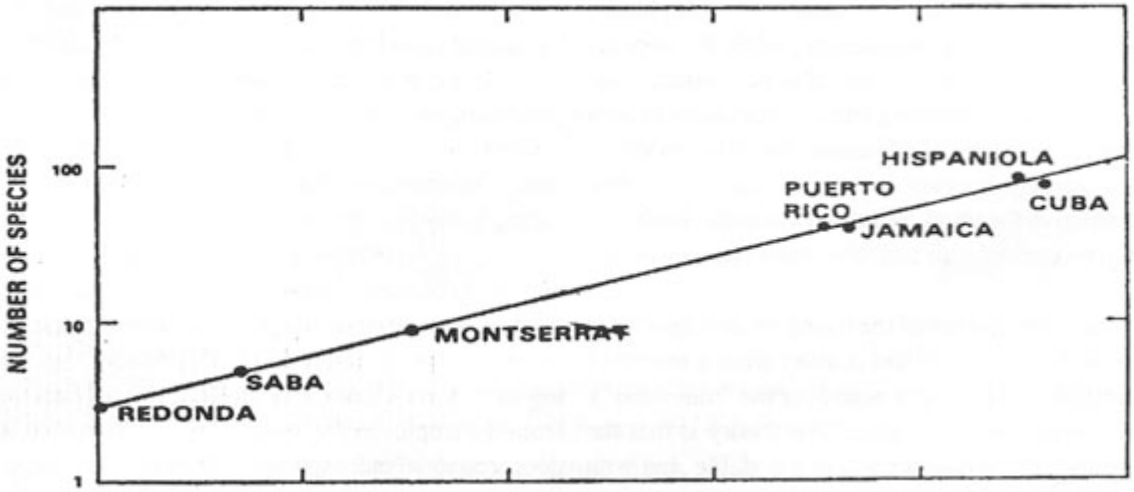

Figure 1.11: A species area plot showing the number of different species of amphibians and reptiles found on seven West Indies islands of different sizes, from MacArthur and Wilson (1967).

Besides the area effect just described, the species numbers on islands also often exhibit a distance effect, in which more remote islands tend to have fewer species. The distance effect is especially important when distances are great (as in the case of oceanic islands) or when the species of interest are poor dispersers. While most forest birds can easily fly across moderate expanses of open water, some species are behaviorally resistant to crossing even small expanses of uninhabitable land or water. Yet given the vastness of time and the numerous accidents and contingencies that occur, even the most remote islands assemble communities surprisingly rich in species, even including relatively poorly dispersing species.

A classic case is Krakatau, an island in the Indian Ocean completely sterilized by a volcanic explosion in 1883. In less than a century it had been recolonized by hundreds of plants, invertebrate, and vertebrate species. In addition to “volunteer” immigrants, storms blew birds off course and “rafts” of vegetative debris floated ashore carrying invertebrate species as well as small mammals, reptiles, and amphibians. As the island filled up, untold competitive, predator-prey, and parasite-host relationships unfolded as species sorted out their roles. This “sorting out” may include some populations being cut from the team, so to speak.

As alluded to above, the presence of habitat that includes the resources for a particular species niche is no guarantee that the species will survive. There must also be a large enough habitat area to ensure survival given the vicissitudes of abiotic and biotic circumstances over time. Usually, insurance against chance events of devastation (such as storms or disease) requires that multiple populations exist, as a bet-hedging “strategy.” Even long-established island and/or continental communities experience regular extinctions, especially in smaller islands or areas where bet-hedging opportunities are few. However, in stable ecosystems populations can be kept “topped up” over the long term with the ongoing arrival of new immigrants.

Piecing these facts together led to one of most important ideas of modern ecological science, the **equilibrium theory of island biogeography**. This theory by Robert MacArthur and E.O. Wilson (1967) points out that the number of species in an isolated place can be described in terms of the rates of immigration and extinction, as shown in Figure 1.12.

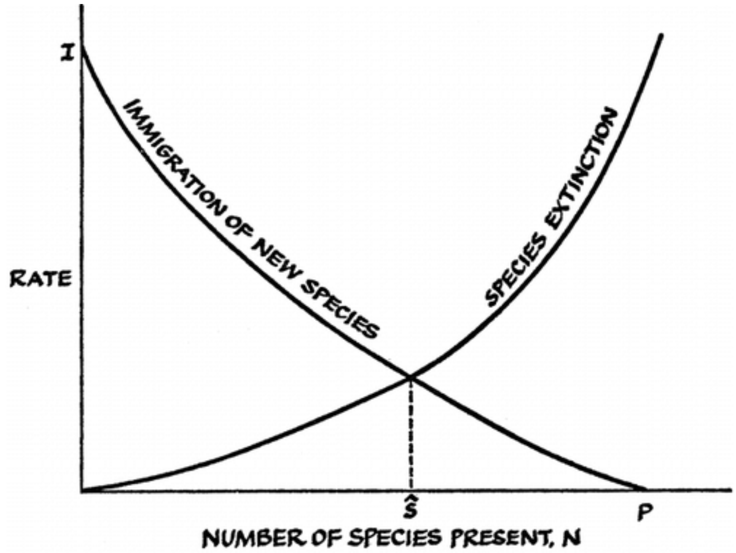

Figure 1.12: Population equilibrium in island biogeography. This simplified diagram charts the immigration rate for new species and the extinction rate for established species. The intersection defines the equilibrium species number. From McArthur and Wilson (1963).

Importantly, this theory does not apply only to true islands; It applies to ecosystems in general, whether true islands or “habitat islands” represented by patches of one kind of habitat. For example, forest patches within a distinct landscape such as grassland, cropland, or city are ecosystems that operate according the island biogeography theory. So, this theory also applies to patches of land that are cut off from other patches by highways or other human-made barriers. As land is fragmented, increasingly small and isolated fragments can become functional islands.

Disassembling communities

An equilibrium number of species is maintained in a community only if the habitat remains intact and a pool of potential immigrants exists within dispersal distance. MacArthur and Wilson anticipated that neither of these conditions exists for long, especially in a world where the loss of natural habitat has been accelerating. Later, others began investigating the patterns and processes involved in the disassembly of communities. The breakdown of community relationships due to habitat loss or other stresses is not fully understood. However, some effects are clear.

The species most vulnerable to habitat loss and degradation are those at high trophic levels, especially predators. Examples include mammals such as cat, dog, weasel, and mongoose, as well as raptors such as hawks and eagles. As these species decline, the principal effect is reduced population control of prey species. As a result, prey species such as deer, antelope, pigs, and rodents often increase in abundance.

This loss of “top down” control results in a number of consequences for ecosystem functioning, which have particular implications for human health. These stem from a tendency toward “hyper-abundance” of animal populations at lower trophic levels. With predation reduced, primary consumers overgraze available vegetation and create imbalances within ecosystems that undermine the normal regulation of pathogens and disease. For example, when herbivore species overgraze or otherwise disturb vegetation cover they may cause soil erosion and disrupt the normal capture and filtration of materials in runoff. These enter streams, rivers, and ultimately lakes, reservoirs, and coastal waterways. This can result in chronic as well as acute episodes of non-point source "releases" of toxins and pathogens into drinking water and recreational waters. Thus, pollution of the environment by toxins, pathogens, and excess nutrients can result from loss of filtering, recycling, and digestion ecosystem services provided by vegetation and healthy community relationships.

A second consequence of disturbances to ecosystem community equilibrium is enhanced pathogen transmission. Species achieving abnormally high population densities are more prone to become pathogen reservoirs when they exceed critical threshold densities, and may be more likely to contact humans and spread disease when they are hyper-abundant. Lyme disease is a prime example (see Box 1.4).

<START BOX 1.4>

Box 1.3: Landscape Change and Lyme Disease

Lyme disease in North America is a classic case of how ecological changes can play a primary role in the emergence of an infectious disease, and especially exemplifies how habitat alteration affects a pathogen's transmission cycle.

Lyme disease is caused by pathogenic bacteria (of the genus *Borrelia*), which are transmitted to humans and other mammals by a tick **vector**. Causing fever, rashes, and fatigue, as well as more serious joint, heart, and nervous system damage when left untreated, Lyme disease is especially prevalent in the Northeastern region of the United States. In many parts of the Northeast, deforestation and suburban sprawl have produced a fragmented landscape, which in turn has caused incomplete assemblages of species at upper trophic levels. Such reduced predation, combined with reduced habitat availability, has led to abnormally high densities of prey species such as deer and rodents. At such high densities, deer and rodent populations function as more efficient reservoirs for Lyme disease bacteria. For example, White-footed Mouse (*Peromyscus leucopus*) and White-tailed Deer (*Odocoileus virginianus*) have become especially hyper-abundant in the Northeast. In addition, these species are highly competent pathogen **hosts** (*i.e.* they are especially capable of transmitting the infecting bacteria from themselves to a tick vector such as the common Black-legged Tick, *Ixodes scapularis*). Thus, tick populations flourish with plentiful hosts upon which to feed, and Lyme disease bacteria flourish with plentiful host reservoirs and easy transmission from host to host via ticks. The result has been increased incidence of Lyme disease in humans, due ultimately to ecosystem community disassembly by altered landscapes, along with increased human populations living near edge habitats.

<END BOX 1.4>

THE ECOLOGY OF POPULATIONS

The major subdiscipline of population ecology is in many ways at the core of all ecological science. The ecological definition of a **population** is "a group of interbreeding individuals in a particular locality." The processes and mechanisms operating at the population level determine the abundance and distribution of species, the outcome of which are communities and ecosystems!

Ecological science has long been interested in precisely how a population size changes, including the mathematical details of such life history parameters as birth rate, death rate, reproductive age, and longevity. In many cases, it is not clear why the numbers of a particular organism are what they are at any given time. Yet, this understanding is important not only for forest, wildlife, and fishery management, but also for the control of organisms responsible for human, animal, and plant diseases.

The elemental population processes are births, deaths, immigration, and emigration. The largely academic question about “the abundance and distribution of species” can be more simply restated as “how does the environment affect these population-based, or demographic, parameters?” Ultimately, the answer will explain why a species occurs in some places and not in others. Knowing such an answer can be of critical public health importance when managing the abundance and distribution of beneficial and/or harmful species. The latter include host and vector populations responsible for most of the re-emerging and newly emerging infectious diseases.

The potential for a species to increase in numbers at a fantastic rate is perhaps best demonstrated by the Earth’s human population (Figure 1.13). This can be juxtaposed with examples of species undergoing catastrophic population declines, which have become near-daily news items. Historically, the American Passenger Pigeon (*Ectopistes migratorius*) and American Bison (*Bison bison*) provide useful examples of species extinctions. Both numbered in the millions before being extinguished in the wild by habitat loss and hunting in the 19th century. The Passenger Pigeon never recovered and the last individual died in a zoo. The remaining American Bisons have since been reintroduced, but only as managed populations to national parks and some private lands. In these cases of humans, pigeons, and bisons, the causes of change in population size are fairly evident. However, the population dynamics of most species, including the underlying mechanisms responsible for the abundance or scarcity of a particular species, are usually more subtle and complex. The basic properties of population growth and regulation described in Box 1.5 are a sampling of the most fundamental aspects of population ecology.

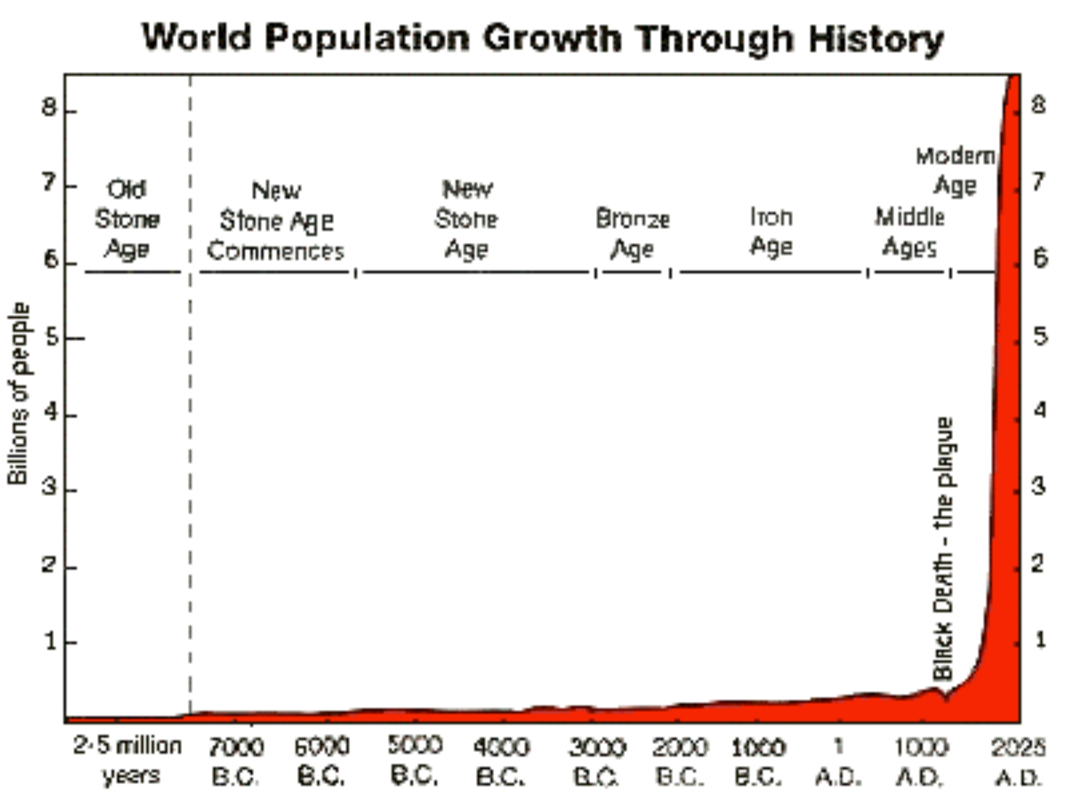

Figure 1.13: Human population growth since prehistoric times; an example of a steep exponential population growth curve.

There is an important distinction between the role of other species and the role of the physical environment in population regulation. These biotic and abiotic factors are associated with two different modes of population regulation: **density-independent regulation** and **density-dependent regulation**. Abiotic factors such as temperature, humidity, and rainfall operate independently of population size, while biotic factors such as competition, predation, and parasitism tend to have greater impact with greater population density.

Mosquitoes that act as disease vectors provide a useful example of these population ecology concepts in practice. In tropical and subtropical regions of the Americas, the geographic distributions of diseases such as dengue fever, yellow fever, and malaria largely follow the distributions of *Aedes* and *Anopheles* mosquitoes. Species of these genera are typically most abundant in wet tropical areas where there is plentiful rainfall, numerous natural and/or artificial water containers, and ideal temperature and humidity. Such abiotic factors provide optimal conditions for mosquito growth and survival. In contrast, mosquito populations diminish, and sometimes disappear altogether, at higher altitudes and latitudes where breeding, egg laying, and larval growth are limited by low temperature, low humidity, and/or scant rainfall. However, even in places were the abiotic conditions are optimal, biotic factors can control mosquito population sizes. For example, both adult and larval mosquitoes are subject to competition, predation, and parasitism. Indeed, these biotic factors can play a very important role in regulating mosquito numbers: spraying of non-specific pesticides intended to control mosquito numbers can often actually result in greater mosquito abundance by eliminating the suite of natural predators, competitors, and parasites that keep a population in check. That is, pesticides can negatively disrupt the biotic factors that normally regulate the density of mosquito populations (Ellis and Wilcox, 2009).

<START BOX 1.5>

Box 1.5: Population Growth and Minimum Viable Populations

Population ecology began in earnest in the early 19th century, after Thomas Malthus published his famous volume, *An Essay on the Principle of Population* (1798), in which he focused attention on the problem of population regulation and the limits to population growth imposed by the environment. Malthus was famous for pointing out the "geometric tendency" of accelerating human population increase, in contrast to the slower growth and limited nature of the food supply. The ideas of Malthus inspired several generations of scientists whose work ultimately provided the foundation of modern population ecology, as well as scholars and popular authors writing about the environmental carrying capacity. **Carrying capacity** is the population size that can be supported in a given area, within the limits of available food, habitat, water, and other needed resources.

The fundamental principles of population growth and regulation were later formalized using calculus by the physicist Alfred Lotka (1925): In general, the size of a population can be expressed as

$$dN/dt = f(N)$$

which simply states that the rate of change in the number of individuals (N) over time (t) depends in some way on the number of individuals present. For an ideal population, this becomes

$$N=e^{rt}$$

which is the **exponential equation for population growth**, where r represents the unrestricted rate of increase per individual (birth rate minus death rate). Figures 1.13 and 1.14(a) show growth curves for populations increasing in size exponentially.

However, in the real world of resource limitations, population growth is eventually limited. For example, Malthus reasoned that food production could only increase geometrically and this ultimately meant eventual starvation and deprivation for human populations that had increased exponentially.

Population growth of organisms, including humans, is potentially limited by many factors besides food. Lotka's exponential expression was therefore expanded to acknowledge these limiting factors by adding a second term:

$$dN/dt = rN(K-N/K), \text{ or}$$

$$N=K/1+e^{-rt.}.$$

This is the **logistic equation for population growth**, where K represents carrying capacity. As shown in Figure 1.14(b), population size increases rapidly at first, but then slows as it approaches the value of K, producing a sigmoid-shaped curve. This is the simplest possible model of density-dependent population regulation.

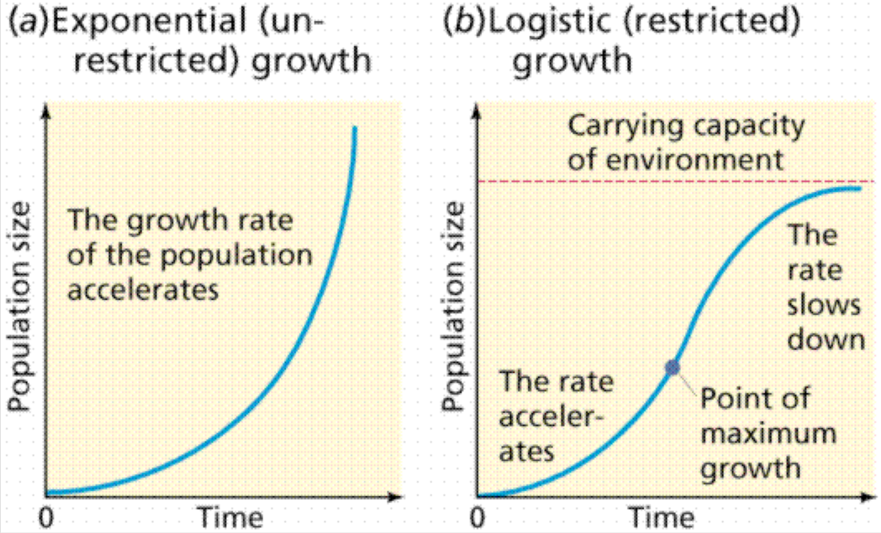

Figure 1.14: Exponential (a) and logistic (b) curves describing population growth.

However, real populations rarely increase in size smoothly and then stay at a particular level. Rather, because environmental conditions are never constant, including the abundance of food and other resources, population sizes fluctuate around their carrying capacity. These fluctuations occur as a result of factors whose effects are independent of population size, such as weather and catastrophic events.

A **viable population** is the demographic and genetic profile necessary for a population to persist over time, in the face of chance events and environmental change (Morris and Doak, 2002). The lower limits of a viable population can be viewed as a threshold line something like K of the logistic curve, except that it operates in the opposite way: Instead of a population being elastically pulled below a threshold K where it regains a positive rate of change, populations that dip below their viability threshold continue in a “downward spiral”. For example, a population might be initially reduced by overharvesting or habitat destruction. Once below this threshold, factors such as chance events in the lives of individuals, as well as the loss of genetic variability that reduces capacity to evolutionarily respond to environmental changes, abruptly reduce the probability that the population will persist for many generations. This threshold is highly species- and situation-specific. However, for most vertebrate species it is believed to be on the order of several hundred to over a thousand individuals. Note that population sizes of large bodied wildlife species in national parks and other protected areas are often smaller than this, which does not bode well for their future!

<END BOX 1.5>

Most species consist of more or less discrete “local” populations occupying areas of suitable habitat across a limited geographic range. The exceptions are large bodied animals, especially predators such as lions and bears, and ocean predators such as sharks and swordfish, that are habitat generalists and whose individual home ranges encompass relatively large areas.

We often refer to a population loosely, to describe the all individuals of a species in a circumscribed area. However, when the area of interest is large relative to the typical dispersal distance of an individual of the species in question, “population” is technically a misnomer: Ecologists often find that such “regional populations” actually consist of multiple local populations separated by gaps of habitat less suitable to their needs. The term **metapopulation** is used to describe such a population structure.

Moreover, habitat patches tend to vary in terms of resource quality and quantity. The bigger and better that a habitat patch is in this regard, the more robust the population residing there will be. The more robust populations tend to “export” their excess individuals, while the less robust populations occupying the smaller and less productive patches tend to be recipients of dispersing individuals. The flow of immigrants from “source” patches may be the only reason a patch of marginal habitat even has a population which behaves as a “sink”. These source-sink dynamics are thought to be fundamental to understanding why a species (including pest species) persist in some landscapes and not others (Hanski, 1991).

LANDSCAPES AND LAND USE CHANGE

A convenient way to grasp systemic changes that operate and link processes across scales—from ecosystem to populations—is through the perspective of landscape ecology. Landscape ecological studies focus on the structure of the landscape, particularly on spatial patterns uncovered using remote sensing and geographic information systems. These patterns can be studied analytically using quantitative methods to assess findings that are biologically meaningful.

The composition and arrangement of landscape features such as natural and anthropogenic vegetation cover, and human land uses (such as for urban, agriculture, watershed, and conservation) have a large and often unappreciated effect on human health and well-being. Examples range from altered landscapes that contribute to environmental disasters such as Hurrican Katrina, to landscape features that influence the environmental mobility and fate of toxins and pathogens. In fact, the resurgence of existing infectious diseases, as well as the emergence of new ones, can largely be attributed to the transformation of landscapes on a global scale (Patz *et al*., 2004).

A concept associated with landscape ecology with special relevance to human health is **landscape heterogeneity**. Heterogeneity refers to irregular spatial patterning, including variability in the distribution of habitat types. For example, natural landscapes tend to have greater heterogeneity than agricultural landscapes which often consist of relatively large areas of only one kind of land cover (*i.e.* a particular crop). In general, heterogeneity tends to constrain ecological processes involving energy and material flows, including population growth and dispersal of organisms. For example, pest outbreaks that otherwise would be spatially limited in a heterogeneous landscape, instead readily spread and may even become catastrophic within a homogeneous agricultural monoculture.

How the landscape patterns of natural vegetation, especially forests, change with the expansion of human land uses across a regional landscape has become an important area of applied ecological research that meshes with community ecology. As discussed in Box 1.4, the landscape perspective is especially valuable in understanding how land use patterns, including human-created fragmented forests, affect infectious disease epidemiology.

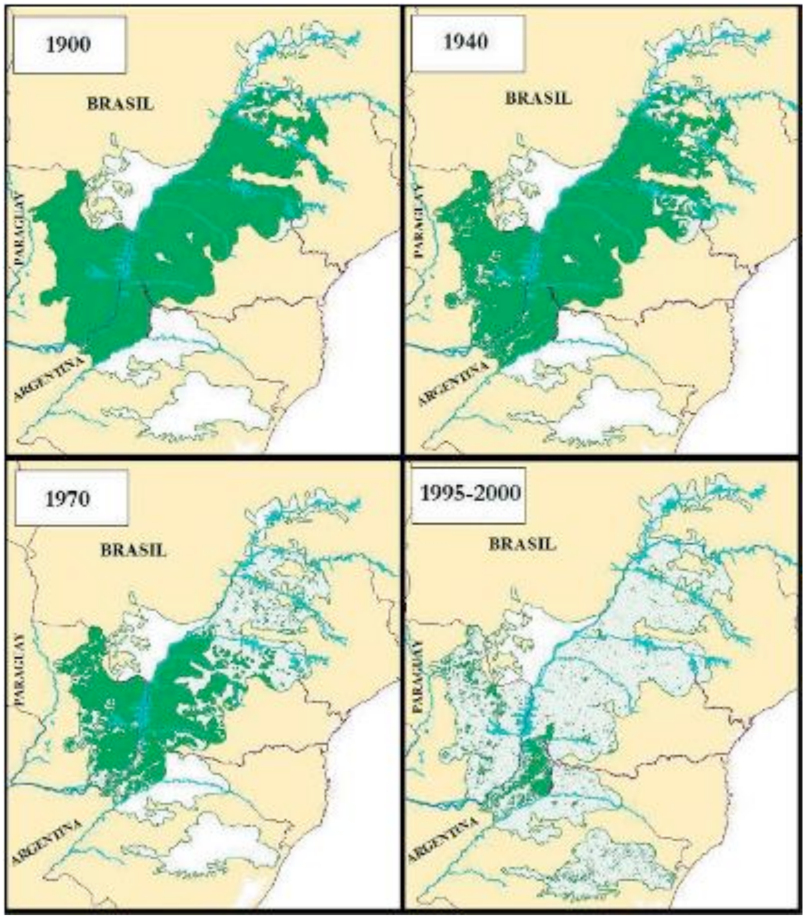

Figure 1.15: Forest fragmentation in the Upper Paraná region, 1900-2000, from Di Bitetti *et al.* (2003).

With urbanization, suburban sprawl, and expansion of cropland, the clearing of natural habitat, especially wetlands and forests, has been pervasive and dramatic in recent decades. The scale and intensity of landscape change in the world's tropics, driven by the demand for land and resources fueled by human population growth and globalization, has been historically unprecedented in recent decades (Fig. 1.15). The associated process of forest fragmentation includes not only the loss of total habitat area available to species, but also the ecological isolation of remnant habitat patches. Such landscape patchiness can have profound negative consequences for biodiversity and human health (Laurance and Bierregaard, 1997). Overall, these processes in which urbanization, agricultural intensification, and habitat alteration interact to bring about ecological changes at genetic, population, and landscape levels, and which results in pathogen emergence, are illustrated in Figure 1.16 and are discussed further in Box 1.6.

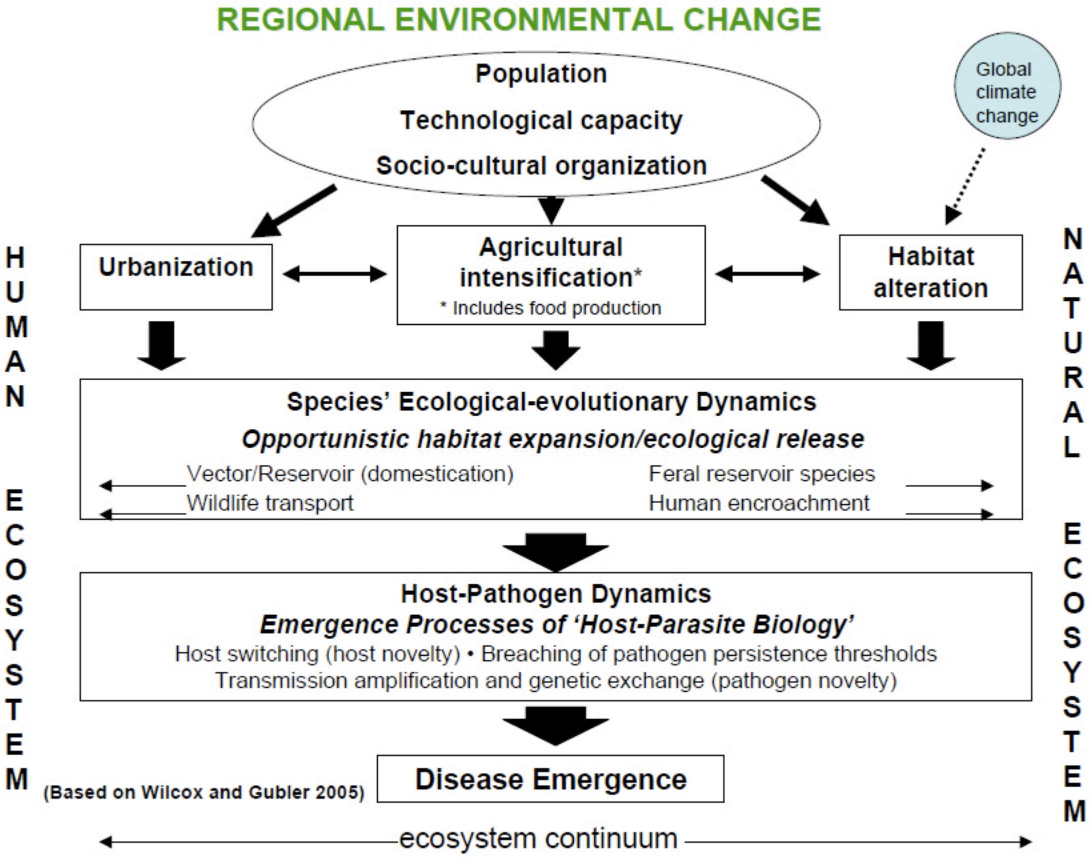

Figure 1.16 –The interaction of urbanization, agricultural intensification, and habitat alteration, from Wilcox and Gubler (2005).

In the larger scheme, the ecological phenomena associated with habitat losses are only part of the environmental transformation that occurs as agricultural activity and urbanization expand and intensify. The hydrological cycle and biochemical cycles are modified as well. Also, with intensified agriculture, industry, and other human activities come increasing waste streams: gaseous pollutants and air pollution, solid waste, and toxic and hazardous wastes.

<START BOX 1.6>

Box 1.6 – Ecology and Emerging Infectious Diseases

The resurgence (or re-emergence) of “old” infectious diseases and the emergence of new ones, together referred to as **emerging infectious diseases** (EIDs), represent one of the most significant environmental health challenges today. In 2002, an estimated 26% of deaths worldwide were attributable to infectious and parasitic diseases (Fauci, 2005); 24% of the global burden of disease was caused by infectious diseases (World Health Organization, 2004). The role of ecological science is increasingly being recognized as critically important in research, intervention, and control of EIDs. As Wilcox and Colwell (2005) point out, the vast majority of EIDs recognized by the World Health Organization and the United States Center for Disease Control are **zoonotic** (*i.e.* transmitted from animals to humans). It follows that environmental factors play a key role in disease emergence. Host life cycles, pathogen transmission dynamics, and therefore disease incidence, are largely a function of ecological factors.

What is responsible for the current surge in EIDs? The 20th century was a landmark in the control and eradication of infectious diseases that had afflicted people throughout human history. New drugs, vaccines, insecticides, treatments, and control strategies reinforced public health programs already in place and provided the tools necessary to control many of the worst diseases. These diseases included smallpox, typhus, yellow fever, malaria, dengue fever, and others. By the late 1960s, the “war on infectious diseases” was declared won by leading experts in the field and by the Surgeon General of the United States.

However, two sets of factors contributed a startling reversal of this situation, which began to appear just as the above premature claims were being made. These were a shift in attention and resources away from infectious disease prevention, and explosive human population growth. Environmental change in the form of uncontrolled and unplanned urbanization, intensification of agricultural production, deforestation, and biodiversity loss has all resulted from the human population explosion. Thus, these two factors, along with the accelerated movement of people, goods, and thus pathogens—locally, regionally and globally—have been major and inter-related drivers of the re-emergence of epidemic infectious diseases (Gubler, 1998; Wilcox and Gubler, 2005).

Old diseases that were once effectively controlled have or are now beginning re-appear in epidemic as well as endemic forms. These EIDs include dengue fever, Japanese encephalitis, West Nile virus, yellow fever, measles, plague, cholera, tuberculosis, leishmaniasis, and malaria. In addition, numerous newly recognized diseases have begun to cause epidemics, such as HIV/AIDS, the hemorrhagic fevers, hantavirus, arenaviruse, avian influenza, Hendra and Nipah encephalitis, severe acute respiratory syndrome (SARS), Lyme disease, Chikungunya, ehrlichiosis, and others. In addition to some of the ecological factors mentioned above, evolutionarily-derived resistance of pathogens to antibiotics and insecticide resistance in mosquitoes has also played a role in the emergence and re-emergence of infectious diseases as a global public health problem (Gubler, 1998; 2001; Smolinski *et al.,* 2003).

<END BOX 1.6>

Thought Questions

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