1 *Biodiversity change*

1.1 Biodiversity

At the beginning of the Holocene, around 12,000 years ago, the vast majority of terrestrial and marine systems were barely impacted by humans. Today, there is arguably no ecosystem on earth that is not impacted by humans to some degree. All ecosystems are affected by anthropogenic climate change. Most have been altered by changes in land use and land cover, or have been impacted by the off-site effects of such changes. Of the fourteen major terrestrial biomes only tundra and boreal forests have been left relatively intact. All others have been transformed to some degree, and in six (temperate grasslands, Mediterranean forests, tropical dry forests, temperate broadleaf forests, tropical grassland, and flooded grasslands) the area converted to agriculture, forestry, or urban industrial, commercial, domestic, or other activities currently lies somewhere between a half and two-thirds (Millennium Ecosystem Assessment 2005a). Much of the earth's biodiversity now lies outside natural systems, in systems created or at least heavily impacted by people.

The term biodiversity refers to the diversity of genes, species, and ecosystems (Wilson 1988). Many people use the term in a more restricted way to mean the diversity of species in wildlands, but it goes far beyond that. It encompasses the variety of species used in human production and consumption activities: the food we eat, the biologically derived fuels and fibers that support production of a wide range of commodities, and the varying landscapes that we access for inspiration, recreation, and learning. It encompasses the genetic diversity of cultivated crops, of crop pests, of wild crop relatives, and of weedy species. It encompasses the range of diseases that affect humans, animals, and plants, and the species used to counter those diseases – traditional medicinal plants and the plants used as the source of modern pharmaceuticals. It encompasses the species that underpin biotechnology-based industries as well as those that support more traditional forestry and fisheries.

Biodiversity change reflects the fact that we have redesigned the world around us. During the Holocene the human population is thought to have grown from around one million to around seven billion. It is expected to stabilize at something below ten billion towards the end of this century. That growth has been possible both because we have appropriated an increasing share of the earth's ecosystems for our own use, and because we have changed the species in ecosystems converted for our use in ways that have dramatically improved both the quality and quantity of biomass we have been able to extract. The process has not been smooth. Moments of innovation have punctuated periods of stasis. Whether population growth was caused by or caused such moments of innovation is a matter of debate, but during the Holocene there has been a strong association between the two. The second half of the twentieth century was such a moment of innovation. The MA concluded that within the last four decades of the century, wheat yields in developing countries rose by 208 percent, rice yields by 109 percent, and maize yields by 157 percent (Millennium Ecosystem Assessment 2005a). While there is increasing concern that agricultural productivity growth has not been maintained at levels that will allow this to continue (Fuglie 2008; Piesse and Thirtle 2010), the transformation of crop genetic diversity has been hugely important in accommodating the pressures that led Paul Ehrlich to warn that the world population growth was outpacing the production of food (Ehrlich 1968).

In much the same way, the parasites, fungi, bacteria, and viruses to which people are exposed reflect the choices they make about where to live, whom to conquer, and whom to engage in commerce, how to structure their biophysical environment, and so on. Of course not all illnesses are due to microorganisms, and not all disease controllers are biotic, but many are. This makes the choices that affect our exposure to diseases or that harness disease controllers a part of the biodiversity change problem. Anthropogenic biodiversity change is a "directed" process. It is not random. People choose the species they wish to associate with. They deliberately simplify ecosystems to make them more "productive" or less "harmful." People have transformed many of the earth's ecosystems to increase the abundance of domesticated species – the source of foods, fuels, and fibers – and to reduce the risks posed by pests and pathogens. In so doing they have destroyed habitat for other species, and extirpated competitor species such as weeds, pest species such as bird or insect predators, and disease vectors (Scherr and McNeely 2008). In their place people have introduced cultivated crops, livestock strains, and a host of commensals (Williamson 1996).

People have also created entirely new ecosystems with new combinations of species. The Holocene is the age of agriculture, but it is also the age of urbanization. When the first Levantine cities were established – around 7000 BC – most of the people on earth were still nomadic. Today, a majority of the earth's human population lives in cities: constructed ecosystems with a completely different mix of species than occur anywhere else. Moreover, every city is a node in a communications web that is increasingly tightly connected globally. The net result is what Jeff McNeely has termed "The Great Reshuffling" (McNeely 2001). Species have been moved around the world in ways and at levels that are wholly unprecedented. Sometimes deliberately, sometimes not: sometimes harmfully, sometimes not.

I write these lines from the small coastal town of Baiona in Galicia, in northwestern Spain. The town celebrates the fact that this is where the first of Columbus's vessels to return to Europe, the *Pinta*, made landfall on March 1, 1493. For the townspeople this made them the first in Europe to learn of the existence of the New World. But it also marked the completion of the first move in what has come to be called the Columbian exchange: the transmission of a range of species across the Atlantic first through explorers, then through the conquistadores, and later through trade (Crosby 1972).

The Columbian exchange involved a wide range of species including livestock, crops, ornamental and medicinal plants. Some have transformed agriculture around the world. Crops introduced from the New World include, for example, maize (*Zea mays*), potato (*Solanum tuberosum*), tomato (*Solanum lycopersicum*), rubber (*Hevea brasiliensis*), cacao (*Theobroma cacao*), and tobacco (*Nicotiana rustica*). Crops introduced to the New World include wheat (*Triticum spp.*), rice (*Oryza sativa*), coffee (*Coffea*), and fruit such as oranges (*Citrus sinensis*), banana (*Musa*), and mango (*Mangifera*) (Crosby 1972, 1986). The Columbian exchange also involved an exchange of diseases between the Old and the New Worlds that has had a lasting impact on both. Common Old World diseases that had devastating effects on the human populations of the New World included the bubonic plague, cholera, influenza, leprosy, measles, scarlet fever, smallpox, typhoid, typhus, and yellow fever. In the century after Columbus's first voyage, the population of central Mexico, for example, was reduced to little more than 5 percent of its pre-Columbian levels by the effects of smallpox, influenza, measles, and typhus. Many of the social and political systems of the Americas were effectively destroyed as populations collapsed. In exchange, the Old World was introduced to syphilis and its close relatives, bejel and pinta, as well as Chagas disease (Crosby 1972; McNeill 1977).

The Columbian exchange may have transformed the world, but it was also just one step in a longer, punctuated process of directed biodiversity change. The Columbian exchange was not the first time species had been dispersed by human agency. The bubonic plague, the suspected cause of the Black Death in Europe in the fourteenth century, had been introduced along the silk route – the main trade route between China and Europe. It led to recurrent outbreaks of plague for the next three centuries that resulted in the deaths of up to half the population of affected cities (Herlihy 1997). Indeed, by the time of Columbus's first journey to the Americas, Europe had experienced three waves of biological exchange. The first was associated with the arrival of the Neolithic complex from southwest Asia, the second came with the expansion of the Roman empire, and the third with contacts between Europe and the Islamic world between 1000 and 1350 (McNeill 2003). In more recent times the introduction of mass air travel has sharply reduced the time it takes for emerging diseases such as HIV/AIDS and severe acute respiratory syndrome (SARS) to spread, dramatically increasing the number of people who are susceptible (Tatem, Rogers and Hay 2006a; Tatem, Hay and Rogers 2006b).

The dispersal of species has had profound effects on human wellbeing, but it has had equally profound effects on ecosystems. A recent study of the level of plant invasion in different regions, for example, calculated the proportion of the most widely distributed plant species that had been introduced. It found that aliens accounted for 51.3 percent of the 120 most widely distributed plant species in North America, 34.2 percent in Chile, and 29.7 percent in Argentina. The result has been the homogenization of the floras of these regions (Stohlgren *et al.* 2011), and the transformation of the functioning of affected ecosystems.

The common threads in the process of directed biodiversity change are the search for foods, fuels, fibers, and other products deriving from living species; protection against pests, pathogens, and predators; and the dispersal of species as a byproduct of the progressive integration of human societies. The search for foods, fuels, and fibers is what has led to the fragmentation and loss of habitat, to the pollution of both aquatic and terrestrial ecosystems, and to the harvesting of wild-living species. Protection against pests and pathogens is what has led to the use of pesticides and antibiotics, the elimination of "nuisance" species and the disruption of species mobility through "cordons sanitaires." The dispersal of species as trade goods themselves, or as passengers on trade goods, is what has led to the problem of biological invasions.

Anthropogenic biodiversity change is driven by our interest in altering the mix of species around us to produce the goods and services we want, to reduce our exposure to pests and pathogens, to foster domesticates, and to counter wild predators or competitors. It is not enough to lament this process. We need to understand why people make the choices they do, what they think they are gaining and losing, and what gains and losses they ignore in the process. We need to acknowledge that much is at stake: the food people eat, the fuels they burn, the fibers they use to clothe and shelter themselves, their vulnerability to storms, floods, drought, fire, and disease. We need to recognize that if the choice is to clear land to grow crops or to starve people will clear land to grow crops. We should not sit in judgment of that choice. It follows that the problem of biodiversity change is about the way that people's choices are structured by the biophysical world and the society in which they find themselves. What people do and do not know matters. The technologies available to them limit both their production and consumption possibilities. Their understanding of the wider and longer-term consequences of their actions limits their ability to take these into account. But so do the social rules and norms that guide their behavior, and the income, wealth, rights, and obligations that constrain their options.

The biodiversity at issue is the mix of all genes, species, and ecosystems that affect our wellbeing. It is the mix of species used to generate foods, fuels, fibers, and other commodities, or harnessed as inputs in biotechnology industries. It is the variety of pathogens behind diseases of humans, animals, and plants and the species used to counter diseases. It is the range of complementary species that insure us against the effects of environmental change, or the impact of extreme events. It is the genetic blueprint for future evolution on the planet. Biodiversity in all these senses affects human wellbeing. Sometimes the effect is quite localized and immediate. Sometimes it is global in reach and means more for the wellbeing of future generations than it does for the well-being of the present generation.

In every case, though, we can ask how human wellbeing is affected by a change in the variety of genes, species, or ecosystems. Few generalizations are possible. Two, however, stand out. First, more biodiversity is not always and everywhere better than less biodiversity. The progressive simplification of the world's ecosystems since Neolithic times to increase the production of foods, fuels, and fibers has underpinned every other mark of progress we have. It has enabled the specialization that lies behind productivity increases in every sector of the modern economy. At the beginning of the Neolithic revolution close to 100 percent of the population would have been involved in food production through hunting, gathering, or the beginnings of agriculture. At the beginning of the twenty-first century less than 1 percent of the population is engaged in these activities in many countries. In the same interval, control of the abundance of pests and pathogens along with enhanced nutrition has increased life expectancy at birth from around age twenty to age sixty-seven (ranging, in 2012, from forty-eight to forty-nine in a number of Sub-Saharan African countries to nearly ninety in Monaco) (World Bank 2012).

It is true that not every ecosystem service requires the simplification of ecosystems. A recent review of the evidence on the relation between biodiversity, ecological functioning, and ecosystem services found that biodiversity has a positive but saturating effect on ecosystem services that depend on biomass alone, such as carbon sequestration (Cardinale *et al.* 2012). For most services of interest to people, however, the optimal level of species diversity will be strictly less than the level of species diversity expected in a natural system. Indeed, that is the motivation for the simplification of ecosystems. Wherever people are interested in specific traits of plants or animals, they will eliminate species that do not have those traits, or that do not support species having those traits. The question to ask of modified systems is whether the extent to which they have been simplified is in the best interests of society, given its goals and resources. Within simplified systems intraspecific diversity may matter more than species diversity. Crop yields, for example, are generally increasing in intraspecific genetic diversity (Cardinale *et al.* 2012).

A second generalization we can make is that one of the main reasons for being concerned about biodiversity trends is the fact that we live in a risky world. This is not the only reason that biodiversity matters, of course. The myriad of life forms encountered in both terrestrial and marine environments have individual traits that we value for many different reasons. But the composition of species, and the genetic variation within species, matters because we live in a fluctuating environment. The diversity of species, like the diversity of financial assets in a portfolio, helps us negotiate a risky world. And how much diversity is needed within a portfolio of species depends both on the expected range of environmental conditions, and on the covariance in the response of distinct species to differences in environmental conditions. The greater the expected variation in conditions, and the less the covariance in species' responses, the greater will be the required diversity (Elmqvist *et al*. 2003). So, for example, yield stability increases with species diversity in fisheries, and resistance to invasive species and pathogens increases with species richness in plant communities (Cardinale *et al*. 2012).

There are, or course, very good reasons why people might not choose a portfolio of species, or of genes within species, that is in the collective interest. Much of this book is concerned with the factors that compromise decisions people make about the simplification of production systems and the conservation of protected areas: the incompleteness of markets (externalities), the public good nature of the benefits of biodiversity, and the effects of poverty and poverty alleviation. Because many of the benefits generated by the diversity of genes or species are jointly produced ecosystem services, and because many of these are not marketed, we may expect that decisions driven by markets for foods, fuels, and fibers will have unanticipated effects on co-produced services. Moreover, these effects will be widespread wherever co-produced services have the characteristics of public goods.

Since people's decisions are made in a social context, they are also hostage to the institutions constructed at many different levels. The social context includes our collective understanding of the world and of the consequences of biodiversity change. It includes our culturally formed preferences over states of nature, along with the social mores and norms that structure our behavior. It includes the legal and regulatory environment and the property regime that determine our rights and responsibilities. It includes the institutions we have created at local, national, and international levels to govern resources that lie in the public domain, and to address the consequences of the failure of markets to signal the true value of those resources.

This book is about the biodiversity change that has been one of the main consequences of the increasing dominance of humankind. People have altered their environment in ways that have been directly responsible for dramatic changes in the relative abundance of many species, including the local extirpation of many and the global extinction of some. For the most part these changes have been purposeful. People have deliberately chosen to convert habitat, to drive out pests and predators, to control harmful microorganisms, to promote domesticates and their symbionts, and to protect landscapes of special appeal. They have accepted that the growth of agriculture, forestry, fisheries, mining, and industry, the spread of cities, the development of roads, railways, dams, oil pipelines, and power transmission lines have had consequences for other species by reducing and fragmenting habitat, by diverting water, and by polluting air, soils, and water. Their choices may not always have been well informed. Sometimes decision-makers have ignored the costs of actions taken to alter the mix of species in some landscape. Sometimes they have simply misunderstood the consequences of their actions. But they have made choices nonetheless.

This is the real nature of the problem of anthropogenic biodiversity change. It is by far the most significant environmental problem confronting humanity. It dwarfs climate change, freshwater scarcity, particulate pollution, or any other of the environmental issues currently attracting attention. All biologically based production, all human, animal, and plant health management, and all biotic environmental regulation are affected by biodiversity change. More than that, since the global gene pool offers the blueprint for all future evolution on the planet, its erosion has consequences that potentially compromise all future generations.

1.2 The Holocene extinction

The MA reached many alarming conclusions, but none more so than this:

> Over the past few hundred years, humans have increased the species extinction rate by as much as 1,000 times over background rates typical over the planet's history . . . Some 10–30% of mammal, bird, and amphibian species are currently threatened with extinction. (Millennium Ecosystem Assessment 2005a)

Current rates of extinction are comparable to the most significant of the extinction events observed in the fossil record over the last 540 million years (Raup and Sepkoski 1986). Of these, the Cretaceous-Tertiary extinction event 65 million years ago saw 50 percent of all genera go extinct. The Triassic-Jurassic and Devonian-Carboniferous transition extinction events 205 and 360–375 million years ago respectively were of similar magnitude. Larger events at the Ordovician-Silurian transition between 400 and 450 million years ago, and the Permian-Triassic transition 251 million years ago, accounted for more genera – 57 percent and 83 percent respectively. Current rates of change in the numbers of species identified as being at risk of extinction may partly be an artifact of improvements in measurement and monitoring, but if they are anywhere close to reality, and if they are sustained in the centuries ahead, the final outcome of the Holocene extinction could be as severe as any of these.

Two things characterize the current extinction event. The first is its suddenness. All past events (including those induced by asteroid impacts) occurred over much longer periods of time. The second is that it is caused by a single species. It is due to human agency. The only species to have increased in either range or abundance are those that are valued by people, those that thrive in human-modified landscapes, and those benefitting from the establishment of protected areas. The stark result is that 12 percent of bird species, 23 percent of mammals, 25 percent of conifers, 32 percent of amphibians, and 52 percent of cycads are currently threatened with extinction (International Union for Conservation of Nature (IUCN) 2004; Millennium Ecosystem Assessment 2005a).

In recent years two papers have reviewed the status of vertebrates (Hoffmann *et al.* 2010) and selected other groups of species (Butchart *et al.* 2010). Motivated by an interest in checking progress towards the CBD's 2010 target to reduce the rate of biodiversity loss, both provide evidence that the extinction risks faced by these species are growing on very short timescales. Using the updated IUCN Red List of threatened species, Hoffman *et al.* evaluated changes in population trends and threat status since 1984 for 25,780 vertebrate species (all mammals, birds, amphibians, cartilaginous fishes, along with representative samples of reptiles and bony fishes) (Table 1.1).

They found that for every class of vertebrate assessed the net expected rate of species extinctions had increased in the period since the MA was undertaken (Figure 1.1). Over the whole period assessed they concluded that an average of fifty-two species of mammals, birds, and

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Table 1.1 *Percentage of species in each IUCN Red List category threatened for all vertebrates and all completely or randomly assessed non-vertebrate and plant groups*

	Mammals (5,489)	Birds (10,027)	Amphibians (6,284)	Cartilaginous fishes (1,044)	Reptiles* (1,500)	Bony fishes* (1,436)	Dragonflies* (1,498)	Freshwater crabs (1,280)	Freshwater crayfish (589)	Corals (845)	Conifers (619)	Cycads (303)	Seagrasses (72)
Threatened/ extant assessed	21	13	30	17	18	12	8	16	24	27	28	62	14
Threatened/ extant assessed-DD	25	13	41	33	22	15	13	31	32	33	29	63	16
Threatened + DD/extant assessed	36	13	56	64	37	33	43	65	47	44	32	63	26
Proportion of extant assessed as DD	15	1	26	47	19	21	35	49	23	17	4	1	13

Notes: DD = data deficient. Threatened includes species in categories vulnerable, endangered, and critically endangered; asterisks indicate those groups in which estimates are derived from a randomized sampling approach.
Source: Supplementary on-line material (Hoffmann *et al*. 2010).

