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10.1. Introduction

In “An Essay on the Principle of Population” (1798), Thomas Malthus established one of the first scenarios that linked natural constraints (agricultural production) with demography and economic growth. This essay was an essential contribution not only to the development of economic theories but also to ecological and evolutionary theories with the concept of a limiting capacity within a given environment. The Malthusian view of human demography is at the core of the book by Ehrlich and Ehrlich “The Population Bomb” [EHR 68], which called for active control of births in order to avoid famine, resource depletion and corporate collapse.

However, it was the Meadows report “The Limits to Growth” [MEA 72] that marked the beginning of global environmental scenarios that were based on modeling and computer simulations. The Meadows report was also part of a neo-Malthusian view that biological and therefore human populations tend to grow until they reach the limit that their environments can bear [BAR 11a] (Figure 10.1). The initial model used in “The Limits to Growth” takes many factors into account while addressing the interactions between the five main factors: human population, non-renewable resources (minerals), renewable resources (agriculture), capital resources and pollution. A review of the scenarios from the first Meadows model was produced in 2004: “Limits to Growth: The 30-Year Update” [MEA 06].

Negative criticism on the report by Meadows mainly focused on his Malthusian view of the dynamics of human societies and errors in his predictions, particularly on the depletion of certain non-renewable resources
predicted for the end of the 20th Century. More recently, critics have been more positive, pointing out that scenarios in the Meadows report continue to provide useful projection elements, while stressing that models should now integrate climate change and the biodiversity crisis [BAR 11a].

![Diagram of demographic growth patterns](image)

**Figure 10.1.** The relationships between demographic growth patterns and limiting capacity of the environment [MEA 06]

The Malthusian approach to interactions between human societies and their environment, with the stance that humans are disruptive agents of ecosystems, has hampered collaborations between ecological and social sciences [FIS 16]. However, thanks to the UNESCO’s “Man and the Biosphere” (MAB) program, which was initiated in the 1970s (Chapter 11), collaborations were nonetheless able to be developed.

This chapter illustrates some elements of the prospects, scenarios and models for studying interactions between biodiversity and health.
10.2. Prospects and global scenarios

The elements of prospects or global scenarios (Box 10.1) are generally drawn up in broad sectoral areas: demography, urbanization, globalization, land use, agriculture and livestock, and living resources. These areas, which are usually analyzed individually but sometimes in interaction, have independent effects on health and biodiversity and on the nature of biodiversity/health links.

Extrapolation is the simplest method of projection into the future. It is based on data from the past and assumes that trends in the past will continue into the future. Extrapolation is used to project the change in distribution of an infectious agent vector, such as mosquitoes, with climate change.

Phenomenological models are used to combine quantitative components. They help to unravel the underlying mechanisms and carry out projections on the values of parameters. Phenomenological models are widely used in ecology, hence the relationship between the abundance and distribution of a species (such as a parasitic species).

Prospecting was introduced in the United States by the Rand Corporation with the development of the Delphi method and the scenario method, which was based on expert opinion. The scenario method requires analyzing different possible states of the future, according to different alternative conditions. Experts construct extreme, best and worst-case scenarios, or typical and alternative scenarios [ROW 99].

Futurology is the study of possible futures, both probable and preferable, using quantitative and qualitative data.

As Sutherland [SUT 06] pointed out, predicting consequences linked to the emergence of new conditions is particularly difficult, especially for the emergence of a very rare event.

Traditionally, projections contemplate the various current options that may influence future states of the system or domain being analyzed. An alternative method is to determine the strategies needed to reach a desired future state or to avoid paths that lead to an unwanted future state [DUP 04].

Box 10.1. Definitions: scenario, model, prospect, projection (adapted and complemented by Sutherland [SUT 06])
10.2.1. Demography

Global population growth projections are regularly reviewed by UN agencies. According to the latest United Nations projection, the world’s population is expected to reach 11.2 billion by 2100 [UNI 15a] (Figure 10.2). Several important characteristics for the interactions between biodiversity and health are associated with this growth of world population and are worth noting. Thus, the population will continue to grow in tropical regions until 2100, while it will decrease in temperate regions of the world (Figure 10.2). Human population growth will be affected in areas that are rich in biodiversity and endemic infectious diseases (Chapter 2). Second, demographic changes concern the ratio between rural and urban areas, to the benefit of the latter (Figure 10.3). Increased urbanization will have consequences on land use, transport and agricultural production. Finally, the decline in population growth will be accompanied by aging and an expected change in public health policies.

Figure 10.2. Projections of changes in world population growth according to latitude (taken from McDonald et al. [MCD 13], based on the 2010 United Nations data). There is a decrease in population in the temperate zones of the Northern hemisphere and an increase in population in the tropical zones across the globe. The top right graph gives estimates of population growth by 2100 [UNI 15]. For a color version of the figure, see www.iste.co.uk/morand/biodiversity.zip
The consequences on biodiversity of population growth in urban areas have been analyzed by McDonald et al. [MCD 13], projecting population growth data for the world population on the 34 biodiversity “hotspots” [MYE 00] (Figure 10.3). Over half of the biodiversity hotspots will be significantly affected by an increase in urbanization by 2050, with consequences on biodiversity in terms of urban infrastructure and road communication networks ([IBI 16], Chapter 5). A direct impact of cities on biodiversity relates to changes in land use associated with urban growth. Urban areas currently occupy about 3% of the land area [MCG 06] and urban growth will be an important factor in land-use change with increased deforestation and loss of agricultural land [MCD 13].

Bloom et al. [BLO 08] noted a strong correlation between the level of wealth of a country and the proportion of its population that lives in urban areas. These areas do indeed offer richer market structures and higher productivity than the rural world. Bloom et al. [BLO 08] pointed out that rapid urbanization is associated with environmental degradation. The lack of correlation between increased urbanization and economic development [BLO 08, CHE 14] suggests that this increase contributes to greater pressure on the environment, and hence on biodiversity, while not providing the economic resources needed for public health systems.
The environmental impact of urban growth can be estimated through the increase in energy consumption seen in urban buildings. Globally and by 2050, this increase in energy consumption for heating and cooling is estimated to be between 7% and 40% compared to 2010 [GÜN 17]. Increased urbanization will affect renewable and non-renewable sources of energy, as well as carbon sinks and biodiversity [SET 12a].

In addition to the expansion of urbanization, significant changes are expected in agricultural and forest areas [DAN 15, BRE 17]. The results obtained from models based on the extrapolation of historical trends predict a more or less significant increase in agricultural areas according to development scenarios: maintaining current economic globalization and sustainable development (Figure 10.5). Forest areas are particularly affected by economic globalization.
Figure 10.5. Evolution of agricultural and forest land cover between 1970 and 2050. Data on changes between 2010, 2030 and 2050 are derived from modeling in various scenarios: the scenario of economic globalization is in blue, sustainable development is in green (simulation values are given by the dotted lines) (from [OEC 15, FAO 12] historical data). For a color version of the figure, see www.iste.co.uk/morand/biodiversity.zip

10.2.2. Agriculture and livestock

The increase in world population has been accompanied by an increase in production of cereals and meat (see also Chapter 5 and Figure 5.4 on the evolution of different animal productions over past decades). Here also, the values derived from modeling are highly dependent on economic scenarios. The scenario of economic globalization is accompanied by significant production of animal meat.
This production of animal proteins requires significant energy resources, in terms of agricultural areas needed for animal feed (see also Figure 5.3), inputs, pesticides, and veterinary health products such as vaccines and antibiotics (Figure 10.7, [VAN 14, PRI 15]). Increased use of antibiotics can
thus be extrapolated from existing data. Consequences on the emergence of resistant bacteria at the environment/livestock/human health interfaces therefore need to be considered (see Chapters 5 and 6).

### 10.2.3. Climate change

Economic scenarios serve as a basis for future climate models [IPC 13], taking into account estimates of greenhouse gas emissions from urbanization, transport, livestock and land use (carbon sinks or sources). The projections obtained by synthesizing different models show an increase in average global temperatures, although the amount of change depends on the economic scenario.

The effects of climate change on changes in the distribution of living organisms and on the phenology of organisms can be observed [LOV 05, PEC 17]. Projections of the effects of climate change on infectious diseases also concern vector range changes [DEL 08, ALT 13]. Published models show that the distributions of many infectious diseases will really change, especially for diseases that require the presence of vectors to ensure transmission of infectious agents. These models predict new territories that are at risk due to changes in climatic environmental niches, which will become favorable for the establishment of infectious cycles [GUI 11]. Models generally show a shift in the environmental niches of infectious diseases with displacements from distribution areas towards higher latitudes (as for dengue) or higher altitudes (as for malaria).

Statistical congruences between distributions of pathogens (or their vectors) and changes do not demonstrate a direct impact of climate change on the incidence of infectious diseases [LAF 09, GET 10], bearing in mind that most of the studies are based on modeling scenarios [MAY 15]. The transmission of an infectious agent also depends on local biodiversity conditions, which requires building models that integrate changes in biodiversity with climatic variables [GAL 09].

Climate variability has had a major impact on the history of civilizations [FAG 09]. Climatic phenomena such as El Niño/La Niña are known for their consequences on many infectious diseases. Abnormal events of extreme rainfall favor vector or reservoir-borne diseases such as dengue fever, Japanese encephalitis, malaria or hantavirus hemorrhagic fever [ANY 12].
Inter-annual climate variability, as measured by indices such as ENSO (El Niño South Oscillation) or NAO (North Atlantic Oscillation), is linked to the impacts of several infectious diseases. A temporal and spatial correlation can be seen between the values of these climatic variability indices and the incidence of leptospirosis or dengue in Southeast Asia, or those of hantavirus hemorrhagic fever in Europe [MOR 14]. Teleconnection predicts the incidence and outbreaks of many more infectious diseases using these indices [ANY 12, MOR 14a].

Recent climate models suggest that climate change is changing the intensity and frequency of climate variability [CAI 14]. The El Niño/La Niña events will be more intense in the coming decades. Models predict that the monsoon routine on which African and Asian agriculture depends will see a decrease in volume of average annual rainfall and there will be a greater number of abnormal years characterized by intense droughts or floods. We could assume that the epidemiological environment will be affected by this variability, resulting in an increased risk of epidemics for all water-borne diseases transmitted by vectors or dependent on wild reservoirs, thus affecting humans, domestic animals and wildlife.

Models suggest that climate change will increase the number of extreme weather events and flood risks in many parts of the world [HIR 13]. Combined with other environmental change factors, the risks to water security and biodiversity are particularly significant in the intertropical regions of the world [VÔR 10].

10.2.4. Biodiversity

Estimated past and current extinction rates and projections of extinction rates for the 21st Century have been summarized by the CBD (Convention on Biological Diversity; [LEA 10]). These rates are estimated for the distant past (fossil data), for recent times (IUCN Red List data) and for the future following different global environmental scenarios: for birds [JET 17], for the period between 2000 and 2050 based on scenarios on change in land use), vascular plants ([VAN 06], for the period between 1995 and 2050 for four scenarios of global change), and various plant and animal taxa ([THO 04] for the period 2000 to 2050 in relation to scenarios on climate change, Malcolm et al. [MAL 06] for the period 2000 to 2100) (Figure 10.8). The models give projected extinction rates with high uncertainties, all of which
are higher than the current extinction rates, which are themselves well above the extinction rates of the fossil record.

Figure 10.8. Estimated extinction rates for the past (fossil record), recent times (IUCN Red List data) and for the 21st Century. These rates are estimated as extinctions per million species-years. Different global scenarios are presented for the future: for birds ([JET 17], for the period 2000 to 2050), vascular plants ([IVAN 06], for the period 1995 to 2050), and various plant and animal taxa ([THO 04], for the period 2000 to 2050, [MAL 06], for the period 2000 to 2100) (taken from [LEA 10]). For a color version of the figure, see www.iste.co.uk/morand/biodiversity.zip

The Convention on Biological Diversity (CBD 2010) has set itself the 20 Aichi targets for biodiversity by 2020 (Chapter 11). Tittensor et al. [TIT 14] evaluated a set of indicators for progress against indicators associated with the Aichi objectives. The authors projected the trends of these indicators to 2020 using a statistical method that incorporates the specific properties of an individual time series for these indicators. The conclusions were that when public policy efforts are faced with a biodiversity crisis, they are not in a position to halt the negative trends estimated for 2020. Biodiversity pressure variables (human appropriation of biological productivity), the status of biodiversity (Living Planet Index) and responses with biodiversity benefits (number of domesticated breeds, Red List of pollinators) show a foreseeable decline in biodiversity with negative consequences on resources and ecosystem services (Figure 10.9).
Figure 10.9. Projections to 2020 of four indicators for Aichi objectives: pressure on biodiversity (human appropriation of net biological productivity), status of biodiversity (Living Planet Index) and responses in terms of benefits linked to biodiversity (terrestrial domestic animal breeds, Red List of pollinators). The model corresponds to the red lines with 95% confidence intervals (colored areas). Significant differences with the 2010 estimates are given by the horizontal dotted line (from [TIT 14]). For a color version of the figure, see www.iste.co.uk/morand/biodiversity.zip

10.2.5. Human health

Each decade in the last century is characterized by an important epidemiological transition with a shift from infectious disease-related human health to non-communicable diseases (Chapter 4) [MAT 06]. This transition was accompanied by a reduction in mortality (infant and adult) and a reduction in fertility, the consequences of which are highlighted in the WHO projections (see section 10.2.1). The Millennium Development Goals aim to speed up the decline of infectious diseases in low-income countries.

Dye [DYE 14] provided projections on the causes of human deaths by 2050. The projections show a significant decrease in deaths from infectious disease, from 16 million deaths in 2010 to 13 million deaths per year by 2050. However, this is still far from total eradication of infectious diseases. The projections predict an explosion in deaths from non-communicable diseases from 31 million in 2010 to 83 million deaths per year by 2050. Such
projections question the capacity of public health systems to cope with both the impacts of communicable diseases and the increase in non-communicable diseases.

The effects of environmental changes on human health have been analyzed in a conceptual framework proposed by Myers et al. [MYE 13]. On the basis that these changes can provide both benefits and disadvantages for human health, such as hydraulic development (dams, irrigated agricultural perimeters), the analysis showed that the levels of infrastructure (engineering) and access to the market economy prevail in the evolutionary trajectories of the population’s health level relative to environmental degradation (Figure 10.10).

![Ecological, epidemiological and economical transitions](image)

**Figure 10.10.** Conceptual diagram of the link between population health and ecological transition, adapted from Myers et al. [MYE 13]. People are moving from a primary dependency on natural systems for health-related ecosystem services to a state where these populations depend on engineering infrastructure for these services and market access. The trajectory of transition depends on many factors that can alter the vulnerabilities and health levels of populations such as economic equity, quality of governance and environmental characteristics (mediation space) (modified from [MYE 13]). For a color version of the figure, see www.iste.co.uk/morand/biodiversity.zip
The point of the conceptual framework from Myers et al. [MYE 13], in addition to identifying research gaps, is to integrate the dimension of human health into decision-making and governance in the areas of land-use planning and environmental conservation.

10.2.6. Animal health

The level of animal health affects the level of health and well-being of human populations, as well as the economic level [GRA 12]. Estimating the burden of infectious diseases that will affect livestock depends on the capacities of animal health systems, which vary widely depending on the economic development of countries. Despite knowledge biases, a study by Perry et al. [PER 13] showed that animal infectious diseases decline in rich countries following the trends of human infectious diseases. On the contrary, poor countries continue to suffer the impact of endemic infectious diseases and major epidemics, such as recurring epidemics of Rift Valley fever disease. Infectious diseases that affect animals are more intensively studied in developed countries, with the exception of diseases with pandemic potential for which the agents come from developing or emerging countries (such as H5N1 avian influenza). Projections of this are difficult to achieve, but Perry et al. [PER 13] identified three future trajectories: a growing concern in developed countries for disease surveillance and control; intensive and market-oriented livestock production systems in many developing countries, where health risks will be significant; traditional production systems in poor countries for which the diseases will remain neglected.

10.3. Worst-case scenarios

10.3.1. Thresholds and tipping points, planetary limits

Rockström et al. [ROC 09] defined thresholds as nonlinear transitions in the functioning of human/environment coupled systems. The thresholds are therefore intrinsic characteristics of systems (Figure 10.11). Not all processes are associated with threshold effects, such as regional or continental land-use change (for a critical threshold on a local scale, see Kéfi et al. [KÉF 14]). Nonlinear changes from a desirable state to an undesirable state can affect key ecological functions, leading to major functional collapses. Thresholds and tipping points are therefore states that can be
determined by mathematically studying human/environment coupled systems.

Planetary limits are human values defined to maintain a control variable at a “safe” distance from a hazardous level, a risk zone that encompasses thresholds and tipping points ([ROC 09]; Figure 10.11). Determining a safe distance involves normative judgment, which companies choose when faced with risk and uncertainty. Planetary limits can thus be affected by global processes (climate change) or can be aggregated from regional to global (Figure 10.11).

Figure 10.11. Description of planetary thresholds and limits according to Rockström et al. [ROC 09]. The planetary limit is designed to be a boundary beyond which a critical threshold at the local, regional or global scale affects a process in the terrestrial system (climate change, land-use change), as given in the table on the right. Insufficient knowledge of threshold dynamics generates an uncertainty zone and positions the planetary limit. Exceeding the planetary limit causes threshold effects, which can lead to tipping points. For a color version of the figure, see www.iste.co.uk/morand/biodiversity.zip

An application of the concept of threshold and planetary limits was given by Pelletier and Tydmers [PEL 10] for animal production systems and their
effects on environmental changes. By comparing contributions from the global livestock sector in 2000 with estimated contributions from the sector in 2050, Pelletier and Tydmers [PEL 10] highlighted three important environmental consequences of livestock on: climate change, nitrogen mobilization and appropriation of plant biomass on a global scale. Environmental sustainability requires animal production systems to meet critical thresholds and limitations for these three effects. The proposed scenarios illustrate various expected impacts that are associated with companies’ choice of diets. Pelletier and Tydmers [PEL 10] highlighted the magnitude of estimated impacts in relation to the limiting condition of sustainability, which requires prioritizing the livestock sector within global environmental governance (see also [TIL 11]). Let us note that this study does not take into account the indirect effects of livestock on human health.

10.3.2. Collapse

The reason for the collapse of societies or civilizations has turned historians [MCN 76, TAI 88, CLI 14] into natural scientists and environmental scientists [DIA 05, SMI 08, TUR 14]. All these studies highlight the cumulative effects of health and environmental crises on societies, which are often characterized by high levels of organization and complexity but for which resilience is too low to overcome the crises. The significance of health crises in the risk of collapse has always been emphasized [GAR 01]. The Ebola epidemic in West Africa in 2015 illustrated the difficulty of containing an epidemic in countries with health systems that have been weakened by different economic crises and in some cases, civil war.

Motesharrei et al. [MOT 14] constructed a model of human population dynamics by incorporating accumulated wealth and economic inequality into a predator–prey model, in other words the use of natural resources by humans. The model is simple with four equations that describe the demographics of “elites”, “common people”, nature and health. The model incorporates an economic stratification and an ecological constraint. Collapse can be avoided if the degree of depletion of nature is limited and inequality is reduced. The simplicity of the model has obviously been criticized, including by the authors, but the results of simulations support the importance of defining planetary limits to avoid tipping points and collapse [COS 07]. Interestingly, the model emphasizes the importance of economic
inequality in the risk of collapse, which is negatively correlated with the subjective value of well-being (Chapter 8, Figure 8.1).

10.4. Global risks and “preparedness” for the worst

Worst-case scenarios have direct implications for state governance and particularly for national security.

A report commissioned by the Institute of Medicine of the US Academy of Sciences in 1991 to the Committee on Emerging Microbiological Threats to Health highlights the unrealistic likelihood of a victory over the multitude of existing microbial diseases (and those yet to emerge), and the impossibility of predicting the temporality and spatiality of new infectious diseases that are certain to emerge [LED 92]. While recognizing the coevolving nature of the global ecology of emerging diseases, the committee highlights the difficulty of establishing projections.

In the early 2000s, the CIA published a report on the risks of infectious diseases and bioterrorism for national security, following the 2001 attack on New York and letters laced with anthrax, with the adoption of a law on biological threats by the American Congress. A Pentagon report alerted the Federal Administration of the need to seriously consider climate change and the resurgence of infectious diseases, which were presented as an imminent threat to national security [COO 06a].

The United States believes in preparing for emerging infectious diseases, including bioterrorism, under situations of maximum uncertainty. These are “preparedness” and “worst-case scenarios”, which have been developed by successive US administrations [ZYL 13, ZYL 16]. They involve considering that emerging diseases, and terrorism, are driven by similar processes of coevolving races. The war on microbes, like the war on terrorism, would be deemed to be permanent. This amounts to a perpetual war that is declared against whoever integrates the evolutionary processes of living organisms [COO 06a].

More recently, in an unclassified report to the US Senate (Daniel R. Coats, May 11, 2017, Statement for the US Intelligence Community, Senate Select Committee on Intelligence), the Director of US National Intelligence summarized the global threats to US security. Among these threats, the report mentioned wildlife trafficking and illegal fishing, climate change, loss
of biodiversity, increased antibiotic resistance and pandemic-risk infectious diseases. According to the report, the links between poaching, the illegal wildlife trade, instability, corruption, crime and challenges to the rule of law are clear. The potential collapse of global fisheries and especially the increase in illegal fishing threaten food and economic security. Illegal fisheries benefit transnational crime and trafficking of human beings and undermine efforts to implement sustainable fisheries policies. Countries with high populations in their coastal areas are particularly vulnerable to climate change and extreme tropical weather events. The degradation of air quality could provoke protests against authorities, such as those seen in recent years in China, India and Iran. Tensions over shared water resources are sources of potential conflict in some parts of the world. Biodiversity will continue to decline as a result of habitat loss, overexploitation, pollution, disruption of ecosystems that support life, including human life. The risks of emergence or re-emergence of highly pathogenic microbes (avian influenza, MERS-CoV) and the report citing World Bank estimates for the cost of a global influenza pandemic could cost the equivalent of 4.8% of global GDP ($3 billion). Finally, it suggests increased resistance to antibiotics, which is likely to exceed the development of new drugs with drug-resistant forms threatening progress in the control of diseases such as tuberculosis or malaria. A recent study showed a link between the level of governance and corruption and the level of antibiotic resistance [COL 15].

10.5. Towards integrated scenarios

The IPBES [IPB 16] highlights the need to build integrated models for societies/biodiversity/ecosystem services by addressing links between ecosystem services through studying the interactions between land-use change and biodiversity [NAG 13].

It is not possible to present all the approaches and studies in this field (see [IPB 16] and Chapter 9), but we can focus on those that explicitly address the links between biodiversity and health.

The social ecology approach presents this application by explicitly linking ecological/biological metabolism with social metabolism [FIS 16]. Social systems are seen as hybrid systems between cultures (communication exchanges) and environments (metabolic exchanges). Human societies are
characterized by stocks and flows that involve: population and its
demography; biophysical stocks (infrastructure, livestock) and
trade/production; land and its biological productivity.

An important parameter is HANPP (Human Appropriated Net Primary
Productivity). This has doubled in the 20th Century [KRA 13] and the
scenarios presented below suggest that this appropriation will continue to
increase considerably in the coming decades. Human appropriation of
primary production (HANPP) is an appropriate indicator for research into
the impact of human intervention on biodiversity [HAB 07, PLU 16]. This
aggregate indicator measures the impact of land use on energy availability
(net primary production) in ecosystems and links human activities, such as
agriculture or urbanization, to ecosystem processes. Its usefulness lies in
directly linking human appropriation of environmental metabolism with
ecological theories on biodiversity, like the species-energy hypothesis [VIT
86, WRI 83, WRI 90].

A conceptual framework has been put forward with a dynamic interactive
network that links “drivers” (food consumption, energy), pressures (land use,
HANPP), states (biodiversity change and extinction of species), impacts
(reduction of the quality of ecosystem services) and responses (governance,
land planning, conservation) (Figure 10.12). This conceptual framework
makes it possible to address the link between biodiversity and health. The
species-energy hypothesis is valid at the country level with a positive
correlation between HANPP and declining biodiversity. The hypothesis of a
reduction in ecosystem services for the regulation of infectious diseases
seems to be confirmed with an increase in zoonotic disease epidemics and an
increase in HANPP (Figure 10.12).

Social ecology has similarities with the co-viability approach, with the
latter aiming to combine social and environmental dynamics. However, a
shift to a territory scale is needed. Methods for producing scenarios coupled
with landscape changes – changes in biodiversity [EWE 13] – or changes in
the provision of ecosystem services are developing [NAG 13], although
regulation of infectious and non-infectious diseases are still underdeveloped.
Figure 10.12. Conceptual framework of dynamic interactive network that links “drivers” (food consumption, energy), pressures (land use, HANPP), states (biodiversity change and extinction of species), impacts (reduction of quality of ecosystems) and responses (governance, land planning, conservation) (modified from [PLU 16]). This framework is based on the species-energy hypothesis [VIT 86, WRI 83, WRI 90], where a decrease in biological productivity, notably through human appropriation (HANPP), translates to loss of biodiversity ($\Delta$ biodiversity). This conceptual framework finds empirical support in the correlations which we observe between HANPP ([IMH 06] data, http://sedac.ciesin.columbia.edu/ data/collection/hanpp) and the number of endangered species (IUCN Red List data), and between HANPP and the number of zoonotic disease epidemics (data from GIDEON, [MOR 14a]). For a color version of the figure, see www.iste.co.uk/morand/biodiversity.zip

A conceptual framework (Figure 10.13) that combines retrospective modeling and future scenarios of land-use changes and their health consequences can thus be proposed. As economic aspects are one of the elements of mediation [MYE 13; Figure 10.11], local and national governance must be considered as the essential driver for land planning (agriculture, conservation, urbanization) and public health (including veterinary health). Retrospective modeling based on phenomenological/statistical models allows us to analyze and highlight determinants and interactions between factors of change and consequences on public health.
Prospective scenarios are based on models that incorporate processes (such as multi-agent models, epidemiological models, etc.) and, depending on external conditions (climate change, global economy, demography), produce potential scenarios of changes in land use through mediation of local/national governance. These scenarios, which can be “worst-case” or “best-case” (i.e. desirable), in turn enter mediation by affecting various elements of governance that will lead to new scenarios. The process is therefore iterative and requires close collaboration with different actors in the socio-ecosystem.

Figure 10.13. Conceptual framework to produce retrospective modeling and predictive scenarios for the links between land use (agriculture, conservation, urbanization) and public health (including veterinary and phytosanitary). Retrospective modeling that is based on phenomenological/statistical models allows us to analyze the determinants and interactions of factors of change and their consequences on public health. Prospective scenarios are based on models that incorporate processes (such as multi-agent models, epidemiological models, etc.), which integrate external conditions (climate change, global/local economy, sociodemography) and produce potential scenarios for land-use change in the mediation of local/national governance. These “worst-case” or “best-case” (i.e. desirable) scenarios are incorporated into mediation to produce new scenarios. The process is iterative and requires close collaboration with the different elements in the socio-ecosystem. For a color version of the figure, see www.iste.co.uk/morand/biodiversity.zip
Various public health elements can be incorporated, such as well-being, mental health, infectious diseases and autoimmune diseases (allergies, diabetes) [LID 16].

10.6. Observations and observatories

International agencies, as mentioned in previous chapters, provide many socio-economic, cultural, environmental and health data (WHO, FAO, OIE, World Bank, OECD, UNICEF, IUCN, WWF, BirdLife, etc.). Most of these data are aggregated across countries. Biodiversity data are georeferenced more accurately through the GBIF program (http://www.gbif.org/) and its online databases. Recently, the PREDICTS project (Projected Responses of Ecological Diversity in Changing Terrestrial Systems, www.predicts.org.uk) compiled a large database of comparable biodiversity samples from multiple sites that differ according to the nature or intensity of human impact linked to land use [HUD 17]. The 2017 version of the database contains over 3.2 million samples from 26000 sites, representing over 47000 species. This database analyzes patterns of biodiversity on local, regional and global scales.

The need to collect long-term data in a standardized manner in order to develop scenarios for eco-evolving dynamics of zoonoses and their reservoirs and vectors is the core of the NEON initiative ([SPR 16]; Figure 10.14). In the light of the scarcity of long-term chronological data on infection rates in vectors and reservoirs, the National Ecological Observatory Network (NEON) collects measurements and samples on vectors and zoonotic diseases on a continental scale (the territory of the United States). Springer et al. [SPR 16] described sampling models and sampling priorities, field and analytical methods, and management of archived data and samples that will be made available for research. The knowledge generated by this sampling will help to better understand and predict changes in dynamics of zoonotic diseases in an interdisciplinary and collaborative manner.

A key source of biodiversity information is remote sensing [SEC 14, WAL 17], which supplements other sources of biodiversity data [PRO 16]. The integration of spatial data into geographic information systems allows us to develop statistical models for changes in biodiversity [MOU 15] and in vectors and reservoirs of infectious agents [PET 14].
Citizen science [BOA 16] and participatory epidemiology [ALL 17] are constantly developing. In addition to making valuable data available to the scientific community, citizen science enables the science/society dialogue to be developed within the science/policy dialogue and ultimately reinforces the rigor and relevance of the scientific approach [BAL 13]. In addition to methods such as the “Health Impact Assessment” (see [LAJ 15a]), participatory methods can better analyze perceptions of health and environmental risks in terms of local knowledge and local governance [STI 09, FIS 16].
10.7. Experts and representation of knowledge

Scenario co-construction is the preferred tool for decision support [NAS 17]. This co-construction is based on participatory methods and brings into play the effects of individual and collective decisions on a future that human and non-human communities want and (must) share. The “health” or “conservation” service can thus be represented at different spatial and temporal scales. Mapping these services makes it possible to represent land use conditions (conservation, water regulation, carbon sequestration) that are directly linked to these services. Innovative participatory methods have been developed for these mappings [NAS 17].

However, some difficulties have been encountered in the representation of disease control services. For example, if the regulation of both communicable and non-communicable diseases is based on a habitat fragmentation index that is associated with forest cover, the service will be difficult to map directly. It will require a recommendation on the level of fragmentation of forest areas. We also emphasize that mapping presents the danger of “freezing” the landscape and losing an adaptive overview of landscapes.

It is crucial to communicate scenarios and models to policy-makers, professionals and local communities [SUT 12]. Thus, it involves communicating consensus, uncertainty and controversy. The link between biodiversity and health is an example of communication problems in terms of scientific expertise. There is a good scientific consensus on the erosion of biodiversity, epidemiological transition and emergence of non-communicable diseases, and the emergence of new epidemiological risks such as emerging infectious diseases or antimicrobial resistance. On the contrary, scientific uncertainties are numerous, as they are the effects of land-use changes on epidemiology. These uncertainties must be resolved through new studies. Finally, there are controversies such as the dilution effect, which occurs due to epistemological aspects (the nature of theory and associated hypotheses) and ideological and political aspects (access to funding for scientific projects).
10.8. Conclusion: scenarios for research and governance

As highlighted by Naem et al. [NAE 16], biodiversity and human well-being are two essential components and are linked to each other to achieve sustainable development goals. Responses to health crises have implications for governance, from a local to a global level. This chapter has illustrated the diversity of scenarios for expected changes in demographics, urbanization, agriculture, land use and their implications for biodiversity and health linkages.

The production of scenarios requires observatories and observations and their integration into models that take into account the effects of scale changes that affect socio-economic and ecological processes.

Scenarios become meaningful when they are co-constructed with different elements from socio-ecological systems (users, managers, politicians). This requires a dialogue between science, society and politics, where perceptions and representations of scientific expertise are of central importance.

The construction of predictive ecology and epidemiology has important implications for governance, which takes scenarios of scientific expertise into account (Chapter 11). It also requires questioning oneself on the role of ethics in scientific practices (Chapter 12).