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ECOSYSTEM HEALTH AND PLANETARY WELL-BEING

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Ecosystem degradation decreases planetary well-being

Properly functioning *ecosystems* support diverse processes that sustain life, ranging from climate regulation and oxygen production to maintaining biodiversity. A healthy ecosystem may be defined as a sustainable and resilient system that maintains its function despite external stress (Costanza and Mageau, 1999). A healthy ecosystem provides key services to its biota, and disturbances to the system may impact the *health* and/or abundance of key members of its assemblage, such that they can no longer perform their ecological roles. In this chapter, we discuss the cascading effects that ecosystem degradation has on the health of wildlife, humans, and entire ecosystems and the consequent threat to planetary well-being.

Overexploitation of natural resources by humans has resulted in widespread ecosystem degradation: More than half of all ecosystems on Earth have deteriorated because of human actions (Myers, 2017; Song *et al.*, 2018). This degradation has negatively impacted a range of ecological functions with notable adverse consequences for the well-being of *wildlife* (undomesticated animals and plants inhabiting natural environments) and humans. Environmental change has, for example, directly increased *infectious disease prevalence* in humans and other organisms by facilitating the spread of invasive species, *disease vectors* (organisms that carry and transmit *pathogens* to other organisms), and pathogens (Parmesan and Yohe, 2003).

The interplay between ecosystem, human, and nonhuman health is recognized by several well-established health-related concepts, such as Conservation Medicine (Aguirre *et al.*, 2002), EcoHealth (Charron, 2012), One Health (Gibbs, 2014), and Planetary Health (Lerner and Berg, 2017). These concepts all share the recognition that humans share the Earth with wildlife and the

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need for interdisciplinarity to safeguard health. Nonetheless, they tend to be anthropocentric and emphasize the protection of human health, whereas planetary well-being aims to identify humans as only a part of ecosystems and recognize the needs of nonhuman organisms. Similarly, infectious disease research is biased towards pathogens that cause illness in humans or in economically important species such as livestock. Meanwhile, the potentially devastating effects of *pathogens* (organisms that can cause disease by invading another organism) in nonhuman organisms generally receive less attention. Wildlife disease research is largely directed towards *reservoir hosts* (organisms in which pathogens can reproduce and that serve as a source of infection to other *hosts*) of *zoonotic* pathogens (infections that can be transmitted between humans and other animals). Because of this knowledge bias, the patterns of disease dynamics are best known for vertebrates and their pathogens (reflected also in this chapter), but the general patterns can be expected to extend to other taxa.

In this chapter, we present the role of ecosystem health in the well-being of all organisms. We demonstrate that (1) the health of ecosystems is declining worldwide due to human actions, (2) ecosystem degradation has complex adverse effects on the health of humans and nonhuman organisms by affecting disease dynamics, (3) planetary well-being and the health of ecosystems are interconnected. While planetary well-being is unattainable without sustaining healthy ecosystems, the planetary well-being concept offers a useful approach for finding solutions for global disease burden, for example through improved ecosystem management.

Disease as a part of a healthy ecosystem

All organisms have evolved in contact with a certain ecological community, including beneficial symbiotic organisms as well as *parasites* that exploit the host’s resources, causing loss of health or mortality. These organisms, including pathogens, are important for proper ecosystem function, for example as a means of naturally controlling host population size (Fischhoff *et al.*, 2020). As such, in healthy ecosystems the well-being of parasites is equally important as the well-being of their hosts, however, ecosystem functioning can suffer from a shifting balance of host-parasite associations. Pathogens and their hosts are engaged in an evolutionary “arms race” between the hosts’ immune defences and the diverse solutions evolved by pathogens to bypass the host defences. Many pathogens have a higher rate of evolution than their host, which limits the capacity of hosts to avoid or eliminate pathogens completely. Thus, disease is a natural feature of ecosystem dynamics, but the introduction of a novel pathogen into an ecosystem can have unpredictable consequences when the pathogen is transmitted to a new or sensitive host. A host encountering novel pathogens may be vulnerable to infection due to the lack of evolved defence mechanisms, possibly leading to a more severe disease. For example, when a large proportion of a population is simultaneously in poor health, there can be a concomitant decline in their function within the ecosystem.

Disease spread and disease burden increase due to anthropogenic impacts

Anthropogenic impacts on disease burden in ecosystems

Human impacts on ecosystems, for example, through changes in climate, land use (*e.g.,* agriculture, and growth of urban areas), pollution, and exploitation of natural resources, have caused profound and unpredictable changes in the ecology of pathogens, hosts, and host communities (Figure 4.1). Human activities can impact the infectious disease burden of nonhuman organisms by affecting the distribution and interactions of hosts and vectors, and the susceptibility of individuals and ecosystems to disease. These processes are outlined below.

Changes in the distribution of vector and host species

Human activities and climate change alter the geographic ranges of vectors, hosts, and pathogens on local and global scales (Parmesan and Yohe, 2003),

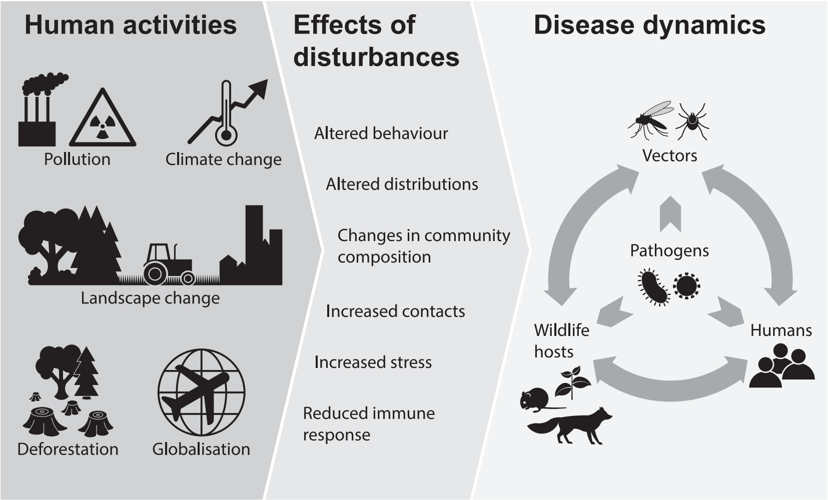

FIGURE 4.1 Disease dynamics of animals and humans are altered due to anthropogenic impacts on changes in the distributions, communities, and susceptibility of organisms to pathogens. Increase in disease risk of wildlife will, in turn, threaten human health and well-being through human–animal–vector interactions. Figure created by Māris Grunskis/@PHOTOGRUNSKIS.

potentially impacting the distribution and emergence of many diseases (Cohen *et al.*, 2020). Changes in the distribution and abundance of vector or reservoir species were implicated in nearly 10% of the 100 largest zoonotic disease outbreaks in the last 47 years (Stephens *et al.*, 2021). For example, some tick species have extended their distribution in the northern hemisphere and thus altered the prevalence and geographic distribution of tick-borne diseases (*e.g.,* anaplasmosis, babesiosis, Lyme disease, and tick-borne encephalitis) (Bouchard *et al.*, 2019). Similarly, there are concerns that certain mosquito species originating from tropical and subtropical areas, such as *Aedes albopictus,* a vector of dengue virus and Chikungunya virus, may be able to thrive in temperate regions in the near future (Caminade, McIntyre and Jones, 2019). Indeed, climate change has been implicated in increasing human malaria infections in Southern Europe and altering the distribution of avian malaria in wild birds (Garamszegi, 2011). At local scales, animals may also change their typical movement behaviours to escape a degraded habitat or new competitors or predators, concurrently spreading pathogens to new communities.

Altered community composition and ecological interactions among species

Changes in the species composition of a community (*e.g.,* through biodiversity loss or spread of invasive species), can influence key ecological interactions and thus impact disease dynamics in wildlife communities and humans (Keesing *et al.*, 2010; Keesing and Ostfeld, 2021). A high-species diversity is thought to reduce disease risk in a community, whereas the loss of species can increase the pathogen burden (*i.e.,* the dilution effect hypothesis; (Keesing and Ostfeld, 2021)). Large mammals (*e.g.,* top carnivores) are more vulnerable to human impacts than smaller mammals (*e.g.,* rodents), which often thrive in human-disturbed ecosystems (Gibb *et al.*, 2020). Certain small-bodied and short-lived host species also support pathogen replication and transmission exceptionally well, making them particularly competent reservoir hosts (Cronin, Rúa and Mitchell, 2014). Human-disturbed ecosystems are therefore expected to have increased disease risk because they support more competent hosts (*e.g.,* small mammals) relative to undisturbed communities.

Human actions can likewise play a critical role in the dynamics of pathogens carried by domesticated species, with potentially far-reaching consequences for host-pathogen interactions in ecosystems. For example, the accidental introduction of canine parvovirus on Isle Royale, USA, led to a major decline in wolf abundance and consequently released moose populations from predation pressure (Wilmers *et al.*, 2006). The introduction of domestic (and thus feral) cats to many ecosystems is responsible for numerous extinctions (Doherty *et al.*, 2017) and for the spread of new pathogens, such as the protozoan *Toxoplasma gondii,* which causes disease or even death in humans, livestock, and diverse wildlife (Dubey, 2008). In contrast, the eradication of cattle plague by humans led to such a significant increase in wildebeest populations in the Serengeti, Tanzania, that its ecosystem impacts include substantially reduced fires, higher tree density, and increased carbon storage in the area (Holdo *et al.*, 2009). Thus, human-associated species can mediate and amplify the effects of human activities on disease dynamics, with diverse and unpredictable ecosystem-level effects.

Immune system functioning and susceptibility to disease

Stressors linked to human activities (*e.g.,* urbanization, pollution, habitat loss, and fragmentation) affect wildlife and human health, including immune system dysregulation and a reduced host *resistance* to pathogens (Martin *et al.*, 2010; Lee and Choi, 2020). For example, in Australia, deforestation has led to the establishment of populations of *Pteropus* bats (flying foxes) in urban gardens. In addition to a change in distribution and movement, the high-density, isolated urban populations of flying foxes appear to have an altered pattern of herd immunity to Hendra virus, characterized by less frequent but larger disease outbreaks (Plowright *et al.*, 2011); this is cause for broader concern as Hendra virus can be fatal for humans and horses.

Increased human–wildlife encounters and pathogen exchange

Human activities promote the spillover of pathogens from host animals to humans through increased contact rates at the "animal-vector-human interface" in interaction with environmental, ecological, and social processes (Jones *et al.*, 2013; Destoumieux-Garzón *et al.*, 2022). Human–animal interactions occur through (wild) animal trade and (wild) meat consumption, or indirectly through humans living in increasingly close vicinity to wildlife due to the growth of urban areas, intensive farming, and unsustainable exploitation of natural resources (Magouras *et al.*, 2020). Several disease outbreaks in humans have been traced back to contacts with wildlife, including Ebola (Marí Saéz *et al.*, 2015) and SARS-CoV-2 (cause of the COVID-19 pandemic (Holmes *et al.*, 2021)).

Disease dynamics at the socio-ecological interface

Human social and economic systems are broadly intertwined with the state of natural systems, including but not limited to a shared disease burden. For example, the COVID-19 pandemic has been presented as a result of the complex dynamic system incorporating human population growth, culture, and actions that altered ecological processes, including climate change (Thoradeniya and Jayasinghe, 2021). Socioeconomic inequality, as well as political and economic disturbances, influence the pressure placed on ecosystems and create conflicts between the needs of humans and nonhuman organisms. For example, threats to human food security due to loss of crops or trade (*e.g.,* disruption of global supply chains following COVID-19 restrictions (Erokhin and Gao, 2020)), or socioeconomic hardship may increase contacts at the human–animal interface, such as increased harvesting of wildlife (Golden *et al.*, 2016). Profit-driven, intensive animal husbandry has resulted in the mass rearing of livestock in conditions that expose animals to suffering and generate opportunities for further disease outbreaks (Jones *et al.*, 2013). Additionally, there is an elevated risk of zoonotic infectious disease emergence and spread among humans in high-density urban hubs near wildlife habitats or agricultural areas, particularly in the absence of effective public health infrastructure (Santiago-Alarcon and MacGregor-Fors, 2020).

Global travel and trade have transformed the spread of pathogens, vectors, and hosts

Few human activities have transformed disease dynamics and distribution of pathogens as fundamentally as the increased human mobility and trade on a global scale. Human mobility across countries and continents has a long history of facilitating infectious disease spread, but high-volume air travel has multiplied that potential (Findlater and Bogoch, 2018). For example, air travel has been implicated in the global distribution of *Aedes aegypti* and *A. albopictus* mosquitos, important vectors of many infectious diseases (Kraemer *et al.*, 2015). Global trade of live and dead animals and plants has dramatically transformed the way pathogens and vectors can spread to new geographical locations, causing many infectious and zoonotic diseases to spread across continents (Jones *et al.*, 2013; Can, D'Cruze and Macdonald, 2019). The globalized scale of disease spread has resulted in profound consequences, such as increased *morbidity* and mortality and economic losses, as well as threatening the well-being of many species, populations, and entire ecosystems (examples in Table 4.1).

The COVID-19 pandemic has exemplified the effects of human mobility on the spread of infectious diseases. Initially detected in a single location in China, the SARS-CoV-2 virus rapidly spread in human populations around the globe, aided by international travel and trade (Sigler *et al.*, 2021). More than 585 million cases and 6.4 million deaths have been confirmed in humans (as of August 2022; World Health Organization (WHO), 2022). This pandemic has likewise emphasized the inequalities present in the globalized world, for example, low vaccine availability in low and lower-middle-income countries and the lack of human preparedness to deal with large disease outbreaks. Additionally, spillback of SARS-CoV-2 from humans to wildlife (Chandler *et al.*, 2021) and domestic animals (Shi *et al.*, 2020) have been observed, further highlighting the global-scale interconnectedness of human and animal health.

TABLE 4.1 Examples of the *globalization* of disease dynamics by human activities and consequences for ecosystems

Disease name	*Pathogen type, species*	*Host organism and area affected*	*Outcome*	*Anthropogenic factors affecting the disease spread or outcome*	*References*
NA	Bacterium. *Xylella fastidiosa*	Hundreds of plant species. Global	Local biodiversity loss and loss of crops → economic loss	Introduced to Europe from North America	Godefroid *et al.* (2019)
Bovine tuberculosis	Bacterium, zoonotic. *Mycobacterium tuberculosis*	Domestic cow (*Bos taurus*), European badger (*Meles meles*). United Kingdom	Slaughter of infected cows, extensive culling of wild badgers	Wild animal culling as zoonotic disease management—badgers were culled to slightly lower tuberculosis prevalence in cattle and lower the economic loss	Downs *et al.* (2019)
Chytridio-mycosis	Fungus. *Batrachochytrium dendrobatidis, B. salamandrivorans*	>500 species of amphibians. Global	90 species confirmed or suspected extinct, more experience severe population declines	Pathogen distribution facilitated by global trade of various amphibian species	Fisher and Garner (2020)
White-nose syndrome	Fungus. *Pseudogymnoascus destructans*	Bats (Chiroptera). North America	Decimation of populations	Disease spread by cavers, bat researchers, and tourists	Hoyt *et al.* (2021)
Chestnut blight	Fungus. *Cryphonectria parasitica*	American chestnut (*Castanea dentata*). North America	Near wipe-out of American chestnut, previously the dominant tree species in Eastern USA	Imported with seedlings from Asia	Jacobs (2007)
NA	Nematode. *Anguillicoloides crassus*	European eel (*Anguilla anguilla*). Europe	Population decline	Import of the parasite's native host, Japanese eel (*Anguilla japonica*), exposing the European eel, a novel host species, to the pathogen	Currie *et al.* (2020)

(*Continued*)

TABLE 4.1 (Continued)

Disease name	*Pathogen type, species*	*Host organism and area affected*	*Outcome*	*Anthropogenic factors affecting the disease spread or outcome*	*References*
Crayfish plague	Oomycete (fungus-like pathogen). *Aphanomyces astac*i	Many native crayfish species. Eurasia and Australia	Decimation of populations	Legal and illegal crayfish trade from North America	Martín-Torrijos *et al*. (2021)
NA	Virus. *Varroa destructor* mite vector for deformed wing virus	European honey bee (*Apis mellifera*). North America and Europe	Colony collapse	Asian honey bee *Apis cerana* transported from Asia together with *V. destructor*. European honey bee—a novel host.	Nazzi *et al*. (2012)
African Swine fever	Virus. African swine fever virus	Domestic and wild pigs. Global	Mass mortality of domestic and wild pigs, economic losses via loss of domestic pigs	Legal and illegal trade of pigs and swine products	Beltran-Alcrudo *et al*. (2019)
Myxomatosis	Virus. *Myxoma virus*	European rabbit (*Oryctolagus cuniculus*). Europe	Severe population declines	Introduction of new species as pest control. Virus from South America was purposefully introduced to control rabbits in Australia but then spread to rabbits in Europe.	Kerr (2012)

Harnessing principles of disease ecology as ecosystem health indicators for planetary well-being

Human activities that prioritize human needs over ecosystem health have led to a worldwide disruption of disease dynamics, with severe consequences for planetary well-being. The rapid evolution of microbes allows pathogens to effectively take advantage of beneficial conditions created by human actions to spread and infect susceptible hosts. The failure of disease control mechanisms in disrupted ecosystems can lead to a cascade of altered disease dynamics through socio-ecological systems at a global scale.

The recognition of these dynamics raises a difficult question: Is it possible for modern human societies to integrate as part of healthy ecosystems? Such assimilation may be achievable when small human societies use natural resources sustainably and locally, but in the globalized world most ecosystems that are affected by humans are linked to practically all other ecosystems on the planet. This facilitates potential universal sharing of pathogens among those ecosystems, risking both nonhuman and human health and well-being all over the world. This potential for global negative impacts begs questions such as whether it is ethical to allow any human activity within the relatively few thus-far undisturbed ecosystems, even when such activity is beneficial for human individuals and has no immediate destructive effects. Reaching comprehensive solutions requires shifting the focus away from the satisfaction of human needs and towards the well-being of whole ecosystems, in line with the planetary well-being approach.

Tools and data are needed to evaluate the impacts of different policies and practices on pathogen spread and changing pathogen burden, including pathogens with no immediate economic significance. Tools such as the Red List Index, an integrative measure of species extinction risk (Kortetmäki *et al.*, 2021) could serve as a proxy measure of planetary well-being from the perspective of disease burden, as (novel) pathogens and diseases not only threaten organismal well-being but also induce population declines, increase species extinction risk, and can have cascading effects in communities and ecosystems. Tools are also being developed that allow decision makers to estimate the economic cost through public health costs of altering habitat (see examples in Myers (2017)). These approaches could be complemented with indicators of (1) ecosystem health and functioning, such as measures of biodiversity, resilience, and pathogen or disease prevalence in the system; (2) societal characteristics (urbanization, socioeconomic equality, healthcare, *etc.*); and (3) risk factors for the spread of invasive species and pathogens (*e.g.,* global travel and trade). Developing reliable and compatible indicators for these complex issues is challenging but increasingly important because the combined information from such indicators could help in navigating trade-offs between human and nonhuman needs, supporting decision-making.

Training public health experts and decision makers with the use of such tools and applying the planetary well-being perspective is a potentially effective way to improve human and wildlife well-being. For example, the objectives of evidence-based ecological restoration policies could include both higher biodiversity and lower disease risk. The approaches under such policies might include *e.g.,* reintroductions of top predators, which have a demonstrated positive effect on community functioning and eventually reduced disease burden (Rey Benayas *et al.*, 2009). Solutions for reducing risky contacts among humans and domesticated or wild animals include reducing the use of animal-origin foods in human diets and ending the practice of keeping live animals in crowded conditions in live markets by developing improved monitoring and cold storage (Naguib *et al.*, 2021). At the same time, contacts with healthy natural ecosystems can benefit humans in terms of *e.g.,* beneficial microbes, clean air, nutrition, and mental health (Andersen, Corazon and Stigsdotter, 2021), with possible feedback through an increased commitment to protecting healthy ecosystems.

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