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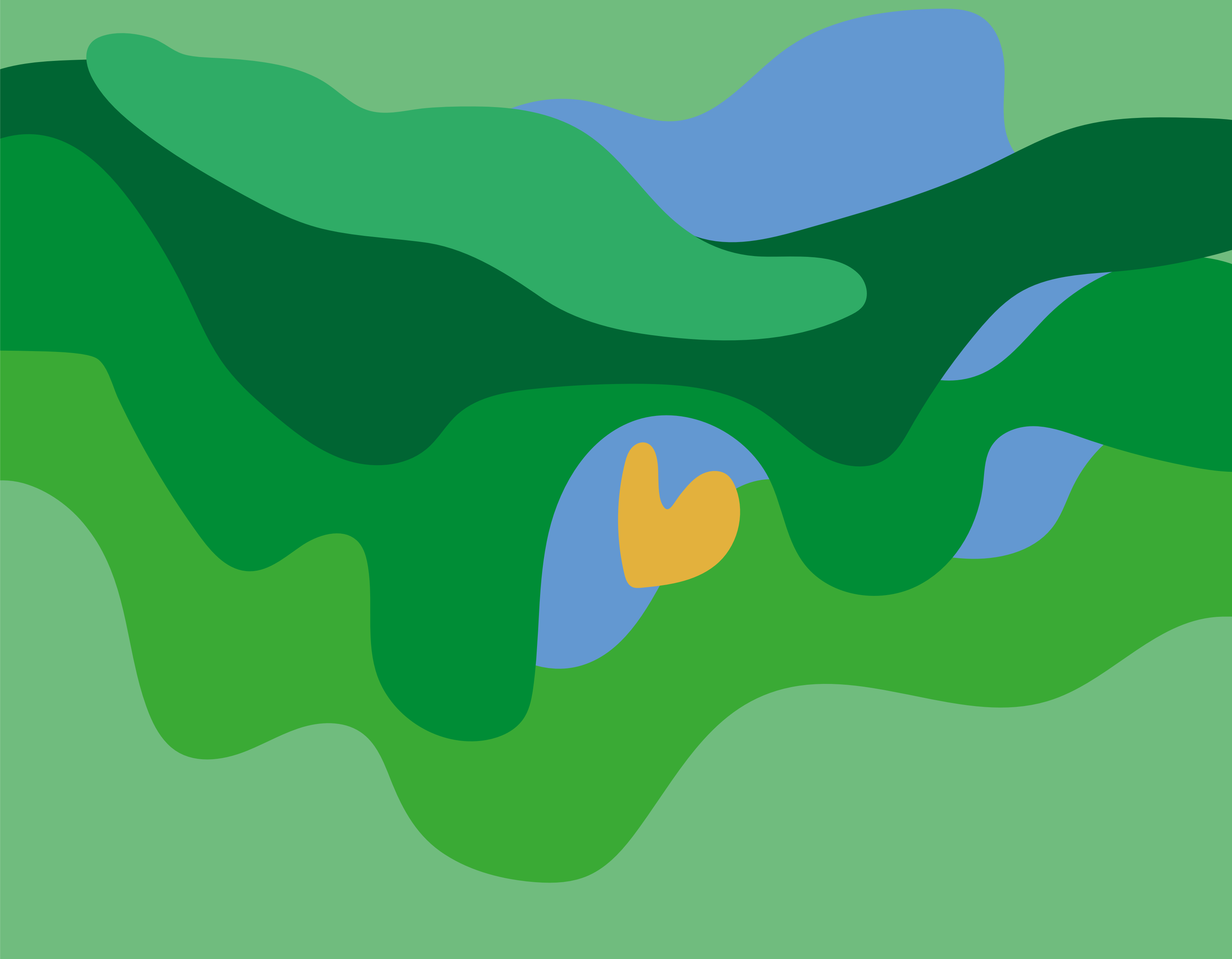
A health perspective on the role of the environment in One Health



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ABSTRACT

One Health is a cross-disciplinary approach to improve human health at the human-animal-environment interface. The role of the environment in this triad is often overlooked, however. This report explores and clarifies this role from a health perspective. In animal-mediated diseases, the environment plays a threefold role, acting as a reservoir where substances are accumulated and transported; as a focal point for ecological and chemical processes; and as a health mediator where disease agents from the environment are transferred to and affect animals and humans. The environment thus plays a substantial role in human physical and mental well-being. Anthropogenic stressors - including land use change, biodiversity loss, climate change and pollution - further affect the role played by the environment in the human-animal health interface. While One Health has traditionally focused on communicable diseases, this report suggests that the human-animal-environment interconnections provide insights into certain noncommunicable diseases, such as those caused by the human consumption of animals and animal products contaminated by chemicals, and injuries.

Keywords

ONE HEALTH
ENVIRONMENT
ECOSYSTEM SERVICES
ENVIRONMENTAL STRESSORS
ZOONOTIC DISEASE
ANTIMICROBIAL RESISTANCE
POLLUTION

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Abbreviations

AMR	antimicrobial resistance
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
DDT	dichlorodiphenyltrichloroethane
EID	emerging infectious disease
FAO	Food and Agriculture Organization of the United Nations
OIE	World Organisation for Animal Health
POP	persistent organic pollutant
SARS	Severe Acute Respiratory Syndrome
UNEP	United Nations Environment Programme

Executive summary

The COVID-19 pandemic and the increase in emerging zoonotic diseases in recent decades have led to a growing recognition of the importance of the One Health approach. One Health is an integrative, cross-disciplinary approach to designing and implementing actions and policies at the human–animal–environment health interface. The role of the environment in this triad has often been overlooked, however. While One Health traditionally focuses on communicable diseases – such as zoonoses – and diseases caused by antimicrobial-resistant pathogens and unsafe food, this report investigates the role of the environment, from the health perspective, focusing on animal-mediated diseases. It examines how the environment is affected by anthropogenic global stressors including land use change, biodiversity loss, climate change and environmental pollution of soil, water and air, which in turn increase the risks to human health. Consequently, this report expands animal-mediated diseases to include noncommunicable diseases, such as those caused by chemicals. These are relevant in a One Health context, since animals accumulate such pollutants, which are in turn consumed by humans, with adverse effects on their health. The report also includes injuries caused by animals associated, for example, with conflicting demands over land use.

This report notes that the role of the environment in animal-mediated diseases can be summarized as trifold.

- It acts as a **reservoir**, where nutrients and living organisms (microorganisms, plants and animals) are accumulated and transported. This includes disease agents such as bacterial species and antimicrobial resistance genes, among others, together with organic and inorganic residues, chemicals and metals.
- The environment is the substrate for chemical and ecological **processes** that provide myriad ecosystem services to humans, including those essential for human health. Ecological community processes such as food-web interactions, competition and symbiosis regulate species' population sizes. In the disease context, processes transform chemicals to bioavailable and bio-accumulating forms, such as the transformation of mercury to the highly toxic

methylmercury. Evolutionary processes can create new pathogens that may infect humans, or antimicrobial-resistant microbes and AMR genes.

- The environment is a **health mediator**, inducing positive or negative effects on animal and human health, depending on the health condition of the environment itself. This includes effects on the immune systems of animals and humans, which drive the rate of pathogen shedding and transfer.

Anthropogenic stressors cause or exacerbate the environmental role in animal-mediated diseases. **Land use change** causes fragmentation that enhances human contact with natural areas and wildlife. Habitat degradation causes proliferation of generalist and sympatric species that are adapted to humans and live in closer contact with them; they are thus more likely to spread diseases to humans. Increased environmental stress impairs wildlife immunity, causing shedding of pathogens to the environment and infection of other individuals.

Biodiversity decline compromises the dilution effect that often reduces pathogen spread and infection rates of humans. Wildlife hunting and trade is a major cause of biodiversity loss; it is also a central driver of transmission of zoonotic pathogens to humans. Antibiotic use in the growing livestock industry – for example, for prophylactic, therapeutic or growth-promotion purposes – may eventually run off with sewage to contaminate land and water sources. Accumulation of antibiotics and their residues in the environment for prolonged periods promotes gene exchange and mutations within organisms that create new resistant pathogens.

Climate change and rising temperatures lead to the spread of zoonotic hosts and vectors to higher elevations and latitudes, increasing the human population that is exposed to vector-borne diseases. Rising temperatures further stimulate the rate of reproduction of both pathogens and vectors. Foodborne infections also proliferate with increasing temperatures. Floods cause overflow of wastewater, leading to waterborne disease outbreaks.

Pollution such as persistent organic pollutants accumulates in the environment and further in the fatty tissues of animals, making food the main point of human exposure to these pollutants. Mercury and other heavy metals accumulate in fish, causing neonatal defects and neurological problems. Plastic pollution of the ocean accumulates in seafood, leading to endocrine problems and reduced fertility. Wildlife contact with humans in rural and residential areas can lead to injuries, attacks and snake envenoming.

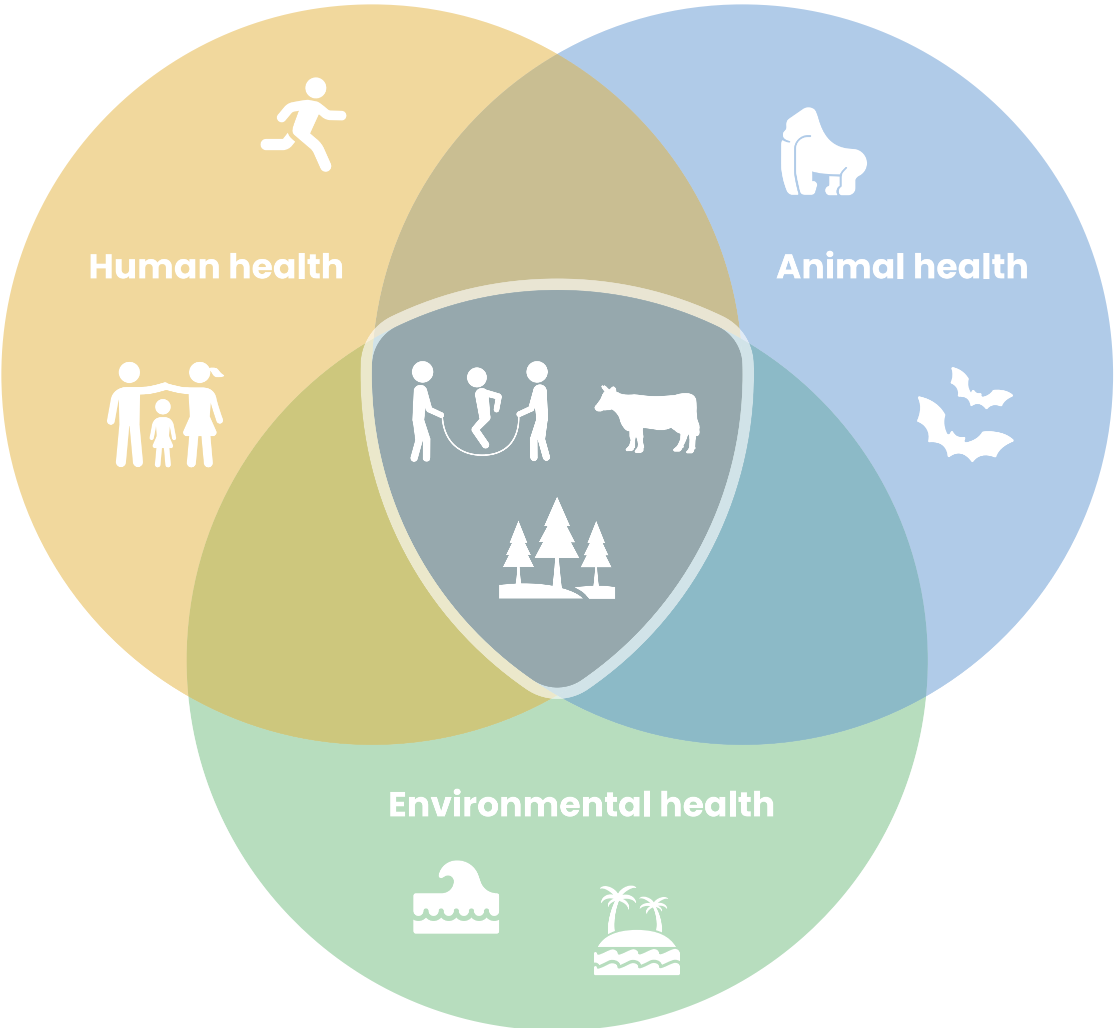
A wide policy base is in place in the United Nations global community and within WHO for stronger action to protect the environment as part of efforts to protect human health. Global initiatives including the Sustainable Development Goals, the Paris Agreement on climate change and the Stockholm Convention on Persistent Organic Pollutants all promote work to protect the planet. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), the Aichi Biodiversity Targets and the UN Decade on Ecosystem Restoration (2021–2030) all aim to protect biodiversity.

Similarly, WHO – both globally and within the WHO European Region – has multiple strategies and reports addressing ecosystem protection, climate change action and the hazardous effects of chemicals. Recent examples are the WHO global strategy on health, environment and climate change, the WHO Manifesto for a healthy recovery from COVID-19 and the report of the Pan-European Commission on Health and Sustainable Development. Within this context, efforts to restore natural habitats, biodiversity and clean environments could be incorporated as matters of human health emergency action. Surveillance of pathogens and antimicrobial resistance genes in the environment itself (in water and soil) using environmental genomics methods could take place alongside growing surveillance methods in wildlife. Ecologists, environmental scientists and evolutionary biologists should gain a more prominent role at the One Health table. Likewise, awareness-raising and capacity-building within the agricultural, urban planning, food safety and energy sectors, as well as within industry, could promote practices that better protect the health of the environment, animals and humans.

1. Introduction

One Health is "an approach to designing and implementing programmes, policies, legislation and research in which multiple sectors communicate and work together to achieve better public health outcomes" (WHO Regional Office for Europe, 2021a). It promotes multisectoral, transdisciplinary collaboration connecting human, animal and environmental health (Fig. 1). The focus of this report is on the role of the environment, from the health perspective, at the intersection where all three circles meet.

Fig. 1. One Health connects human, animal and environmental health



An approach connecting animal and human health can be traced back to ancient times. In the 19th century, scientists like Rudolf Virchow developed an interest in comparative medicine, linking similar disease processes in animals and humans (Zinsstag et al., 2011). The term "one medicine" was coined in 1976 by the "father of veterinary epidemiology", Calvin Schwabe, who proposed a holistic approach to human, animal and environmental health to better protect the health of all (Schwabe, 1984). Recognition of the importance of such integration has grown since the late 1990s, with the increase in emerging zoonoses (Jones et al., 2008) and growing understanding of zoonotic diseases and their way of spreading. In 2004, the Wildlife Conservation Society organized the "One World, One Health" symposium, which was attended by health experts from around the world. The Manhattan Principles formalized during the symposium link actions to promote human health – specifically regarding infectious diseases – with environmental stewardship, with the aim of protecting the biological integrity of the Earth (WCS, 2004).

In the years following the symposium, One Health has become prominent in several global commitments and political declarations. The emergence of H5N1 highly pathogenic avian influenza highlighted the urgency of implementing an integrative approach to address emerging infectious diseases (EIDs). These insights were formalized during the 2007 International Ministerial Conference on Avian and Pandemic Influenza in New Delhi, India. The participants developed a strategy to address EIDs at the animal–human–ecosystem interface that broadly followed the Manhattan Principles. In that meeting, WHO, the Food and Agriculture Organization of the United Nations (FAO) and the World Organisation for Animal Health (OIE) formalized their longstanding partnership in a tripartite commitment to promote multisectoral responses to public health threats originating in the animal–human–ecosystems interface (FAO et al., 2008).

The One Health approach sees human health as deeply interconnected with the health of animals and plants, and with the health of the environment and natural ecosystems. Thus, any area of human health – physical, mental and social – can benefit from an understanding of human connections to the surrounding world (Brymer et al., 2019; Evans & Leighton, 2014; Lerner & Berg, 2015). Some expand the objectives of One Health to achieving animal health and ecosystem resilience as independent goals (Evans & Leighton, 2014). WHO's areas of work in which One Health is commonly applied are control of zoonotic diseases, combating antimicrobial resistance and food safety. WHO also highlights that the One Health approach is relevant to laboratory services, neglected tropical diseases and environmental health (WHO Regional Office for Europe, 2021a).

Strong commitment to address human health challenges using the One Health approach has been renewed recently – specifically following the COVID-19 pandemic. During the pandemic, the United Nations Environment Programme (UNEP) joined the Tripartite Alliance on One Health to strengthen the environmental dimension of One Health approaches (UNEP, 2021). The Rome Declaration at the Global Health Summit of 2021 committed to work towards implementation of the One Health approach (G20, 2021). Similarly, the WHO Manifesto for a healthy recovery from COVID-19 commits to protect nature as the source of human health (WHO, 2020a).

Nevertheless, while the One Health approach acknowledges the role of the environment in the human–animal–environment triad, its role in animal-mediated diseases has not been sufficiently addressed (Essack, 2018; UNEP, 2021). While much emphasis has been put on the link between human and animal health, the function of the environment in the triad has not been formulated.

The purpose of this report is to formulize the role of the environment in the One Health approach – specifically where human health outcomes are mediated by animals (the intersection of all three circles in Fig. 1). From an **environmental health** perspective, it investigates stressors on the environment and the role such stressors play in diseases transferred by animals to humans, hereafter referred to as "animal-mediated diseases". It reviews the impact of four main environmental issues originally raised by the Rio de Janeiro Earth Summit of 1992, including land use change, biodiversity loss, climate change and pollution.

From an **animal health** perspective, the report addresses the environmental role in traditional One Health areas including zoonoses, antimicrobial resistance and food safety, while expanding to include the role of animals in transmitting pollutants.

From a **human health** perspective, the One Health approach has mostly been applied to communicable diseases. This report highlights how noncommunicable diseases and injuries are also highly relevant in this context. Animal-mediated diseases include both communicable (diseases that spread from one individual to another, such as those caused by zoonotic pathogens, resistant microbes and unsafe food) and noncommunicable (non-infectious health conditions, such as diseases caused by chemicals like mercury) diseases. These are relevant in a One Health context, since pollutants accumulate in animals, which in turn are consumed by humans and have adverse effects on their health. Further, injuries caused by animals – both near rural or urban areas and in the wilderness – can also be considered.

The report concludes by raising key points for the way forward and suggestions on how to incorporate the environmental role more fully in One Health. While it focuses on the WHO European Region, it should be noted that long-distance distribution of pollutants, immigration, international travel, global commerce and trade distribute pathogens and other disease agents globally.

2. Main areas of application for One Health

The One Health approach is commonly used in the areas of control of zoonotic diseases, antimicrobial resistance and food safety.

Zoonotic diseases are transmitted to humans from vertebrate animals – either wildlife or domesticated animals. The last few decades have seen a rise in EIDs (and re-emerging infectious diseases) originating in the animal–human interface (Jones et al., 2008). EIDs are newly identified, previously unknown infections, or those previously known to appear only at local levels. Some EIDs have caused devastating pandemics, such as the HIV/AIDS pandemic that started in the early 1980s and the current COVID-19 pandemic. The majority (60%) of EIDs are zoonotic, of which 71% originate from wildlife (Jones et al., 2008). Examples include Lyme disease, hantavirus, dengue fever, West Nile virus and Nipah virus.

There is a danger that environmental degradation and other pressures – such as increased human population densities, global trade and international mass transportation – will exacerbate the emergence of new zoonotic diseases. It is estimated that 1.7 million currently undiscovered viruses exist in mammal and avian hosts, almost half of which may have the ability to infect humans (IPBES, 2020). Since the beginning of the 21st century alone, the world has experienced emerging zoonotic outbreaks including severe acute respiratory syndrome (SARS) coronavirus (2003), Ebola virus (2005 and again in 2017), swine flu (2009), influenza H1N1 (2009), Zika fever (2015), Middle East respiratory syndrome coronavirus (2015) and COVID-19 (2019).

Zoonotic pathogens can be transmitted by direct contact with living or dead animals, by feeding on animals and their products, via vectors or indirectly from the environment – soil, water and air. Environmental degradation influences all these pathways.

Another group of diseases that can benefit from the One Health approach is neglected tropical diseases. These affect more than 1 billion people worldwide and are more prevalent among impoverished populations in remote areas or urban slums. Although neglected tropical diseases are more common in developing countries, immigration from low-income countries and international travel are making their occurrence more frequent in Europe (Calleri et al., 2019; Schlagenhauf et al., 2015). Some of these diseases are zoonotic, including rabies, echinococcosis, taeniasis/cysticercosis and foodborne trematodiases.

WHO declared **antimicrobial resistance (AMR)** one of the top 10 global public health threats facing humanity, and it has been called a "quintessential One Health issue" (Robinson et al., 2016). Annually, 700 000 deaths globally are attributable to infections by drug-resistant pathogens; this imposes significant economic costs (O'Neill, 2016). AMR occurs when a pathogen – including bacteria, viruses and parasites – develops a defence mechanism rendering it unresponsive to medicine, increasing the risk of disease spread, severe illness and death. AMR is driven by misuse and overuse of antimicrobials in human medicine, livestock and poultry production, aquaculture and plant agriculture, and by spread of microbes due to lack of proper sanitation and disinfection. In many countries antimicrobials are used in animal husbandry in subtherapeutic doses for prolonged periods, conditions that are conducive for development of resistance genes. These genes can be transferred to people from other people, from contaminated food, and from the environment (Robinson et al., 2016). Drug resistance to antivirals and anti-parasites, such as malaria medicines, are also a growing health issue.

Food safety is another major One Health concern: every year, an estimated one in ten people worldwide become ill from contaminated food, and 430 000 people die each year as a result, including 125 000 children under the age of 5 years. Foodborne diseases are caused by microorganisms (bacteria, viruses and parasites) or chemical hazards. Many of these pathogens have a zoonotic origin, such as *Salmonella* spp., *Campylobacter* spp., Shiga toxin-producing *Escherichia coli*, *Toxoplasma gondii* and *Echinococcus multilocularis*. Antibiotic residues in food may lead to transfer of antimicrobial-resistant bacteria and have direct adverse health impacts on humans, including immunopathological effects, allergy, mutagenicity, nephropathy, hepatotoxicity, reproductive disorders, bone marrow toxicity and carcinogenicity (Bacanlı and Başaran, 2019). Food safety is strongly related to animals, since a major exposure route for foodborne diseases is contacting domestic or wild animals, or feeding on animals and their products (WHO, 2015a).

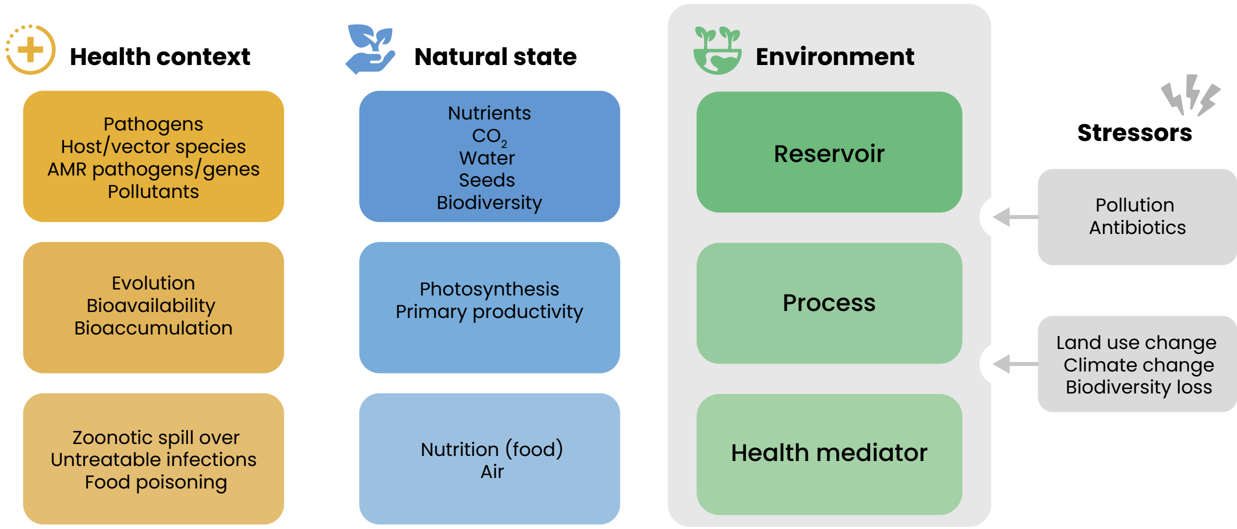
3. The role of the environment in One Health

Definitions of One Health refer to the interaction of human and animal health with the **environment** (as in UNEP, 2021) or **ecosystems** (as in FAO et al., 2008), interchangeably. For the purposes of this report, "ecosystems" are defined as natural communities of organisms, the physical environment with which they interact and their functioning as an ecological unit – mostly unaltered by anthropological land uses. "Environment" includes the complex mixture of physical, chemical and biotic factors, including land, air, water, soil and all living things that interact within it, as well as areas that are natural ecosystems or transformed to various degrees by humans (urban, agricultural and so on). The health of the environment determines its state and its ability to function at its best, including how free it is from non-native pollutants.

The state of the environment, changes and processes occurring in it play a central role in animal-mediated diseases. The One Health approach has promoted collaborations between health and veterinary professionals; much attention has been given in recent years to the relationship between human and animal health, focusing on zoonotic disease emergence (the intersection of the human and animal circles in Fig. 1). Similarly, the importance of environmental health – the impact of physical, chemical and biological hazards on human health – has long been recognized (the intersection of the human and environment circles in Fig. 1).

The world ecosystem is the source of life on earth and is essential to every aspect of human lives. Biodiversity, from the microbial to the ecosystem scale, is closely interlinked to human health. More specifically, the function of the environment in the One Health triad can be simplified into three main mechanisms: reservoir, processes and health mediator (Fig. 2).

Fig. 2. The role of the environment, in the context of One Health, in animal-mediated diseases



Note: Stressors on the environment (grey arrows on the right) affect all three functions of the environment, in both its natural state (light blue) and in processes that have adverse health effects (orange).

The environment functions as a **reservoir**, where substances and nutrients are accumulated and transported. The land areas, including its soil, and water bodies harbour communities of organisms inhabiting that area (microorganisms, plants and animals). The environment is also a natural reservoir of pathogens, antibiotic resistance genes and chemicals. Anthropogenic pollution of the air, water and soil deposits toxic chemicals, excess of nutrients, pathogens and antibiotics. These compounds too accumulate in the environment – some for prolonged periods. They are transported through the flow of air and water, as well as on and within the bodies of living creatures.

The environment is the substrate for ecological **processes** that provide myriad ecosystem services to humans, including those essential for human health. Habitat conditions define community composition, and the spatial distribution of the biota – plants, animals, microbes and other living organisms. Ecological community processes such as food-web interactions, competition and symbiosis regulate the population size of these species. These processes also drive the evolution of living creatures. Owing to the short lifecycle of microorganisms (including viruses), environmental stressors may have a more pronounced effect on the evolution of pathogens, resistant microbes and resistance genes. Some chemicals are transformed in the environment. For example, inorganic mercury can be methylated by microorganisms, creating the highly toxic and bioaccumulating methylmercury. Similarly, antibiotics – which are often easily degradable – can adhere to soil particles, making their effect durable for extended periods.

The environment acts as a **health mediator**, producing positive or negative effects on animal and human health, depending on the health condition of the environment itself. Chemicals, genes and pathogens are transferred to humans and animals either directly from the soil, air and water, or by feeding on or contact with infected animals. The health of the environment also affects the immune systems of animals and humans, driving the rate of pathogen shedding (the expulsion of disease-causing microorganisms into the environment) and transfer.

These three environmental mechanisms must be understood better in the context of the human–animal–environment interface. In addition, as the environment is constantly changing and being affected by many anthropogenic stressors and natural processes, it is important to understand how environmental degradation further affects these three mechanisms, since stressors have an impact on the dynamics happening within the human–animal–environment interface.

4. Environmental stressors

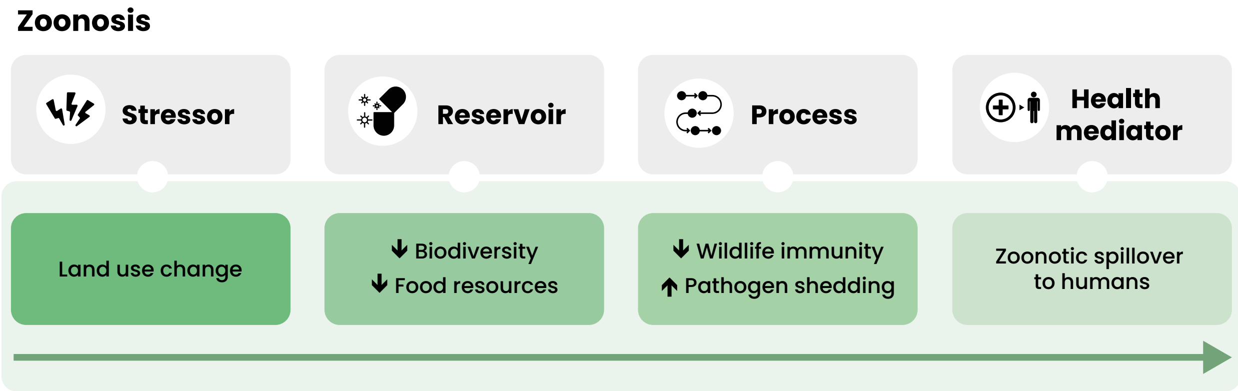
High rates of local, regional and global pathogenic exchange are driven by human population growth; high population density; and globalization characterized by massive exchange of people, commodities, animals and food products. While some trade is local, regional and global trade are accelerated over land, marine and air transportation, expediting the transmission of pathogens, chemical and toxins. These stressors play a major part in animal-mediated diseases. In this report, direct anthropogenic stressors to the environment are reviewed in the context of how they cause or exacerbate animal-mediated diseases. The stressors discussed here include land use change, biodiversity decline, climate change and chemical pollution (of the land, air, water and oceans).

4.1 Land use change

Humanity dominates life on earth, and is causing severe decline in terrestrial, freshwater and marine ecosystems. Around 75% of the land surface has been significantly altered, 66% of the ocean area is experiencing increasing cumulative impacts, and over 85% of wetland area has been lost. Land use change is driven primarily by agriculture, forestry and urbanization (IPBES, 2019).

Changes in land use increase the risk of zoonotic diseases. A global analysis shows that emerging zoonotic disease risk is elevated in forested tropical regions experiencing land use change and converted to agricultural cultivation or pastureland, and where mammal species richness is high (Allen et al., 2017). Habitat degradation is a leading cause of biodiversity decline and one of the mechanisms by which land use change leads to increasing rates of zoonotic disease emergence (Fig. 3).

Fig. 3. Mechanisms by which land use change leads to increasing rates of zoonotic disease emergence



Fragmentation of ecosystems elongates the edge between natural habitat and human settlements, thereby increasing human–wildlife–livestock contacts. Fragmented landscapes enhance human encroachment into forests and increase extraction of bushmeat and other forest products, while increasing wildlife dispersal into agricultural and residential areas (Faust et al., 2018).

Agricultural expansion occupies one third of all land surface and is an important driver of EIDs. Agriculture dangerously expanding in tropical forests, where biological diversity is remarkably high (IPBES, 2019). A global analysis shows that, since 1940, agricultural drivers have been associated with 25% of all and 50% of the zoonotic infectious diseases that emerged in humans (Rohr et al., 2019). People who live or work on agricultural land are more likely to be infected with a pathogen than those who are not exposed, including vector-borne and zoonotic diseases (Shah et al., 2019; Zukiewicz-Sobczak et al., 2013). Livestock cultivation plays an important role in zoonotic spread as 77% of livestock pathogens are capable of infecting multiple host species, including wildlife and humans (Rohr et al., 2019).

The abundance of zoonotic host species – specifically of passerine birds, bats and rodents – tends to increase in human modified habitats (Gibb et al., 2020). Generalist species can exploit a wide range of resources, and are proportionally increasing in fragmented and disturbed habitats (Devictor et al., 2008). Such species can move closer to human residents, and are more likely to transmit pathogens to humans. For example, fragmentation and reduced mammalian species diversity in the United States of America elevate the population density of white-footed mice – a generalist host species that spreads Lyme disease. Nymphal ticks showed higher infection with Lyme bacterium, *Borrelia burgdorferi*, in smaller forest patches due to fragmentation (Allan et al., 2003).

Habitat degradation increases inter- and intra-species competition and reduces available shelter from predators. Such environmental stress can have dramatic effects on immunocompetence of wildlife; sustained stress increasing adrenal hormones that have powerful anti-inflammatory and immunosuppressive properties. Immune response may also be affected directly by pollutants that have accumulated in terrestrial and aquatic ecosystems. Wildlife species may harbour a large variety of potential pathogens at undetectable levels for years, but poor immune responses increase the susceptibility of wildlife to pathogens that could previously be harboured asymptomatically. Compromised immunity increases both shedding of pathogens to the environment and infection rates of other individuals and other species. Movement of pathogens among species promotes gene exchange; this may increase the chance of evolution of genes that can infect and persist in humans, thereby elevating the probability of spillover – the cross-species transmission of a pathogen from animals to humans (Acevedo-Whitehouse et al., 2009).

Urbanization is another major environmental stressor responsible for land use change, causing myriad environmental problems, including climate change and pollution. Urban density is constantly growing: 55% of the human population lived in cities in 2018 (United Nations, 2018). Urbanization can influence the emergence and spread of infectious disease due to high human population density and a multitude of interactions, as well as potential for greater contact with urban wildlife.

Land use change caused by urbanization leads to soil sealing and the disruption of natural ecosystems. Destruction of habitat of local wildlife forces individual animals to invade cities (Grimm et al., 2008). Densities of mammal species can be higher in metropolises than the surrounding countryside generating a higher potential of human–wildlife conflict, human injury and distribution of zoonosis. For example, foxes have colonized the majority of Estonian towns, entered houses and attacked domestic animals, killing cats and poultry. Foxes have been found to carry sarcoptic mange – a disease that also infects domestic animals – and the life-threatening tapeworm *Echinococcus multilocularis* (Plumer et al., 2014).

In large urban centres, thousands of tonnes of food waste are left uncollected daily. Waste attracts domestic and wild animals, and – importantly – impoverished people, and becomes a focal point of pathogen spread (FAO, 2013). Human food waste becomes the main food source for animal species, causing uncontrolled population growth. Wild boar (*Sus scrofa*) are establishing a permanent presence in many cities in Europe. They are accustomed to humans and can be even observed during daylight approaching humans very closely, thereby posing a threat and potentially causing injuries (Stillfried et al., 2017). Importantly, wild boar harbour zoonotic diseases such as leptospirosis, hepatitis E virus and foodborne zoonoses, including bacterial diseases (brucellosis, salmonellosis, tuberculosis and yersiniosis) and parasitic diseases (toxoplasmosis and trichinellosis) (Fredriksson-Ahomaa, 2019).

Urbanization creates new habitats for reservoir host species. For example, leishmaniasis is a vector-borne disease endemic to the Middle East, caused by a protozoan parasite of the genus *Leishmania* and transmitted by phlebotomine sand flies. Urbanization and construction waste created new habitats for rock hyraxes (*Procavia capensis*), a reservoir host of *Leishmania*. This has increased the frequency of sand flies and Leishmania infection near their colonies, close to human residences (Salah et al., 2020).

Synanthropic species such as rodents and urban birds carry zoonotic pathogens that pose a particular threat because of close contact with high human population densities. Urban rodents carry a number of zoonotic pathogens associated with significant human morbidity and mortality; they contaminate food and may have an impact on mental health (Parsons et al., 2020). Urban transport development can further increase the prevalence of synanthropic rodents, as with the case of rat infestation of Manhattan subways in the United States.

Local and international trade centred in cities – with rapid exchange of people, food and consumer goods – increases exchange of pathogens and elevates the risk of epidemics and global pandemics. Large traditional and "wet" markets pose a specific threat for zoonotic spillover from consumed wildlife products to humans.

Urban natural parks and increased biodiversity in cities offer solutions to many urban environmental problems, such as air pollution, noise, heatwaves and floods. Urban nature harbours myriad benefits for human health and well-being

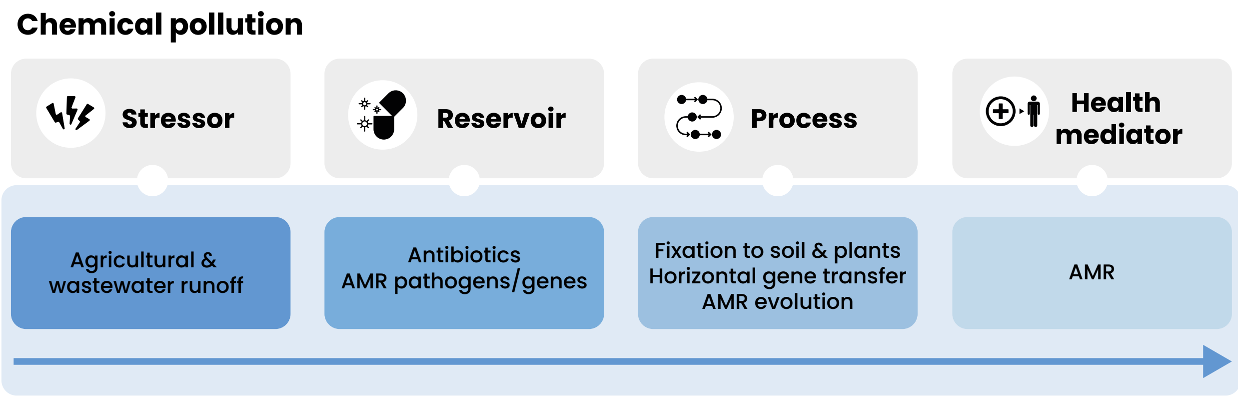
(European Commission, 2020). Demand for urban parks has increased during the COVID-19 pandemic (Geng et al., 2021); however, increases in wildlife populations in urban natural parks can increase the risk of injuries and zoonoses.

AMR is also affected by land use change – particularly change to agriculture. Antimicrobial agents are often overused and misused in human and veterinary medicine, animal farming and industrial settings. Antibiotics are commonly added to animal feed for therapeutic/prophylactic use or for growth promotion, and are excreted in urine and faeces. This results in residues of antibiotics, bacteria and antimicrobial-resistant metabolites and AMR genes, which accumulate in wastewater, agricultural fields and agricultural runoff. Plants grown in soil with applied animal manure were found to absorb chlortetracycline antibiotics (Kumar et al., 2005). Antimicrobials used in crops can be additional sources of resistance evolution (Thiele-Bruhn, 2003).

Antibiotics may be easily bio- or photo-degraded; in soil, however, antibiotic degradation is hampered through fixation to the soil matrix, and by organic and mineral exchanges of antibiotics in the soil. Land therefore serves as a reservoir for AMR accumulation, evolution and transmission (Thiele-Bruhn, 2003). Although antibiotics can be found in soil only in low concentrations, over prolonged periods, resistance can be provoked in soil microorganisms. There is evidence that antibiotic resistance occurs in nature and has an ancient origin. These genes can evolve new resistance mechanisms when they reach an environment with high concentrations of antibiotics (Allen et al., 2010). AMR genes can move through horizontal gene transfer – borne on plasmids, integrons and gene cassettes – from bacteria in manure to native soil and water microbial populations. Antibiotic residues and AMR genes are then transferred back to animals and to humans, through feed and even via fruit and vegetables (Kumar et al., 2005).

Excess manure from the livestock industry – or manure used as fertilizers – and wastewater runoff flow into natural water sources and the land (Fig. 4). They may all contain antibiotics administered to farm animals or humans, resistance pathogens and free resistance genes. They are accumulated in the environment for a long time, promoting horizontal gene transfer and evolution within natural bacteria to develop new resistant genes and pathogens. Those are transferred back through food or contact to humans, and proliferate AMR.

Fig. 4. Linking an environmental stressor to AMR



4.2 Biodiversity decline

Global rates of species extinction are tens to hundreds of times higher than the background extinction rate over the past 10 million years, and this rate is accelerating. Human actions have already driven at least 680 vertebrate species to extinction since 1500. Of an estimated 8 million animal and plant species, around 1 million are threatened with extinction. The five major anthropogenic drivers of biodiversity decline are land use change, overconsumption, disease, invasive species and climate change (IPBES, 2019).

Biodiversity loss has been strongly linked to increases in prevalence and an elevated risk of zoonotic disease. For example, prevalence of hantavirus increases when mammalian diversity decreases (Suzán et al., 2009). Similarly, the rise of West Nile virus is correlated with a reduction in bird species richness (Allan et al., 2003; WHO & CBD, 2015). High biodiversity serves as a buffer against disease transmission through several mechanisms. Ecological community processes – such as competition and predation – control population densities of natural zoonotic host reservoirs and arthropod vector densities, thereby reducing encounter rates between vectors and reservoir hosts or among hosts. Disruption of this balance by reducing the diversity of species in the community may cause irruption of zoonosis-harbouring species (Ostfeld, 2009).

The **dilution effect** postulates that a reduction in biodiversity has a strong correlation with increased zoonotic infection risk. It has been demonstrated that host diversity inhibits parasite (bacteria, viruses, ecto- and endo-parasites) abundance in a variety of ecosystems and pathogen types – including significant evidence for dilution effects of zoonotic parasites in humans (Civitello et al., 2015) – although in other cases the reverse relationship was demonstrated (Faust et al., 2017).

Disease is one of the causes of global biodiversity decline. Zoonotic diseases often spill over back to wildlife, though either contact with livestock or consumption of infected prey animals, causing further decline to animal biodiversity (Gortázar et al., 2007). Toxic chemical pollution is another major driver of ecosystem degradation and biodiversity decline (IPBES, 2019; Liang et al., 2020), which exacerbate the effects of zoonotic spread.

Overconsumption of wildlife due to hunting is among the main drivers of extinction. Concurrently, hunting, butchering and consuming wildlife considerably increase the risk of new disease emergence. It is estimated that 71% of zoonotic infections originate from wildlife (Jones et al., 2008). Devastating zoonoses including Ebola (bats, primates), HIV (chimpanzees), anthrax (ungulates), Simian foamy viruses (gorillas) and monkeypox emerged in humans via consuming or handling bushmeat (Faust et al., 2018). Increases in demand for bushmeat drive illegal hunting further. It is estimated that a total of 4.5 million tonnes of bushmeat are extracted annually in the Congo Basin alone (Wolfe et al., 2005).

Wildlife trade has adverse effects on biodiversity and ecosystem function, increases zoonotic spillover to humans and to domesticated animals, and provides a worldwide disease transmission mechanism (Karesh et al., 2005). Trade in species at risk of extinction was restricted by CITES as early as 1973, but wildlife trade is expanding regionally and globally as a result of increasing demand for products and meat. Global illegal trade in wildlife is estimated in billions of dollars annually (UNEP, 2020a). Importantly, wildlife trade is also prevalent in the Global North; this poses a potential global health and biosecurity risk. Annually, about 5 tonnes of wildlife meat is smuggled through a single airport in western Europe (Katani et al., 2019), and 2 million wildlife transports arrive in the United States (Eskew et al., 2020).

Millions of wildlife transports flow through trading centres daily, coming into contact with countless other wild species, livestock and humans. These close and repeated interactions increase chances for pathogens to evolve to transmittable pathogens and to spill over to humans (Karesh et al., 2005). Wet markets sell live poultry, livestock and wildlife. They are common in Asia but can be found worldwide. The origin of SARS coronavirus was linked to wildlife markets in Guangdong Province in southern China, and live poultry markets in the United States have been associated with the emergence of H5 and H7 influenza viruses (Webster, 2004).

The number of **invasive plant and animal species** has increased globally through human trade and travel, and is expected to escalate further as a result of climate change. Invasive species pose a significant threat to local diversity, and interfere with local wildlife community dynamics. In parallel, they affect human health by introducing new pathogens and exposing humans to bites and stings (WHO & CBD, 2015).

Some invasive species are vectors or reservoirs for pathogens. For example, the Asian tiger mosquito has been linked to more than 20 diseases, including yellow fever, dengue fever and chikungunya fever. Climate change projections show that the mosquito is likely to extend its range further north. Raccoon dogs and red foxes are becoming new reservoirs for rabies as they spread into new eastern European habitats, following the accidental release of animals used in the fur trade (WHO & CBD, 2015). Aquatic invasive species, such as the zebra mussel, promote blooms of toxic cyanobacteria like *Microcystis aeruginosa*, which may cause accumulation of microcystins, hepatotoxins and cancer via eating fish. Zebra mussels also threaten the availability of clean water supplies, and pose other significant health threats (WHO & CBD, 2015).

4.3 Climate change

Climate change is a "threat multiplier" to other environmental problems, a human health threat and a driver of biodiversity decline. Climate change alters habitat conditions, driving organism migration to higher latitudes and altitudes. Migration of species disrupts synchronicity between interacting species and changes tropical cascades. Such changes may interfere with natural control of wildlife populations and cause outbursts of disease vectors or host species (Patz & Hahn, 2012).

Increasing temperatures drive range expansions of disease vectors (such as fleas, ticks, aphids and mosquitoes) and of zoonotic hosts by facilitating survival in higher latitudes and altitudes (as in the case of *Aedes albopictus* mosquitoes). Several neglected tropical diseases can now be found at higher latitudes.

Climate change affects the transmission of vector-borne pathogens such as dengue, chikungunya, Zika, Japanese encephalitis and West Nile viruses. Rising temperatures accelerate the population growth of some vector and pathogens. For example, rising temperatures in east African highlands from 1950 to 2002 coincide with increases in malaria incidence, probably because of marked increases in mosquito populations. The incubation periods of pathogens decrease and their replication rates increase with elevated temperatures, expanding the pathogen load within vectors. For example, the rate of dengue virus replication in *Aedes aegypti* mosquitoes increases directly in line with temperature in the laboratory (Mills et al., 2010).

Climate change increases the rate of extreme weather events and weather disasters including floods, fires and hurricanes. Heavy rainfall events increase the risk of wastewater overflow, and cause waterborne disease outbreak (Patz et al., 2008). Weather-related disasters such as floods and fires destroy natural habitats, creating a threat to biodiversity, which is important in zoonotic control. Extreme temperatures and drought cause stress to wildlife and impair immune responses, thereby increasing shedding of zoonotic pathogens (Acevedo-Whitehouse et al., 2009).

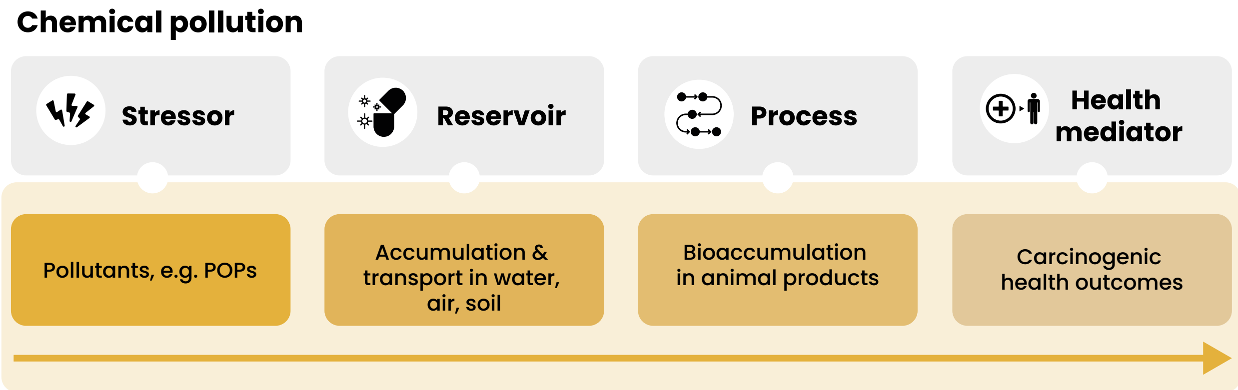
Foodborne diseases are also affected by fluctuations in temperature. An estimated 30% of reported cases of salmonellosis across Europe have been attributed to warm temperatures, and food poisoning in the United Kingdom was strongly correlated with temperatures in the previous weeks (Patz et al., 2008).

4.4 Ecotoxicity and chemical pollution

The One Health concept has traditionally mostly focused on zoonoses, AMR and food safety in relation to communicable diseases. Chemical- and poison-related illnesses occur in animals, however, and can be directly related to human health and thus to the One Health concept (Buttke, 2011; Frazzoli & Mantovani, 2018; Ladeira et al., 2017). Toxins that affect animals are likely to affect humans; this serves as the basis of comparative and translational medicine. Domestic and wild animals affected by environmental pollution may act as an early warning of human illness, hence serving as a basis for shared risk analysis (Carson, 1962; Rabinowitz et al., 2010). In additions, toxins accumulating in animals cause adverse health effects in humans feeding on animal products. Chemical pollution mainly pertains to noncommunicable animal-related disease (Fig. 5). A particularly useful example of using the One Health approach in a chemical-outbreak investigation occurred during an epidemic in Dhaka, Bangladesh. Toxicologists at the Centers for Disease Control and Prevention in the United States, who examined both humans and animals, found a common etiology caused by carbofuran – a carbamate-type pesticide (Buttke, 2011).

Persistent organic pollutants (POPs) such as polychlorinated biphenyls, dioxins and dichlorodiphenyltrichloroethane (DDT) are used as pesticides, industrial chemicals and production by-products; these may be emitted in the air or water through industrial processes. POPs become globally distributed in the environment as a result of natural processes involving soil, water and particularly air. They stay intact in the environment for exceptionally long periods, and can be transported over large distances by wind or water (UNEP, 2020b).

Fig. 5. The role of the environment in linking chemical pollution to both animal and human health



A particularly toxic POP is 2,3,7,8-tetrachlorodibenzo para dioxin, which is a by-product of industrial processes (WHO, 2010). POPs and dioxins are lipophilic; they are concentrated in fatty tissues of animals and bioaccumulate through food chains. Dioxins are highly toxic in animals: they cause birth defects and stillbirths in mammals and induce death in fish. More than 90% of human exposure to dioxins is through food – mainly meat and dairy products, fish and shellfish (Kannan et al., 2002). Human exposure to dioxins causes cancer, interferes with hormones, causes reproductive and developmental problems, and damages the immune system (WHO, 2010).

Meat production has tripled in the last 50 years, and rising demand for animal-based protein in the developing world is driving further expansion of this industry (Ritchie & Roser, 2009; FAO, 2013). Consumption of red meat may, however, have adverse health effects resulting from accumulations of fat-soluble environmental toxins (Domingo & Nadal, 2016). Such toxins include heavy metals (arsenic, cadmium, mercury and lead), polycyclic aromatic hydrocarbons, pesticides, polychlorinated dibenzo-p-dioxins and dibenzofurans, polychlorinated biphenyls, polybrominated diphenyl ethers, polychlorinated diphenyl ethers, polychlorinated naphthalenes and perfluoroalkyl substances. While use and production of some of these chemicals have been discontinued, they still can be found in the environment because of their strong durability. These compounds were found in meat, eggs, chicken and dairy in studies across Europe (Domingo, 2017; Domingo & Nadal, 2016). Many of these compounds are included in comprehensive regulations on contaminants in food, in national and European Union legislation, and in global trade regulations. Nevertheless, the pervasive and global nature of the chemicals necessitates multisectoral collaboration. Foodborne illness from dioxins alone is estimated to affect 193 447 people annually (WHO, 2015a).

Mycotoxins are toxic secondary metabolites of fungal origin (such as *Aspergillus*, *Penicillium* and *Fusarium* genera) and contaminate agricultural products; they may appear in 24–50% of commodities globally. They cause damage to crops and have adverse health effects in farm animals. Mycotoxins can be transferred to humans from plant-based food or be accumulated in meat, milk and eggs. They have direct effects on human health, including acute poisoning and long-term effects such as immunodeficiency, liver cancer, oesophageal cancer, neural tube disorders and stunted growth (Ladeira et al., 2017).

4.5 Air pollution

Air pollution emitted by industry, fossil fuel combustion, urbanization, transportation, unmanaged and illegal burning of waste and agriculture production leads to major adverse health effects and is a leading cause of climate change. About 7 million people die annually as a result of air pollution (4.2 million from ambient air pollution and the rest from indoor air pollution), which can cause heart disease, stroke, chronic obstructive pulmonary disease, cancer and pneumonia (WHO, 2019). While air pollution has numerous connections to human morbidity, this report focuses on those related to the human–animal–environment interface.

POPs are semi-volatile, and some are emitted to the air. POPs are toxic and carcinogenic through dermal absorption, air inhalation and ingestion of contaminated soils. As noted above, however, consumption of animal products is the main source of human exposure to these air pollutants (UNEP, 2020b).

Air pollution damage affects plants and animals, reducing their ecosystem functioning. Air pollutants penetrate plants, mainly through the leaves; it causes oxidative stress, disrupts photosynthesis and can cause massive plant death. Acid rain causes leaching of the mineral elements calcium, potassium and magnesium from plants. Nitrogen compounds and acid deposition cause eutrophication and the acidification of natural environments, and ozone accelerates ageing of vegetation. Air pollution also effects plant–insect relationships by changing plant colour, disturbing chemical communication between plants and insects, and interfering with pollen production (Misztal et al., 2015). Fluorides from air pollution accumulated in crops fed to animals cause bone and teeth damage that may even harm the animal's ability to eat. Other pollutants injurious to animals include carbon monoxide, hydrogen sulfide, bromine, iodine and mercury vapour (Gheorghe & Ion, 2011).

Reports of sickness, toxicity and death of wildlife and domestic animals due to air pollution are widespread (Liang et al., 2020; Newman, 1979; Peterson et al., 2017). This can have an indirect effect on the spread of zoonotic disease by suppressing animals' immune systems and via biodiversity decline, although some surprising evidence showed a reduction in parasitic infections in pheasants and hares with higher air pollution (Newman, 1979). Effects on plant production and animal survival can also pose a human food security problem.

Heavy metals cadmium, lead and mercury are common air pollutants. They can be transported over large distances in the air, and accumulate in the soil. Cadmium is a potential human carcinogen, causing lung cancer. Lead exposure has developmental and neurobehavioral effects on fetuses and children, and elevates blood pressure in adults. Soil microorganisms make metals bioavailable, and they are further accumulated in animals through the food-chain. Consumption of plants contaminated with heavy metals and organic compounds affects human health (Misztal et al., 2015).

Pasture grasses and hay in metal processing region in Kazakhstan were found to have high lead, cadmium and zinc concentrations. Subsequently, high concentrations of these heavy metals were found in the tissues of meat (cattle, horse and sheep) used for human consumption (Farmer & Farmer, 2000). As with mercury, the main toxic effect of lead is on neurological development of fetuses. In adults, it causes adverse blood problems, reproductive dysfunction, damage to the gastrointestinal track, nephropathies, damage to the nervous system and interference with heme synthesis. The toxic effects of cadmium cause renal dysfunction, hypertension, arteriosclerosis, growth inhibition, damage to the nervous system, bone demineralization and endocrine disruption (González-Weller et al., 2007).

4.6 Water pollution

Waterborne zoonotic diseases are transmitted by drinking or coming into direct contact with contaminated water. In addition, indirect exposure to waterborne pathogens occurs through use of contaminated water for irrigation or food preparation. The proportion of zoonotic pathogens among all waterborne pathogens is unknown, but it is estimated to be substantial. Examples include *E. coli* O157:H7, *Campylobacter*, *Cryptosporidium*, *Shigella* and hepatitis E virus (Cotruvo et al., 2004). Approximately 4 billion cases of diarrhoeal disease occur each year, leading to nearly 2 million deaths.

Climate change increases flood events that compromise water quality. Conversely, climate change causes water shortages and drought, further exacerbating water contamination by reducing water flow and increasing pathogen concentration. An outbreak of human leptospirosis in 2018 was linked to faecal contamination of cattle and wild boar origin of water bodies, worsened by low precipitation, which caused water stagnation (Dadon et al., 2018).

Livestock or human faeces is the major source of water contamination. Large-scale livestock production produces enormous amounts of manure. While some of it is applied to agricultural fields, it is problematic to dispose of the excesses that remain. Animal manure, sewage discharge and overflow from agricultural fields cause nitrate and phosphorous leaching to the ground and runoff to watersheds. Excess nutrients in water lead to microbial and algal proliferation and eutrophication. Toxic harmful algal blooms affect health through direct exposure to toxic cyanobacteria, and impose a food safety hazard by accumulating in shellfish that ingest these toxins. The toxins cause health conditions ranging from mild skin or respiratory irritation to gastrointestinal illness (Buttke, 2011).

Runoff from pastureland with free-ranging animals is also a major cause of faecal water pollution. Free-ranging animals have wide distribution and access to river and lakes, spreading pathogenic microorganisms such as *Campylobacter*, *Cryptosporidium* and *Giardia* into streams and rivers, compromising the safety of water sources (Cotruvo et al., 2004).

Water polluted by agricultural discharge, hospital waste or sewage disseminates antibiotics, resistant bacteria, resistance genes and infectious bacteria into the environment. Aquatic environments – surface water and groundwater bodies – therefore provide a setting for the transport and horizontal exchange of mobile genetic elements encoding antibiotic resistance. In addition, antibiotics released to the environment can have a selection pressure on antibiotic-resistant bacteria (Marti et al., 2014).

4.7 Ocean pollution

Ocean pollution is worsening worldwide. Anthropogenic emissions of carbon dioxide lead to ocean acidification that destroys coral reefs, impairs shellfish and dissolves calcium-containing microorganism that are the basis of the marine food web. Agricultural and sewage runoff brings heavy loads of fertilizers and nutrients that lead to harmful algal blooms and eutrophication. Other pollutants include toxic metals, plastics, manufactured chemicals, petroleum, urban and industrial waste, pesticides and pharmaceutical chemicals. These have negative impacts on marine ecosystems, impair photosynthesis and threaten marine mammals and fish. Pollution also brings to the ocean pathogenic and antimicrobial-resistant bacteria (Landrigan et al., 2020).

Nonetheless, 20% of the human population depend on protein from seafood sources. Pollution causes damage to marine fisheries and may cause nutrition deficiencies. Pollutants and pathogens accumulate in seafood, with impacts on human health. Heavy metals commonly found in fish and seafood include mercury, arsenic and lead. Mercury is a heavy metal that pollutes water mainly from coal combustion, small-scale gold mining and other industries. Transportable inorganic mercury becomes bioavailable by bacterial methylation. Methylmercury accumulates through the food-chain in predatory fish in lakes and seas, and these are the main routes of human exposure. It is a potent neurotoxin, especially in fetuses. Adult exposure to methylmercury leads to an increased risk of cardiovascular disease and dementia (Landrigan et al., 2020).

Other carcinogenic pollutants that accumulate in seafood include polychlorinated dibenzo-p-dioxins and dibenzofurans, and polychlorinated biphenyls (Domingo, 2016).

Bacteria that carry AMR genes arrive in oceans from land-based sources and can be passed to marine bacteria or to indigenous pathogens such as *Vibrio* through horizontal gene transfer (Landrigan et al., 2020).

More than 10 million tonnes of plastic enter the oceans annually. Ingestion of microplastics by marine organisms can cause blockage of the intestinal tract, inflammation, oxidative stress, hormone disruption, reproductive impacts and metabolic and behavioural changes (Almroth & Eggert, 2019). Plastic waste also accumulates in seafood. Consuming plastic-related pollutants by humans can disrupt endocrine signalling, reduce fertility, damage the nervous system and increase risk of cancer (Landrigan et al., 2020). Microplastic can be colonized by microbes and potential pathogens (Almroth & Eggert, 2019).

Marine pollution promotes proliferation of zoonotic viruses and parasites that infect humans through fish consumption. Anisakiasis is a zoonosis caused by the fish parasitic nematode and is spreading in Japan and Europe. European anchovy from the Mediterranean shows a 75% infection rate. Diphyllobothriasis is another emerging marine parasite that is associated with the consumption of raw Pacific salmon (Landrigan et al., 2020).

5. The animal–environment nexus and noncommunicable diseases

Environmental issues cause a variety of noncommunicable diseases, including cardiovascular diseases, cancers, respiratory diseases and diabetes. In addition, environmental pressures – and specifically ecosystem degradation – compromise the ability of natural environments to provide ecosystem services that may protect and promote health and well-being.

The One Health approach often focuses on infectious (communicable) diseases, but animals are also connected to human health by causing certain noncommunicable diseases – notably those brought about by consumption of animals and animals' products contaminated by pollutants. Meat and other animal-based products including seafood, dairy and eggs are a major route of human exposure to toxic chemicals. Accumulation in animal fatty tissues concentrates toxins to dangerous levels that may cause severe health conditions including cancer, endocrine disruption and damage to immune and neurological functions.

On the positive side, however, closer human connection to nature and animals – both wildlife and pets – has been offered as a possible approach to alleviate the rise in mental health disorders (Brymer et al., 2019). For example, one study found a positive relationship between bird species richness – a proxy indicator for environmental quality – and good human health. Bird songs were associated with restorative and stress-reducing effects (Methorst et al., 2020). Biodiversity is associated with mental health benefits, physical activity and cultural services that reduce stress and may improve immunocompetence.

Microbiome diversity on the skin and within the gut of the human body plays an essential role in health functions and is influenced by both the environment and the animals humans interact with. Microbiome may be acquired from animal products and from contact with animals such as farm livestock and pets. Therefore, applying the One Health approach to the microbiome facilitates consideration of both pathogenic and non-pathogenic microbial transfer between humans, animals and the environment (Trinh et al., 2018).

The internal microbiome has a role in noncommunicable health functions including metabolism, immunity and even mood and brain function, and in protection against pathogenic microorganisms and toxins. Gut microbiota can metabolize and detoxify environmental pollutants with carcinogenic or mutagenic properties, including biodegradation of polycyclic aromatic hydrocarbons, nitro- and nitrated polycyclic aromatic hydrocarbons, some pesticides and polychlorinated biphenyls. The microbiome in the external environment plays an important role in the internal microbiome. Human modification of natural environments, transgenic plants, spread of antibiotics to soil and water, and agricultural practices affect microbiome composition in the human environment and food, and may thus compromise the diversity and function of the internal microbiome (Flandroy et al., 2018).

5.1 Using animals as sentinels

The One Health approach involves a comparative clinical approach that considers shared risk between humans and animals. Wildlife can serve as sentinels to human health by detecting environmental health hazards, thanks to their greater susceptibility, higher environmental exposure and shorter lifespan. Studying disease in wildlife in natural environments may signal potential human health threats posed by pathogens or toxins.

A famous example is birds dying as a result of chemical pesticides such as DDT and other organochlorine compounds, as described by Rachel Carson (Rabinowitz et al., 2010). Polybrominated biphenyl is a flame-retardant POP that was produced for a short time. It caused devastating health problems in cattle exposed to contaminated grains and led to health problems among people ingesting polybrominated biphenyl accumulated in meat and milk. Earlier recognition of the problem in animals could have led to faster diagnosis and prevented human consumption of contaminated animal products (Buttke, 2011).

Using animals as sentinels in One Health is an expansion of comparative medicine that uses animals as model for human disease and therapeutics. In Florida, United States, the Red Tide programme uses the appearance of dead fish on the beach as an early detection system for harmful algal blooms. In some areas of the United States, sentinel flocks of poultry are used to monitor the environmental risk of West Nile virus (Trevejo & Reeves, 2005). Similarly, laboratory rats have been placed under high-voltage power lines to study the effect of electromagnetic field exposure. Animal population studies are used, for example, to examine endocrine disruption in fish exposed to discharges from power plants (Rabinowitz et al., 2010). Fish behavioural responses to pollution have recently been used as a biological early warning system for water pollution (Bae & Park, 2014).

5.2 Food security

A healthy diet protects against both malnutrition and noncommunicable disease; however, about 9.9% of the global human population experience undernourishment. Global prevalence of moderate or severe food insecurity has been slowly on the rise since 2014, with a dramatic increase in 2020 as a result of the COVID-19 pandemic (FAO et al., 2021). Land degradation has reduced land productivity in 23% of the global terrestrial area. Between US$ 235 billion and US$ 577 billion in annual global crop output is at risk as a result of pollinator loss. Local varieties and breeds of domesticated plants and animals are disappearing. These losses of diversity – including genetic diversity – pose a serious risk to global food security by undermining resilience to threats such as pests, pathogens and climate change (IPBES, 2019).

Infectious diseases caused by zoonosis can also risk availability of protein from animal sources. Some zoonotic diseases compromise animal production, since measures such as animal movement control and mass culling are necessary to limit outbreak transmission. For example, during the African swine fever outbreak, more than 40% of China's swine herds were destroyed (Espinosa et al., 2020). Similarly, outbreaks of *Salmonella* or avian influenza lead to culls of millions of poultry, incurring major economic costs and limiting food availability. It is estimated that emerging livestock disease outbreaks around the world since the 1990s have cost the world's economies US$ 80 billion (Karesh et al., 2005).

Leading risk factors for noncommunicable diseases are diet related, including high intake of red meat, trans fatty acids, sodium and sugar. As noted above, animal production is closely related not only to zoonosis but also to land degradation, water pollution and climate change. Sugar-cane production expands rapidly and leads to deforestation of tropical forests where it primarily grows (although much of the production is for biofuel). It can therefore be generalized that what is not healthy for nature is not healthy for humans, which aligns with the WHO call to update food-based dietary guidelines through a full integration of environmental sustainability elements (FAO & WHO, 2019; WHO, 2020a).

6. Injuries

Animals can be a source of injuries and even predation on humans, albeit extremely rarely in the WHO European Region. Large mammals inhabiting human-dominated landscapes may lead to human-wildlife conflict. Although wildlife predation on humans is rare, 12 species of predators have been found to make multiple predatory attacks on humans, although only five (tigers, leopards, sloth bears, lions and brown bears) kill people on a regular basis. In the WHO European Region, brown bears, polar bears and wolves have attacked people, although the only cases of rabid wolf attack in western Europe in recent decades have occurred along the borders with the Russian Federation and Belarus, where rabies is still prevalent. Rabies is, however, widespread in the Middle East, central Asia and India (Linnell & Alleau, 2016).

More common are attacks on livestock and poultry. Wolf predation on livestock is correlated with pressure of wild ungulate hunting. It is important to bear in mind, however, that viable populations of a diversity of carnivores are essential for ecosystems' function; dense human populations and carnivore population can coexist, given proper legislation and management practices (Fernández-Gil et al., 2016). Large wild ungulates can cause considerable damage to agriculture and forestry. For example, in Poland in 2010, €13.7 million was paid as compensation for crop damage by large ungulates such as wild boar, red deer and European Bison (Hofman-Kamińska & Kowalczyk, 2012). Damage to farm products poses a food security threat, specifically in regions without proper compensation mechanisms and in rural areas that depend on subsistence farming.

Snake-bite is a neglected tropical disease, causing 2.7 million envenoming cases and 81 000–138 000 deaths annually, mainly of agricultural workers in the tropics (WHO, 2021). Research has shown that the type of agricultural land use, snake ecology and precipitation patterns influence the probability of snake-bite in Sri Lanka. This is an example of how consideration of the interconnections between the environment, climate, animal ecology and human behaviour can contribute to addressing human health problems (Goldstein et al., 2021).

7. One Health and inequity

Considerable disparities exist in the impact of environmental health on human health in general, and on animal-related diseases in particular. Such disparities are driven by social and economic inequalities, as well as by gender, race, age and pre-existing health conditions. Inequity can be broadly classified to differences in exposure, sensitivity and adaptive capacity to adverse environmental conditions.

Exposure to zoonotic pathogens emergence is greatest among people who come into frequent contact with wild animals, such as hunters, butchers, veterinarians, workers in the wildlife trade and zoo workers. Exposure to zoonotic and AMR pathogens is also high in farmers, animal husbandry workers and health professionals. Indigenous and rural populations are more exposed to zoonotic agents from wildlife, through direct contact – such as bushmeat hunting and handling – or indirectly from the environment, while extracting timber or other forest products. Likewise, there are disparities in exposure to chemicals, water and air pollution: poor communities are more likely to suffer. The burden of foodborne illness related to dioxins is twice as high in low-income regions such as the eastern Mediterranean as in Europe (WHO, 2015a).

Increased **sensitivity** can be driven by gender or age – for example in pregnant women, elderly people or those with immunodeficiencies. Increased exposure to pollution can increase sensitivity by compromising immune response and increasing susceptibility to zoonotic pathogens.

Disparities exist in **adaptive capacity** to health emergencies, outbreaks and climate change. Higher income is often associated with better access to health care, emergency medical services and social adaptive capacity to handle infectious and environmental health emergencies. For example, mortality rates from COVID-19 were higher in people from lower socioeconomic groups in São Paulo, Brazil (Mitchell & Popham, 2008). (Nevertheless, the worldwide death toll was lowest in low-income communities (Our World in Data, 2021)).

Rural poor populations generally have limited access to high-quality human and animal health services, inhibiting timely treatment of zoonotic emergence. Marginalized communities have lower adaptive capacity to environmental change and pollution, and fewer climate change adaptation measures (Mitchell & Popham, 2008). Resilient and equitable health systems are therefore inherent within the One Health concept.

8. Policy relevance

Advancing human and environmental health is well imbedded within United Nations and international initiatives and within WHO's mandate, policies and actions. Policies are in place that address each of the components of One Health: many address human health issues; some are driven by environmental issues; some aim to protect animals, biodiversity and ecosystems; while others address climate change and environmental pollution. In recent decades few initiatives have promoted One Health, but a move to embed the environmental component more clearly has been initiated. The following subsections list the main global and regional United Nations and WHO agreements and initiatives directly related to One Health or to the health of humans, animals or the environment. By listing these policies together, the hope is to highlight actions that – when combined to address the human–animal–environment health triad as a whole – can create powerful synergies, which would be stronger than addressing each of these challenges separately.

8.1 Global United Nations initiatives

Global initiatives under the umbrella of the United Nations include:

- the Sustainable Development Goals, and in particular Goals 3, 6, 11, 12, 13, 14 and 15 (United Nations, 2015a);
- the Global Health Security Agenda (originally launched in 2014 as a five-year multilateral effort, then extended until 2024 by the 2017 Kampala Declaration) – a group of 70 countries addressing global health threats posed by infectious diseases, including issues on AMR, zoonosis, food security and more (GHSA, 2018);
- the Paris Agreement – a legally binding international treaty on climate change adopted by 196 countries in 2015 to limit global warming to well below 2 °C, compared to preindustrial levels (United Nations, 2015b);
- the Stockholm Convention on Persistent Organic Pollutants, adopted in 2001 and dealing with the environmental threats imposed on animals and humans by POPs (Stockholm Convention, 2021);

- the Manhattan Principles of the "One World, One Health" symposium – a list of 12 recommendations for establishing a more holistic approach to preventing epidemic disease and maintaining ecosystem integrity, for humans, animals and biodiversity (WCS, 2004);
- CITES, signed in 1973 – an international agreement aiming to ensure that international trade in wild animals and plants does not threaten the survival of the species (UNEP, 2020a);
- the Strategic Plan for Biodiversity 2011–2020, including the 20 Aichi Biodiversity Targets – a new global framework for managing nature through 2030, which is now in preparation (CBD, 2021);
- the fourteenth meeting of the Conference of the Parties to the Convention on Biological Diversity, Sharm El-Sheikh, Egypt, 2018, and in particular decision 14/4 on biodiversity and health (CBD, 2018);
- the United Nations Decade on Ecosystem Restoration 2021–2030 (UNEP & FAO, 2020);
- the United Nations Political Declaration on Antimicrobial Resistance (United Nations, 2016).

8.2 WHO headquarters initiatives

Initiatives of WHO headquarters include:

- the WHO Global Program of Work (GPW13) – primarily the Health Emergencies Protection Billion goal (WHO, 2020b);
- the International Health Regulations, which provide international guidelines for pandemics readiness (WHO, 2005);
- *Contributing to One World, One Health: a strategic framework for reducing infectious disease at the animal–human–ecosystems interface*, which sets the stage for the tripartite collaboration on zoonotic diseases, and mentions the interests of wildlife and ecosystems (FAO et al., 2008);
- the Global Action Plan on Antimicrobial Resistance (WHO, 2015b);
- the road map to enhance health sector engagement in the Strategic Approach to International Chemicals Management towards the 2020 goal and beyond (WHO, 2017);
- the WHO global strategy on health, environment and climate change, which acknowledges the consequences of global environmental change – including climate change and biodiversity loss – as having important role in human

health, and incorporates cross-sectoral action, including land use planning, agriculture, industry and energy, as relevant for health (WHO, 2020c);
- the WHO Manifesto for a healthy recovery from COVID-19, which commits to protect nature as the source of human health, to invest in water and sanitation, and to act towards climate change mitigation (WHO, 2020a).

8.3 WHO Regional Office for Europe initiatives

Initiatives organized by the WHO Regional Office for Europe include:

- the European Programme of Work, 2020–2025, and specifically core priority 2: protecting against health emergencies, support country efforts to increase the resilience of health care facilities to climate change and natural disasters as part of its goals (WHO Regional Office for Europe, 2020);
- the European strategic action plan on antibiotic resistance (WHO Regional Office for Europe, 2011);
- the Ostrava Declaration on Environment and Health, which recognizes the role of environmental degradation on human health and resolves to prevent disease related to the environment, including pollution, climate change, improved sanitation and healthy cities (WHO Regional Office for Europe, 2017);
- the Pan-European Commission on Health and Sustainable Development, which looks at sustainable and social action as response measures to the COVID-19 pandemic and future preparedness (McKee, 2021);
- *Nature, biodiversity and health* – an overview of the impacts of the natural environment on human health, which sets out the ways nature and ecosystems can support and protect health and well-being, including protection from infectious disease (WHO Regional Office for Europe, 2021b).

Finally, similarly to the global effort, the European offices of WHO, OIE, FAO and UNEP established a regional One Health coordination mechanism in 2021 to strengthen the collaboration of the Regional Tripartite Secretariat for Europe (OIE, 2020).

9. Looking forward

Environmental and nature degradation, including climate change, have multiple effects on human and animal health. In addition, the health of the environment influences, modifies and exacerbates human diseases that are related to animals. Emerging zoonotic diseases and bacterial resistance are of particular concern. A vicious cycle is played out where humans impose unprecedented pressures that degrade the environment; this degradation affects animal health and results in the evolution and spread of new disease agents; and animals transfer these diseases back to humans. This report proposes to break this cycle by focusing on the environment as a focal point for the formation and transmission of disease agents related to animals, addressing it through three main approaches: nature protection, surveillance and human capacity.

9.1 Nature protection

Protecting and restoring ecosystems and biodiversity has intrinsic merit but should also be planned in order to provide the additional role of protecting human health. Framing of ecosystem restoration from a human health perspective may enlist specific enforcement and compliance measures. For example, wildlife trade is restricted by CITES, which prohibits trade in endangered wildlife species. An international treaty restricting consuming and trading wildlife in the context of zoonotic transmission, however, might prove to be more comprehensive for protecting human health. Likewise, while multiple conventions address prevention of deforestation as part of their action plans, a legally binding agreement to prevent deforestation could be planned specifically to protect local communities from exposure to zoonotic spillover from wildlife.

Multiple laudable initiatives, policies and action plans call for biodiversity protection and ecosystem restoration. Recurring emergence of new zoonotic pandemics – including the far-reaching consequences of the ongoing COVID-19 pandemic – and the multiple bodies of evidence connecting zoonotic emergence to nature degradation highlight nature restoration as a matter of global emergency.

9.2 Surveillance

Surveillance is an important part of the One Health approach. There is a danger that environmental degradation and other pressures – such as increased human population densities, global trade and international mass transportation – will exacerbate the emergence of new zoonotic diseases. As noted above, it is estimated that 1.7 million as yet undiscovered viruses exist in mammal and avian hosts, almost half of which may have the ability to infect humans (IPBES, 2020). While initiatives to promote surveillance of new pathogens in wildlife are growing, however, surveillance of the environment itself is lacking. Quantitative real-time PCR and metagenomics sequencing tools have been used within the One Health approach to detect viral and other pathogens that may be transmitted from animals to humans. Genomic sequencing can be used to understand vector and pathogen range shifts due to environmental change (Gardy & Loman, 2017). Surveillance should be expanded to incorporate the power of environmental genetics by sampling soil and water to discover pathogenic and AMR genes (Larsson & Flach, 2021). The spatial distribution of these genes relative to sources of pollution and environmental degradation may shed further light on the relationships between these factors.

Owing to the durable and pervasive nature of organic pollutants, they can pose a threat to human health even after their use has been discontinued. Joint action by the environmental and food safety sectors to survey pollutants in the environment and in animal products may improve efforts to clean the environment and secure human and animal health alike.

9.3 Human capacity

The One Health approach fosters collaborative transboundary, transdisciplinary and international action to promote human health. Understanding the numerous complicated mechanisms by which anthropogenic environmental degradation affects diseases that originate from animals requires another step forward in moving outside silos when addressing human health problems. Such understanding can be enhanced by bring environmental scientists and ecologists to the One Health table, in addition to health professionals, toxicologists and veterinarians. Since the evolution of emerging pathogens and new AMR genes in the environment creates a growing threat to human health, evolutionary biologists may also have an important function in One Health.

WHO plays an important role in local and international capacity-building. WHO's expertise can assist in expanding the role of environmental science within the One Health framework, particularly where environmental issues enhance animal-related human health problems. Cross-sectoral approaches, strong collaborations with local communities and cross-boundary collaborations with industry and for-profit companies, transportation and urban planning may further promote new solutions.

Close collaboration between health and environmental organizations at all levels – from local to international – may play a considerable role in environmental restoration by continuing to identify the impacts of the environment on human health. Such collaboration may facilitate awareness of the explicit role of environmental degradation in animal-mediated disease, investment in cross-disciplinary research and promotion of evidence-based action. In addition, new scientific tools and technologies may shed light on the connections between multiple scales – from genetic evolution of new pathogens to the global ecological processes that spread them.

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The WHO Regional Office for Europe

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