IPBES Workshop on Biodiversity and Pandemics

WORKSHOP REPORT

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This workshop report is released in a non-laid out format. It will undergo minor editing before being released in a laid-out format.

Intergovernmental Platform on Biodiversity and Ecosystem Services

The IPBES Bureau and Multidisciplinary Expert Panel (MEP) authorized a workshop on biodiversity and pandemics that was held virtually on 27-31 July 2020 in accordance with the provisions on "Platform workshops" in support of Plenary-approved activities, set out in section 6.1 of the procedures for the preparation of Platform deliverables (IPBES-3/3, annex I).

This workshop report and any recommendations or conclusions contained therein have not been reviewed, endorsed or approved by the IPBES Plenary.

The workshop report is considered supporting material available to authors in the preparation of ongoing or future IPBES assessments. While undergoing a scientific peer-review, this material has not been subjected to formal IPBES review processes.

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Preamble

The IPBES Bureau and Multidisciplinary Expert Panel, in the context of the extraordinary situation caused by the COVID-19 pandemic, and considering the role that IPBES can play in strengthening the knowledge base on biodiversity, decided that IPBES would organize a "Platform workshop" on biodiversity and pandemics, in accordance with the procedures for the preparation of IPBES deliverables, in particular decision IPBES-3/3, annex I, section 6.1. on the organization of Platform workshops.

This workshop provided an opportunity to review the scientific evidence on the origin, emergence and impact of COVID-19 and other pandemics, as well as on options for controlling and preventing pandemics, with the goal to provide immediate information, as well as enhance the information IPBES can provide to its users and stakeholders in its ongoing and future assessments.

The workshop brought together 22 experts from all regions of the world, to discuss 1) how pandemics emerge from the microbial diversity found in nature; 2) the role of land use change and climate change in driving pandemics; 3) the role of wildlife trade in driving pandemics; 4) learning from nature to better control pandemics; and 5) preventing pandemics based on a "one health" approach.

The workshop participants selected by the IPBES Multidisciplinary Expert Panel included 17 experts nominated by Governments and organizations following a call for nominations and 5 experts from the ongoing IPBES assessment of the sustainable use of wild species, the assessment on values and the assessment of invasive alien species, as well as experts assisting with the scoping of the IPBES nexus assessment and transformative change assessments. In addition, resource persons from the Intergovernmental Panel on Climate Change (IPCC), the Secretariat of the Convention on Biological Diversity (CBD), the Secretariat of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), the United Nations Convention to Combat Desertification (UNCCD) and the World Health Organization (WHO) attended the workshop.

This workshop report has been prepared by all workshop participants and been subjected to several rounds of internal review and revisions and one external peer review process.

Technical support to the workshop has been provided by the IPBES secretariat.

IPBES thanks the Government of Germany for the provision of financial support for the organization of the workshop and production of the report.

Executive Summary

Pandemics represent an existential threat to the health and welfare of people across our planet. The scientific evidence reviewed in this report demonstrates that pandemics are becoming more frequent, driven by a continued rise in the underlying emerging disease events that spark them. Without preventative strategies, pandemics will emerge more often, spread more rapidly, kill more people, and affect the global economy with more devastating impact than ever before. Current pandemic strategies rely on responding to diseases after their emergence with public health measures and technological solutions, in particular the rapid design and distribution of new vaccines and therapeutics. However, COVID-19 demonstrates that this is a slow and uncertain path, and as the global population waits for vaccines to become available, the human costs are mounting, in lives lost, sickness endured, economic collapse, and lost livelihoods.

Pandemics have their origins in diverse microbes carried by animal reservoirs, but their emergence is entirely driven by human activities. The underlying causes of pandemics are the same global environmental changes that drive biodiversity loss and climate change. These include land-use change, agricultural expansion and intensification, and wildlife trade and consumption. These drivers of change bring wildlife, livestock, and people into closer contact, allowing animal microbes to move into people and lead to infections, sometimes outbreaks, and more rarely into true pandemics that spread through road networks, urban centers and global travel and trade routes. The recent exponential rise in consumption and trade, driven by demand in developed countries and emerging economies, as well as by demographic pressure, has led to a series of emerging diseases that originate mainly in biodiverse developing countries, driven by global consumption patterns.

Pandemics such as COVID-19 underscore both the interconnectedness of the world community and the rising threat posed by global inequality to the health, wellbeing and security of all people. Mortality and morbidity due to COVID-19 may ultimately be higher in developing countries, due to economic constraints affecting healthcare access. However, largescale pandemics can also drastically affect developed countries that depend on globalized economies, as COVID-19's impact on the USA and many European countries is currently demonstrating.

Pandemics emerge from the microbial diversity found in nature

- The majority (70%) of emerging diseases (e.g. Ebola, Zika, Nipah encephalitis), and almost all known pandemics (e.g. influenza, HIV/AIDS, COVID-19), are zoonoses – i.e. are caused by microbes of animal origin. These microbes 'spill over' due to contact among wildlife, livestock, and people.
- An estimated 1.7 million currently undiscovered viruses are thought to exist in mammal and avian hosts. Of these, 540,000-850,000 could have the ability to infect humans.
- The most important reservoirs of pathogens with pandemic potential are mammals (in particular bats, rodents, primates) and some birds (in particular water birds), as well as livestock (e.g. pigs, camels, poultry).

Human ecological disruption, and unsustainable consumption drive pandemic risk

- The risk of pandemics is increasing rapidly, with more than five new diseases emerging in people every year, any one of which has the potential to spread and become pandemic. The risk of a pandemic is driven by exponentially increasing anthropogenic changes. Blaming wildlife for the emergence of diseases is thus erroneous, because emergence is caused by human activities and the impacts of these activities on the environment.

- Unsustainable exploitation of the environment due to land-use change, agricultural expansion and intensification, wildlife trade and consumption, and other drivers, disrupts natural interactions among wildlife and their microbes, increases contact among wildlife, livestock, people, and their pathogens and has led to almost all pandemics.
- Climate change has been implicated in disease emergence (e.g. tick-borne encephalitis in Scandinavia) and will likely cause substantial future pandemic risk by driving movement of people, wildlife, reservoirs, and vectors, and spread of their pathogens, in ways that lead to new contact among species, increased contact among species, or otherwise disrupts natural host-pathogen dynamics.
- Biodiversity loss associated with transformation of landscapes can lead to increased emerging disease risk in some cases, where species that adapt well to human-dominated landscapes are also able to harbor pathogens that pose a high risk of zoonotic transmission.
- Pathogens of wildlife, livestock and people can also directly threaten biodiversity, and emerge via the same activities that drive disease risk in people (e.g. the emergence of chytridiomycosis in amphibians worldwide due to the wildlife trade).

Reducing anthropogenic global environmental change may reduce pandemic risk

- Pandemics and other emerging zoonoses cause widespread human suffering, and likely more than a trillion dollars in economic damages annually. This is in addition to the zoonotic diseases that have emerged historically and create a continued burden on human health. Global strategies to prevent pandemics based on reducing the wildlife trade and land use change and increasing One Health[1] surveillance are estimated to cost between $22 and 31.2 billion, reduced even further ($17.7 to 26.9 billion) if benefits of deforestation on carbon sequestration are calculated – two orders of magnitude less than the damages pandemics produce. This provides a strong economic incentive for transformative change to reduce the risk of pandemics.
- The true impact of COVID-19 on the global economy can only be accurately assessed once vaccines are fully deployed and transmission among populations is contained. However, its cost has been estimated at $8-16 trillion globally by July 2020 and may be $16 trillion in the US alone by the 4th quarter of 2021 (assuming vaccines are effective at controlling it by then).
- Pandemic risk could be significantly lowered by promoting responsible consumption and reducing unsustainable consumption of commodities from emerging disease hotspots, and of wildlife and wildlife-derived products, as well as by reducing excessive consumption of meat from livestock production.
- Conservation of protected areas, and measures that reduce unsustainable exploitation of high biodiversity regions will reduce the wildlife-livestock-human contact interface and help prevent the spillover of novel pathogens.

Land-use change, agricultural expansion, urbanization cause more than 30% of emerging disease events

- Land-use change is a globally significant driver of pandemics and caused the emergence of more than 30% of new diseases reported since 1960.
- Land-use change includes deforestation, human settlement in primarily wildlife habitat, the growth of crop and livestock production, and urbanization.

[1] One Health is an approach that integrates human health, animal health and environmental sectors.

- Land-use change creates synergistic effects with climate change (forest loss, heat island effects, burning of forest to clear land) and biodiversity loss that in turn has led to important emerging diseases.
- Destruction of habitat and encroachment of humans and livestock into biodiverse habitats provide new pathways for pathogens to spill over and increase transmission rates.
- Human health considerations are largely unaccounted for in land-use planning decisions.
- Ecological restoration, which is critical for conservation, climate adaptation and provision of ecosystem services, should integrate health considerations to avoid potential increased disease risk resulting from increased human-livestock-wildlife contact.

The trade and consumption of wildlife is a globally important risk for future pandemics

- Wildlife trade has occurred throughout human history and provides nutrition and welfare for peoples, especially the Indigenous Peoples and Local Communities in many countries.
- About 24% of all wild terrestrial vertebrate species are traded globally. International, legal wildlife trade has increased more than five-fold in value in the last 14 years and was estimated to be worth US$107 billion in 2019. The illegal wildlife trade is estimated to be worth $7-23 billion annually.
- The USA is one of the largest legal importers of wildlife with 10-20 million individual wild animals (terrestrial and marine) imported each year, largely for the pet trade. The number of shipments rose from around 7,000 to 13,000 per month from 2000 to 2015. This trade has led to the introduction of novel zoonoses (e.g. monkeypox) and disease vectors or hosts (e.g. tick reservoirs of the cattle disease heartwater) into the USA.
- Wildlife farming has expanded substantially, particularly in China prior to COVID-19, where 'non-traditional animal' farming generated US$77 billion dollars and employed 14 million people in 2016.
- The farming, trade and consumption of wildlife and wildlife-derived products (for food, medicine, fur and other products) have led to biodiversity loss, and emerging diseases, including SARS and COVID-19.
- Illegal and unregulated trade and unsustainable consumption of wildlife as well as the legal, regulated trade in wildlife, have been linked to disease emergence.
- The trade in mammals and birds is likely a higher risk for disease emergence than other taxa because they are important reservoirs of zoonotic pathogens.
- Regulations that mandate disease surveillance in the wildlife trade are limited in scope, disaggregated among numerous authorities, and inconsistently enforced or applied

Current pandemic preparedness strategies aim to control diseases *after* they emerge. These strategies often rely on, and can affect, biodiversity.

- Our business-as-usual approach to pandemics is based on containment and *control after a disease has emerged* and relies primarily on reductionist approaches to vaccine and therapeutic development rather than on reducing the drivers of pandemic risk to *prevent them before they emerge*.
- Vaccine and therapeutic development rely on access to the diversity of organisms, molecules and genes found in nature.
- Many important therapeutics are derived from indigenous knowledge and traditional medicine.

- Fair and equitable access and benefit sharing derived from genetic resources, including pathogens, have led to more equitable access to vaccines and therapeutics, and broader engagement in research, but some access and benefit sharing procedures may impede rapid sharing of microbial samples.
- Intellectual property is an incentive for innovation, but some have argued it may limit rapid access to vaccines, therapeutics and therapies, as well as to diagnostic and research tools.
- Pandemic control programs often act under emergency measures and can have significant negative implications for biodiversity, e.g. culling of wildlife reservoirs, release of insecticides.
- Introduction of travel restrictions to reduce COVID-19 spread have severely reduced ecotourism and other income.
- Reduced environmental impacts from economic slowdown during the 'global COVID-19 pause' (e.g. reduced oil consumption) are likely temporary and insignificant in the long term.
- Diseases that emerge from wildlife and spread widely in people may then threaten biodiversity outside the pathogen's original host range.
- Pandemics often have unequal impacts on different countries and sectors of society (e.g. the elderly and minorities for COVID-19). The economic impacts (and disease outcomes) are often more severe on women, people in poverty and Indigenous Peoples. To be transformative, pandemic control policies and recovery programs should be more gender responsive and inclusive.

Escape from the Pandemic Era requires policy options that foster <u>transformative change</u> towards <u>preventing pandemics</u>:

The current pandemic preparedness strategy involves responding to a pandemic after it has emerged. Yet, the research reviewed in this report identifies substantial knowledge that provides a pathway to predicting and preventing pandemics. This includes work that predicts geographic origins of future pandemics, identifies key reservoir hosts and the pathogens most likely to emerge, and demonstrates how environmental and socioeconomic changes correlate with disease emergence. Pilot projects, often at large scale, have demonstrated that this knowledge can be used to effectively target viral discovery, surveillance and outbreak investigation. The major impact on public health of COVID-19, of HIV/AIDS, Ebola, Zika, influenza, SARS and of many other emerging diseases underlines the critical need for policies that will promote pandemic prevention, based on this growing knowledge. To achieve this, the following policy options have been identified:

Enabling mechanisms:

- <u>Launching a high-level intergovernmental council on pandemic prevention</u>, that would provide for cooperation among governments and work at the crossroads of the three Rio conventions to: 1) provide policy-relevant scientific information on the emergence of diseases, predict high-risk areas, evaluate economic impact of potential pandemics, highlight research gaps; and 2) coordinate the design of a monitoring framework, and possibly lay the groundwork for an agreement on goals and targets to be met by all partners for implementing the One Health approach (i.e. one that links human health, animal health and environmental sectors).

Ultimately the work of the high-level council may lead to countries setting mutually agreed goals or targets within the framework of an accord or agreement. A broad international governmental agreement on pandemic prevention would represent a landmark achievement with clear benefits for humans, animals and ecosystems.

- Institutionalizing One Health in national governments to build pandemic preparedness, enhance pandemic prevention programs, and to investigate and control outbreaks across sectors.
- Integrating ("mainstreaming") the economic cost of pandemics into consumption, production, and government policies and budgets.
- Generating new green corporate or sovereign bonds to mobilize resources for biodiversity conservation and pandemic risk reduction.
- Designing a green economic recovery from COVID-19 as an insurance against future outbreaks.

Policies to reduce the role of land-use change in pandemic emergence:

- Developing and incorporating pandemic and emerging disease risk health impact assessments in major development and land-use projects.
- Reforming financial aid for land-use so that benefits and risks to biodiversity and health are recognized and explicitly targeted
- Assessing how, effective habitat conservation measures including protected areas and habitat restoration programs can reduce pandemics, and trade-offs where disease spillover risk may increase. Developing programs based on these assessments.
- Enabling transformative change to reduce the types of consumption, globalized agricultural expansion and trade that have led to pandemics (e.g. consumption of palm oil, exotic wood, products requiring mine extraction, transport infrastructures, meat and other products of globalized livestock production). This could include modifying previous calls for taxes, or levies on meat consumption, livestock production or other forms of high pandemic risk consumption.

Policies to reduce pandemic emergence related to the wildlife trade:

- Building a new intergovernmental health and trade partnership to reduce zoonotic disease risks in the international wildlife trade, building on collaborations among OIE, CITES, CBD, WHO, FAO, IUCN and others.
- Educating communities from all sectors in emerging infectious diseases hotspots regarding the health risks associated with wildlife use and trade that are known to pose a pandemic risk.
- Reducing or removing species in wildlife trade that are identified by expert review as high-risk of disease emergence, testing the efficacy of establishing market clean-out days, increased cold chain capacity, biosafety, biosecurity and sanitation in markets. Conducting disease surveillance of wildlife in the trade, and of wildlife hunters, farmers, and traders.
- Enhancing law enforcement collaboration on all aspects of the illegal wildlife trade.

Closing critical knowledge gaps on:

- Supporting One Health scientific research to design and test better strategies to prevent pandemics.
- Improving understanding of the relationship between ecosystem degradation and restoration and landscape structure, and the risk of emergence of disease.

- Economic analyses of return-on-investment for programs that reduce the environmental changes that lead to pandemics.
- Key risk behaviors - in global consumption, in rural communities on the frontline of disease emergence, in the private sector, in national governments - that lead to pandemics.
- Valuing Indigenous Peoples and local communities' engagement and knowledge in pandemic prevention programs
- Undiscovered microbial diversity in wildlife that has potential to emerge in future, or to be used to develop therapeutics or vaccines.
- Analyzing the evolutionary underpinnings of host shifts that are involved in zoonotic disease spillover and the adaptation of emerging pathogens to new host species.
- Climate change impacts and related extreme weather events (e.g. flooding and droughts) on disease emergence, to anticipate future threats.
- Obtaining data on the relative importance of illegal, unregulated, and the legal and regulated wildlife trade in disease risk.

Foster a role for all sectors of society to engage in reducing risk of pandemics

- Educating and communicating with all sectors of society, and especially the younger generations, about the origins of pandemics.
- Identifying, ranking, and labelling high pandemic risk consumption patterns (e.g. use of fur from farmed wildlife) to provide incentives for alternatives.
- Increasing sustainability in agriculture to meet food requirements from currently available land, and subsequently reduced land areas.
- Promoting a transition to healthier and more sustainable and diverse diets, including responsible meat consumption.
- Promoting sustainable mechanisms to achieve greater food security and reduce consumption of wildlife.
- Where there is a clear link to high pandemic risk, consideration of taxes or levies on meat consumption, production, livestock production or other forms of consumption, as proposed previously by a range of scientific organizations and reports.
- Sustainability incentives for companies to avoid high pandemic-risk land-use change, agriculture, and use of products derived from unsustainable trade or wildlife farming identified as a particular zoonotic disease risk.

Conclusion

This report is published at a critical juncture in the course of the COVID-19 pandemic, at which its long-term societal and economic impacts are being recognized. People in all sectors of society are beginning to look for solutions that move beyond business-as-usual. To do this will require transformative change, using the evidence from science to re-assess the relationship between people and nature, and to reduce global environmental changes that are caused by unsustainable consumption, and which drive biodiversity loss, climate change and pandemic emergence. The policy options laid out in this report represent such a change. They lay out a movement towards preventing pandemics that is transformative: our current approach is to try to detect new diseases early, contain them, and then develop vaccines and therapeutics to control them. Clearly, in the face of COVID-19, with more than one million human deaths, and huge economic impacts, this reactive approach is inadequate.

This report embraces the need for transformative change and uses scientific evidence to identify policy options to prevent pandemics. Many of these may seem costly, difficult to execute, and their impact uncertain. However, economic analysis suggests their costs will be trivial in comparison to the trillions of dollars of impact due to COVID-19, let alone the rising tide of future diseases. The scientific evidence reviewed here, and the societal and economic impacts of COVID-19 provide a powerful incentive to adopt these policy options and create the transformative change needed to prevent future pandemics. This will provide benefits to health, biodiversity conservation, our economies, and sustainable development. Above all, it will provide a vision of our future in which we have escaped the current 'Pandemic Era'.

Sections 1 to 5

Introduction

The emergence of COVID-19 in late 2019 as a major global pandemic is part of a pattern of disease emergence that highlights linkages among biodiversity, global environmental change and human health. COVID-19 and other pandemics are rooted in biodiversity. They are caused by micro-organisms that are themselves a critical part of biodiversity and are hosted and transmitted by diverse animal species, including humans [1]. COVID-19 is the latest in a series of diseases that are caused by wildlife-origin viruses and have emerged due to anthropogenic environmental changes that bring wildlife, livestock and people into closer contact [2]. These diseases include SARS, Ebola and Nipah virus disease, Zika and influenza, and reflect a predominance of zoonotic (animal origin) viral diseases among the emerging infectious diseases affecting people over the last few decades. Over the past few years, a series of scientific papers have been published that suggest the same environmental changes that threaten biodiversity loss on a global scale (e.g. land use change, such as deforestation or encroachment into wildlife habitat; climate change; unsustainable trade and consumption of wildlife; agricultural intensification; globalized trade and travel) are also driving the increasing spillover, amplification and spread of these novel viral diseases.

COVID-19 is a pandemic: a disease that has caused epidemics of sustained community transmission in multiple countries on two or more continents [3]. Its significance cannot be overstated. It is the first, high-mortality (>0.5% case fatality rate), truly global pandemic since the emergence of HIV/AIDS in the 1970/80s. In efforts to curtail its spread, social distancing and travel bans have led to a significant economic impact (trillions of US$ of global market loss), and the pandemic has disrupted normal life for many months in most countries on the planet, with societal and economic impacts lasting years ahead. The precise chain of events leading to the emergence of COVID-19 is not yet fully known. However, the virus that causes it (SARS-CoV-2) almost certainly originated in (and recently spilled over from [4]) insectivorous bats because it is part of a clade of closely-related SARS-related CoVs found almost solely in *Rhinolophus* spp. bats in nature [5]. SARS-CoV-2 is able to infect other mammals, including mustelids (e.g. mink, ferrets), viverrids (e.g. civets), felids (including lions and tigers in a zoo and domestic cats), raccoon dogs (*Nyctereutes* spp.), pangolins (*Manidae*), domestic dogs, a range of lab animals and people. Substantial evidence points to a likely origin in South China or neighbouring countries, where the greatest diversity of SARS-related coronaviruses is found [6], where contact among people and bats is common [7,8], and where human populations are expanding and encroaching into a rapidly changing landscape [9]. Epidemiological evidence suggests that SARS-CoV-2 was transported either in people, or animals, or both, into a live animal market in Wuhan in late 2019 [5,10]. The involvement of live animal markets and the wildlife trade in the emergence and spread of both SARS and COVID-19 have led to public calls for efforts to reduce this trade in an effort to prevent future pandemics.

Pandemics are a subset of emerging infectious diseases (EIDs) that are caused by pathogens that have recently infected people for the first time, or are showing a trend of increasing frequency of infection or geographic spread [3,11,12]. Pandemics are EIDs that have spread internationally and seeded epidemics of human-to-human transmission in different continents. EIDs tend to originate first in rural regions of tropical or subtropical countries with high wildlife diversity (and therefore likely high viral diversity), human populations that are growing rapidly, and where land use change is driving closer contact among people and wildlife [13]. Therefore, rural communities in developing countries are often on the frontline of disease emergence.

Additionally, these countries may have less resources for early detection of outbreaks, and to combat spillover and spread. Once a new pandemic has developed sustained community transmission in people, global emergence is intimately tied to urbanization, domestic trade networks, globalized trade and international travel patterns. Thus, richer and more developed countries that are highly dependent on globalized trade and travel are often rapidly affected once a pathogen spreads in people, as happened with COVID-19. There is also growing evidence that pathogen spillover, amplification and spread is largely driven by the consumption patterns set up by globalized production and trade that drive encroachment into tropical ecosystems, particularly forested regions (e.g. for crop and livestock production, timber, mining and manufacturing of goods), and exponentially rising rates of international trade and travel. Thus, efforts to identify ways to prevent pandemics will likely need to understand the whole system of interacting drivers and policy options that would affect points along these cycles and pathways.

This workshop was launched to review the scientific evidence behind the origin, emergence and impact of COVID-19 and other pandemics as it relates to biodiversity and the changes that are affecting both. The goals of the workshop were to provide a scientific basis on which to identify potential policy options, and implementation pathways that could reduce pandemic risk and ultimately prevent their emergence, while at the same time having a positive impact on biodiversity conservation. To do that, the experts reviewed scientific evidence on the known pandemics, and the 500 or so EIDs for which there are data on origins, underlying causes, reservoir hosts and impact [11,14]. Almost all pandemics, and the majority of EIDs, are caused by wildlife-origin pathogens. This means that areas with high wildlife diversity that are important for biodiversity conservation are also places where pandemic origins are most likely to occur. This report therefore provides an assessment of trade-offs between the goals of pandemic prevention and control and biodiversity conservation. This includes evidence that the anthropogenic environmental changes that drive pandemics also drive biodiversity loss. Thus, reducing human impacts on the environment to benefit conservation, may also reduce pandemic risk and benefit health.

This report is published at a critical juncture in the COVID-19 pandemic, and in the Great Acceleration of the Anthropocene [15]: a point at which governments in most countries are beginning to realize the long term societal and economic impacts of COVID-19, and many people are looking for solutions rather than hoping to continue business-as-usual. **A movement towards *preventing pandemics* would be a transformative change**: the current approach to dealing with pandemics is to try to detect them early, contain them, and rapidly develop vaccines and therapeutics. Clearly, in the face of COVID-19, this is inadequate, with no vaccines widely available ten months after emergence, and at least a million people dead [16]. This report fully embraces the need for transformative change and uses scientific evidence **to identify policy options to prevent pandemics**, and the organizations and agencies that might implement them. These options aim to reduce pandemic risk, and provide benefits to human health, biodiversity conservation, economies and sustainable development. Above all, they recognize that the current strategy of waiting for diseases to emerge, then hoping for vaccines and therapeutics to be developed, is not a realistic way to escape from what has been termed the ‘Pandemic Era’ [17,18].

Figure 1: The Huanan Seafood Market, Wuhan in January 2020. This is the site where some of the earliest cases of COVID-19 were identified, although it is likely that the disease first emerged elsewhere (Photo: REUTERS – permission pending).

Section 1: The relationship between people and biodiversity underpins disease emergence and provides opportunities for pandemic prevention, control and response measures

Disease emergence is rooted in human interaction with the biodiversity of microbes and their reservoir host species

There are clear links between pandemics and biodiversity. New pathogens usually emerge from a 'pool' of previously undescribed, potentially zoonotic microbes that have co-evolved over millions of years with their wildlife hosts [14]. The diversity of microbes likely increases proportionally with the biodiversity of their hosts. RNA viruses are particularly important as emerging pathogens because they have high mutation rates, undergo recombination and have other characteristics allowing them to evolve diverse assemblages over time [19-21]. An estimated 1.7 million viruses occur in mammals and water birds (the hosts most commonly identified as origins of novel zoonoses), and of these, 540,000-850,000 could have the ability to infect humans [22]. This far exceeds the current catalogued viral diversity from these hosts of less than 2,000 (even if lower estimates of viral diversity prove correct [23]) and suggests that less than 0.1% of the potential zoonotic viral risk has been discovered [22]. Previous authors have concluded that this results in a high potential for the emergence of novel viral pathogens from wildlife, if the current trajectory of environmental change continues, and pushes closer contact among people, livestock, wildlife and the diverse assemblage of potential pathogens they are hosts to [14].

On a global scale, the emergence of new zoonoses correlates with wildlife (mammalian) diversity, human population density and anthropogenic environmental change [11,13]. There is also evidence that biodiversity loss may increase transmission of microbes from animals to people under certain circumstances. The potential mechanisms are complex. For some microbes with multiple reservoir host species, certain hosts may play a more important role than others, i.e. have high 'competence'. This may be because they are preferentially infected, produce and excrete more microbes, have higher contact rates, or otherwise contribute more to pathogen dynamics than low competence hosts [24]. Thus, in regions with high biodiversity a “dilution effect” may exist for some pathogens, whereby highly competent reservoirs represent a small proportion of the available reservoirs, and transmission risk to people is reduced [25-27]. This theory has potential importance for conservation because it suggests that biodiversity loss due to anthropogenic environmental changes may lead to higher zoonotic disease risk, and that conserving biodiversity may benefit public health by reducing this risk. Evidence of the dilution effect has been observed for the West Nile virus [28,29], Hantavirus [30,31] and plant microbes [32]. It has also been well-studied for Lyme disease [32,33], but also widely disputed [34,35]. In particular, evidence suggests that the dilution effect is not generalizable across different disease and host systems [36], and scales [37,38], and that some of the evidence provided to support its generalizability is weak [39]. Large scale analyses suggest that emerging disease risk may be highest in regions of human-altered landscapes [11,13,40-42]. However, rather than this being due to a broadly effective dilution effect [43,44], the mechanistic drivers of risk include increased contact among wildlife, livestock and people driven by settlement and land conversion and specific high-risk activities (e.g. occupational exposure to wildlife, increased hunting of disease reservoirs).

Environmental changes that drive biodiversity loss also drive disease emergence

Disease emergence has followed each step of society’s development. The domestication of wildlife beginning in the Neolithic provided the contact required for pathogens to spill over into people, and coincided with the formation of dense human populations in early cities that allowed their continued circulation [45]. Measles and smallpox viruses likely evolved from domestic herbivore viruses through this process[45-47], while another ancient disease, tuberculosis, appears to have begun as an environmental microbe that infected people, then cycled back into domestic animals and other wildlife [48]. Some diseases, like the viral disease mumps, or the bacterial diseases leprosy and plague appear to have their origin as wildlife microbes that spilled over directly to humans over the last few millennia [49-52]. These diseases have, over historical time become endemic in human populations and are no longer referred to as ‘emerging’, which is a phrase that usually applies to diseases that have increased in frequency or impact in the last few decades [53].

There is substantial evidence that the underlying drivers of almost all recent EIDs are anthropogenic environmental changes, and socioeconomic changes, that alter contact rates among natural reservoir hosts, livestock and people, or otherwise cause changes in transmission rates [11,13,40,42,54] **(Figure 2)**. More than 400 microbes (viruses, bacteria, protozoa, fungi and other microorganisms) have emerged in people during the last five decades, over 70% of them originating in animals (i.e. are classed as zoonotic pathogens), and the majority of those having wildlife as their natural reservoir hosts [11]. Many cause little or no illness in their natural reservoirs. While some zoonotic pathogens are unable to spread from person-to-person and cause limited outbreaks, many have evolved capacity for transmission among people. In many cases, the further expansion of these emerging infectious diseases does not require animal reservoirs but occurs due to community spread through rapidly urbanizing landscapes, megacities and travel and trade networks, as occurred with COVID-19. These emerging infectious diseases have led to a series of outcomes including small clusters of cases, and in some cases significant outbreaks (e.g. Ebola, MERS, Lyme disease) that don’t quite reach the pandemic scale. The transmission (‘spillover’) of pathogens from wildlife to people can occur directly via high risk activities like hunting, farming and butchering wildlife (e.g. Ebola virus); or indirectly from wildlife through livestock to people (e.g. influenza viruses, Nipah virus). Some pathogens have multiple reservoir hosts (e.g. West Nile virus) and may circulate among those in closer contact with people when the environment is encroached upon. They may also have multiple transmission routes from wildlife to humans (e.g. Nipah virus in Malaysia via pig intermediate hosts, in Bangladesh directly from bats to people).

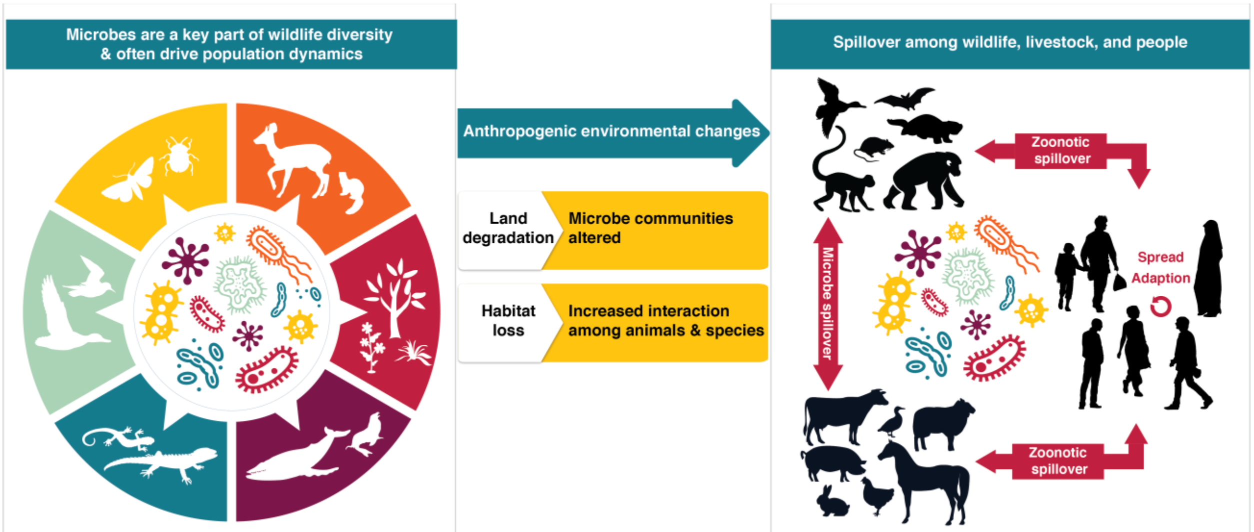


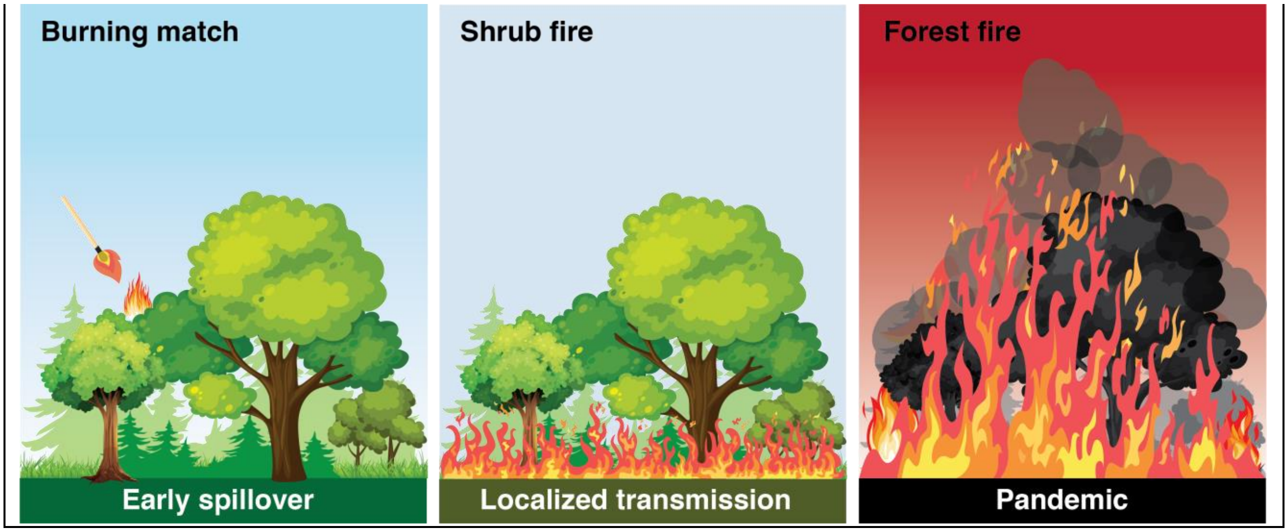
Figure 2: The origins and drivers of emerging zoonotic diseases and pandemics. Microbes have evolved within species of wildlife over evolutionary time **(left)**. They undergo complex life cycles of transmission among single or multiple host species, and often have significant impacts on host population dynamics [55]. These microbes become emerging infectious diseases (EIDs) when anthropogenic environmental changes alter population structure of their reservoir hosts, and bring wildlife, livestock and people into contact **(center)**. These interactions can alter transmission dynamics of microbes within their hosts, lead to interspecies transmission of microbes, spillover to livestock and people and the emergence of novel diseases **(right)**. While many outbreaks are small scale or regional, some EIDs become pandemics when zoonotic pathogens transmit easily among people, and spread in rapidly urbanizing landscapes, megacities and travel and trade networks. Pandemics are a subset of EIDs, and this report reviews the scientific evidence of linkages to biodiversity for EIDs that did not become pandemic (e.g. Ebola), as well as those that did (e.g. COVID-19), so that patterns affecting both can be used to identify policy options to reduce the opportunities for future EID and pandemic emergence.

Truly global pandemics are catastrophic events that are rare relative to initial spillover, or small-scale outbreaks **(Box 1)**. However, the frequency of the emerging infectious disease events that lead to pandemics is increasing [11,56]. COVID-19 has been likened to the Great Influenza pandemic of 1918 in its impact, but pandemics occur more frequently than once per century [1,2]. Since 1918, at least six other pandemics have affected public health including three caused by influenza viruses, the HIV/AIDS pandemic, SARS and now COVID-19 [16]. These represent the tip of the iceberg of *potential* pandemics. Today, a global population of 7.8 billion people has driven medical, industrial and agricultural progress, coupled with rapid demographic, land use, and climate change, replacement of wildlife with livestock and environmental degradation that define the Anthropocene [15,57,58]. The result is increased frequency of wildlife-livestock-human interactions especially in tropical and subtropical regions (low latitudes) rich in diversity of wildlife and their microbes, as shown in field studies of primate, human and livestock interactions and bacterial infections, for example [59,60]. The increased risk of spillover is compounded by land use change and encroachment that bring increasing numbers of people into rural regions and provide a mechanism for disease amplification and spread. The spillover risk is also enhanced by climate change that perturbs wildlife population dynamics and distribution [61] and disrupts the services humans derive from them [62]. Anthropogenic environmental and socioeconomic changes have been linked empirically to the emergence of dozens of novel zoonotic pathogens, including: Hendra virus in Australia (land use change); Nipah virus in Malaysia (agricultural intensification); Ebola virus and Marburg virus in central Africa (wildlife hunting and butchering, land use change and mining respectively); flaviviruses such as Zika and Yellow Fever in South America (land use change, travel and trade) and Dengue in Southeast Asia (urbanization); vector-borne diseases in northern latitudes such as tick-borne encephalitis (climate change); and coronaviruses causing SARS, MERS and COVID-19 (wildlife trade, livestock production and trade and encroachment and/or land use change respectively) [9,63-70].

There is also a large number of emerging infectious diseases affecting livestock and wildlife that are driven to emerge by the same factors that drive EIDs infecting people [53]. This includes the wildlife disease amphibian chytridiomycosis that spread globally through the trade in wildlife for food, pets, as lab animals and the introduction of invasive alien species [71-76]; and the avian disease highly pathogenic avian influenza, that emerged due to intensification of poultry production and spread through the global trade in poultry, as well as through wild bird movement and the illegal pet trade [77,78]. On a global scale, the origins of emerging diseases correlate with environmental change (in particular land use change), human population density and wildlife diversity [11,13,14,38,42]. These global changes increase the risk of repeated spillover of microbes from wildlife to people, and may explain why most emerging infectious diseases and almost all pandemics have been caused by zoonoses [3]. Exceptions include the emergence of drug-resistant strains of microbes and some food-borne infections, for example.

Box 1: Pandemics begin as spillover events that cause small outbreaks which grow in scale.

Almost all pandemics start with a single infection event. For zoonoses from wildlife, this is a person, or group of people that made contact with an animal infected by a pathogen that infects them, replicates in their cells and then is transmitted to others. Surveillance data suggest that spillover events happen frequently around the world, but most infections are unable to cause further transmission among people (the burning match in the figure below). Sometimes, pathogens spill over and are able to transmit to a handful of people, undergoing a few cycles of transmission before the outbreak dies out (the shrub fire below). Where pathogens spread into dense human communities (e.g. COVID-19 within the live animal market and city of Wuhan [10]), and when they are able to easily transmit from person-to-person, they can become pandemics (the forest fire in the schematic). Preventing pandemics will require efforts to reduce the risk each of these stages occurring, through measures that diminish the underlying drivers of spillover, their spread among people and their ability to move globally through rapidly urbanizing landscapes, megacities and travel and trade networks.



Rising demand for meat consumption and the globalized food trade drive pandemic risk, through land use change and climate change

The rising demand for meat, particularly in developed countries and emerging economies, has continued to bolster an unsustainable globalized system of intensive production that threatens biodiversity through a range of mechanisms (e.g. land use change, eutrophication), and contributes to climate change [79]. For example, global demand for meat has indirectly and directly led to deforestation, forest degradation and expansion of pasture in Brazil and other parts of the Amazon [80-82].

By forming unnaturally dense assemblages of often closely related individuals, livestock farming has historically driven the emergence of pathogens within the domesticated species. However, the increasing expansion of livestock and poultry production, the increase in the size and acreage of farms, and in the number of individual animals at a site have led to increasing potential for transmission of pathogens to people, e.g. the emergence of salmonellosis [83], bovine spongiform encephalopathy (BSE) and variant Creutzfeldt-Jakob disease (CJD) [84-86] and some strains of antimicrobial resistant pathogens [87-89]. It has also led to pathogen emergence across the wildlife-livestock-human interface [90-92]. For example, the emergence of novel strains of influenza has been linked to reassortment of viral genes following viral transmission among large poultry flocks mixing with wild birds, pig herds and people [93-95]. Rabies cases in Latin America are linked to vampire bats feeding on cattle hosts [96-98]. The emergence of Middle Eastern Respiratory Syndrome (MERS) in people was due to transmission of a coronavirus that is likely of bat origin [99-105], but became recently endemic in domesticated camels [106,107], allowing repeated transmission to people [108-110].

The *intensification* of livestock production has also been linked to disease emergence. For example, a lethal zoonotic disease caused by Nipah virus emerged in Malaysia in 1998 when the virus spilled over from fruit bats into pigs [111,112]. The emergence of this virus was enhanced by specific intensive methods of pig production that led to extended transmission of the virus for a 2 year period [68]. Outbreaks of a novel bat-origin coronavirus (SADS-CoV) caused the death of over 25,000 pigs in southern China in 2017 [113]. This virus is able to infect human airway cells in the lab, and represents a potential zoonotic disease [114]. The expansion of wildlife farming for food and fur led to civets, raccoon dogs and other mammals becoming infected by SARS coronavirus in Guangdong, China, and potentially acting as an amplification host that allowed the virus to emerge in people in 2002 [115]. It is unknown if captive bred animals played a role in the emergence of COVID-19, but after the virus spread globally through movement of people, it infected mink farmed for fur in the Netherlands, Denmark and the USA, and in the Netherlands was able to then cause further human cases [116,117].

Linkages among consumption, livestock farming, health, habitat destruction, climate change and emerging diseases have led to a number of calls for taxation to act as an incentive to reduce consumption and provide resources to tackle these negative consequences. These include calls for: a 'meat tax' on traded meat or meat products to fund zoonotic disease surveillance and prevention from a US Institute of Medicine Committee [118], and analysis of taxation options [119]; a tax on meat consumption to provide incentives to reduce climate change [120,121]; a tax on red and processed meat to reduce the direct health consequences of meat over-consumption [122]; and a review of a 'livestock levy' option to tackle infectious disease threats including the rise of antimicrobial resistance and climate change [123].

Unsustainable consumption drives environmental change, leading to disease emergence

The proximate causes, or direct drivers, of biodiversity loss and disease emergence include changes to land use (e.g. environmental degradation, deforestation and land conversion for agricultural production), direct exploitation of organisms, climate change, pollution and invasion of alien species, among others [124]. They are caused by economic incentives, new patterns of production and consumption, population pressures, culture, ethics and values [124-126]. Cultural, economic, and political aspects of globalization have created new patterns of consumption, contributing to social and economic inequality [127]. Global demand for specific commodities such as meat, timber, wildlife products (e.g. fur) and others can be linked directly to disease emergence and in some cases may be preferentially driven by consumption in developed countries. For example, the global demand for palm oil drives substantial deforestation and other land use changes in many tropical developing countries that have been linked to increased mosquito abundance in disturbed land and rising cases of malaria [128,129]. During the SARS outbreak, raccoon dogs (*Nyctereutes procyonoides*) in live animal markets were found to be infected, and are also receptive to SARS-CoV-2 infection [130]. Raccoon dogs are legally bred in many countries including China, mainly for fur that is exported to supply the fashion industry in countries with high Gross Domestic Product in Europe, North America and other regions.

Invasive alien species introduction has been linked to disease emergence

The anthropogenic introduction of invasive alien species has been recognized as a cause of disease introduction to new regions [131], and transmission to new hosts including wildlife [132,133], livestock [134,135] and people [136]. The globally significant wildlife disease, chytridiomycosis, has led to amphibian declines and extinctions, and has been definitively linked to a series of introductions and escapes [137,138] of amphibians moved internationally for the pet trade , laboratory use, farming [71], or as biological control agents. Substantial efforts have been made to reduce the risk of introduction or control invasive alien species to reduce their conservation impact, and there are increasing efforts to focus on the risk of disease introduction [139,140].

Investing in conservation may avoid exponentially-rising economic loss due to pandemics

In addition to widespread suffering and loss of human life, the global economic losses from infectious disease outbreaks in the last decades have been significant [141], with the most vulnerable economic sectors being the worst affected [142]. Assessments of the economic impact of emerging diseases vary in their methodology and likely accuracy, but point to often significant economic shocks, even for short, relatively regional outbreaks. In West Africa alone, the 2014 Ebola outbreak had an estimated economic impact larger than US$53 billion [143]. The UNDP in 2017 calculated that the societal and economic cost of the Zika virus in South America and the Caribbean was between US$7 and US$18 billion between 2015 and 2017 [144]. Estimates from the Asian Development Bank suggest that the cost of a 3-6 month social distancing and travel restrictions due to the COVID-19 pandemic could cost the global economy between US$5.8 and US$8.8 trillion (6.4-9.7 percent of global GDP) [145]. While the economic damages from COVID-19 are already substantial, they are likely to continue to rise significantly until vaccines are widely available to contain transmission and reduce costly deaths and economic impacts. The overall cost of pandemics will likely also rise significantly in the future due to the projected increase in frequency of emerging infectious disease events [13], and the exponential increase in economic costs associated with them [56,146-148]. The true impact of COVID-19 on the global economy can only be accurately assessed once vaccines are fully deployed and transmission among populations is contained. However, it is likely to be in the tens of trillions of dollars, with estimates of $8-16 trillion globally by July 2020 [141] and $16 trillion in the US by a presumed containment due to vaccination by the 4th quarter of 2021 [149]. If we assume similar costs for other pandemics during the last 102 years (1918 influenza, HIV/AIDS and others) and add the annual burden of largescale emerging diseases (e.g. SARS, Ebola[146] and others), as well as the $570 billion estimated annual cost of moderately severe to severe influenza pandemics [150], **the cost of zoonotic disease emergence is likely to exceed $1 trillion annually**.

The economic damages from emerging diseases are similar in magnitude to those from climate change [151], and can be used to provide a rationale for investing in conservation programs. For example, real options modelling of the rising cost of pandemics was used to identify an urgent (by the year 2041) need to launch a global One Health strategy [152] to prevent pandemics [56]. The OECD estimated that the total annual financial allocation for global biodiversity conservation was between US$78 and 91 billion per year (2015-17 average) [153], an investment that represents a fraction of the impact of zoonotic emerging diseases. Estimates of the **cost of global strategies to prevent pandemics** based on the underlying drivers of the wildlife trade and land use change, and increased One Health surveillance, **are between $22 and 31.2 billion, reduced even further ($17.7-26.9 billion) if benefits of deforestation on carbon sequestration are calculated [141] – two orders of magnitude less than the damages pandemics produce.** This provides a strong economic incentive for transformative change to reduce pandemic risk.

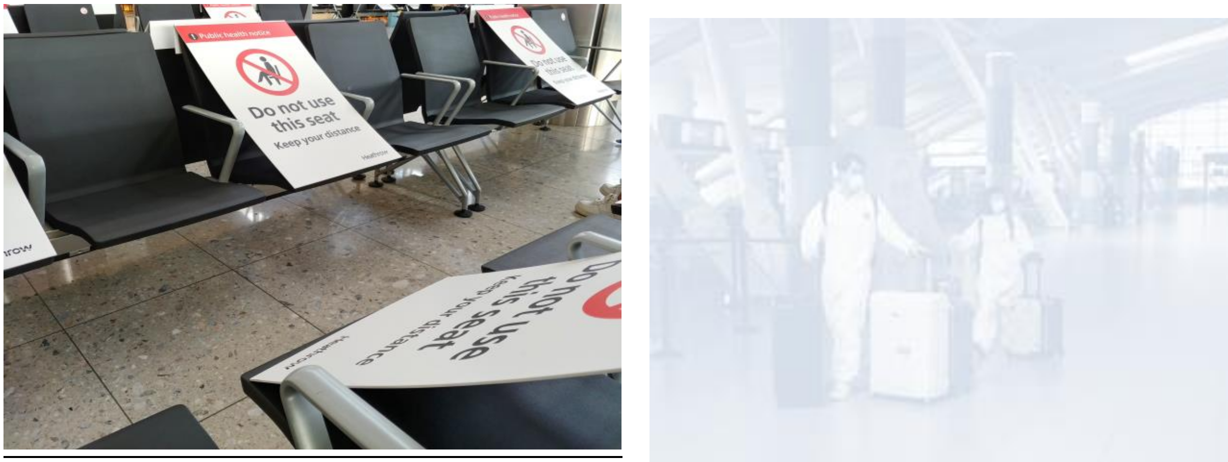


Figure 3: Left, Social distancing measures in place at Heathrow Airport amid the ongoing COVID-19 pandemic. Passenger traffic at London Heathrow fell by 97% in April 2020 in comparison to the same month of the previous year. **Right,** Travelers in protective gear walk through a mostly empty John F. Kennedy Airport in New York City during the March-April 2020 travel restrictions (Photo: Spencer Platt/Getty Images – permission pending).

Reducing anthropogenic impacts in emerging disease hotspots could reduce pandemic risk, protect biodiversity and ecosystem services

Wildlife and microbial diversity, human populations, domestic animals and landscapes are strongly interconnected, with complex dynamic feedbacks that can drive or reduce pathogen transmission. Microbes that exploit these interactions can infect any of these populations separately, and sometimes more than one [53]. Their emergence begins with anthropogenic drivers, and their impacts can be exacerbated by human activities. For example the introduction of cattle infected with the disease rinderpest into Africa led to infection of a wide range of wildlife species, ecosystem disruption at a continental scale and disruption to human settlement [154]. The geographic concentration of disease emergence events in specific high biodiversity regions suggests that a key way to control pandemic risk could be to reduce anthropogenic environmental changes specifically in emerging infectious disease hotspots. This would benefit global health, as well as conservation [53,141,155,156]. However, there are significant challenges. The business case for nature conservation as a protection against emerging diseases needs to be made in all regions, with a major focus on countries that are under highest risk of disease emergence and have high biodiversity, including many developing countries. It will be critical to better quantify the economic costs of pandemic prevention, and the potential economic benefits, as has been done for biodiversity conservation [157]. Efforts to reduce environmental drivers might affect poorer countries disproportionately through a larger requirement for conservation and restoration thus reducing land use options. This could be addressed by a mechanism to compensate biodiverse developing countries for avoiding anthropogenic environmental change. Recent analysis shows that on average, the economic benefits of protecting 30% of the earth's natural assets outweighs the opportunity costs of alternative land uses [158]. Furthermore, reducing pandemic risks substantially through better management of environmental resources would cost 1-2 orders of magnitude less than estimates of the economic damages caused by global pandemics [141].

Protected area systems to conserve biodiversity could also reduce risk of disease emergence

The cross species transmission that may lead to pandemics depends on contact among wildlife, livestock and humans [14,159-161], and is increased when land use change drives encroachment of communities into new regions, or livestock farms are set up in new areas, for example [13,68,162]. The reverse is also likely, that the formation of protected areas that prevent increased human activities, settlement, encroachment or introduction of livestock farming, reduce contact and therefore the risk of disease emergence [44,77,163]. Yet, how to systematically prevent increased human activities in or near protected areas remains a challenge given the diversity of social and political contexts in which they are implemented [163,164].

There may be risks for increasing the flow of pathogens in some landscape conservation approaches. For example, some modelling studies suggest that corridor building strategies to improve wildlife movement may inadvertently increase the flow of pathogens among wildlife leading to disease outbreaks that are a conservation threat [163,165]. However other analyses suggest that for different pathogen-host parameters, the benefits of conservation outweigh the impact of disease spread among endangered species [166,167]. Efforts to design landscape conservation programs that allow for increased wildlife movement, or patterns of agriculture mixed with human settlements and wildlife conservation zones ('mosaic' landscapes) may drive increased human-livestock-wildlife contact and zoonotic disease risk [77,168]. Collaboration among conservation biologists and epidemiologists should be strongly encouraged to provide scientific guidance for measures to reduce risk in these cases, such as culling of non-native species that host zoonoses [169], or launching disease surveillance programs. Furthermore, empirical data that test hypotheses on how different landscape conservation strategies affect pathogen transmission are scarce, despite their potential value in informing conservation policy [170].

Section 2: land use and climate change as drivers of pandemic risk and biodiversity loss

Here, land use change is defined as the full or partial conversion of natural land to agricultural, urban and other human-dominated ecosystems, including agricultural intensification and natural resource extraction, such as timber, mining and oil. Land use and climate change are two of the five most important direct drivers of biodiversity loss [124], and are projected to cause significant future threats to biodiversity and to continue driving the emergence of infectious diseases [124,171-173]. Changes in land use practices have benefited people through economic and social development, but have also damaged human health, driven biodiversity loss and impaired ecosystem functions and the provision of ecosystem services[124]. Land use change has increased exponentially since the industrial revolution, and through a 'Great Acceleration' of Earth System indicators that is considered to mark the beginning of the Anthropocene [15]. Between 1992 and 2015, agricultural area increased by 3% (~35 million ha), mostly converted from tropical forests [124]. By 2015, human use directly affected more than 70% of global, ice-free land surface: 12% converted to cropland, 37% to pasture and 22% as managed or plantation forests. The remaining land with minimal human use consisted of 9% intact or primary forests, 7% of unforested ecosystems and 12% of rocky or barren land [174]. With continued growth in global human population (a 30% increase from 6 billion in 1999 to 7.7 billion in 2019 [175]) and global consumption (a 70% increase in global GDP from US$84 trillion in 1999 to $142 trillion in 2019), the trend of increased land use change is expected to continue, with potentially 1 billion ha of land cleared globally by 2050 [176].

Figure 4: Illegal logging on Pirititi indigenous Amazon lands on May 8, 2018 (Photo: quapan/CC BY 2.0).

Land use change is a major global driver of pandemic risk

Land use change is a significant driver of the transmission and emergence of infectious diseases [40,177-179]. Land use change is cited as the cause of over 30% of emerging infectious diseases, and correlates significantly with the emergence of novel zoonoses globally [13,180]. However, the mechanisms by which diseases emerge are context-specific and scale-dependent. Land use change leads to the loss, turnover and homogenization of biodiversity [181-183]; it causes habitat fragmentation, creates novel ecosystems and promotes the expansion of human populations into landscapes where Indigenous Peoples and local communities have often lived since historical times at relatively low density. These activities create new opportunities for contact between humans and livestock with wildlife, increasing the risk of disease transmission and the emergence of pathogens [34,59,60,184]. Land use change has been linked to outbreaks of EIDs, including Ebola [67] and Lassa fever [185] in Africa, Machupo virus in South America [186], zoonotic malaria in Borneo [129], malaria in Brazil [128] and the emergence of SARS-CoV-2 in China [9]. Wildlife hosts of human pathogens occur at higher levels of species richness and abundance in areas with secondary forest, agricultural and urban ecosystems compared to undisturbed areas, with the strongest effects found in bats, rodents and passerine birds [40,42]. Human dominated habitats favour the invasion and expansion of rodents that are reservoirs for plague, *Bartonella* spp. bacteria, hantaviruses and other zoonotic pathogens [41,187-190]. Populations of reservoirs for Hantavirus Pulmonary Syndrome have increased following deforestation in the Americas [191] and at regional and landscape levels in Central America [192]. Similarly, land use change is linked to increased transmission of vector-borne diseases (albeit some of which are not pandemic threats) such as Dengue fever (with increasing urbanization), Chagas disease [193], yellow fever, leishmaniasis [194,195], Brazilian spotted fever [196-198] and malaria [128,199]. Even the legacy of anthropogenic disturbance can serve as a mechanistic driver of emergence by altering habitat and community structure in ways that shift disease dynamics in wildlife creating novel scenarios for pathogens to jump from wildlife to people [200,201].

Land use change leads to the loss of animal habitat and deforestation-related activities such as road building contribute to the spread of disease vectors, lead to increased contact among wildlife, people and livestock, and provide pathways for novel diseases to spread [128]. The economic drivers of land use change in tropical regions are often clearing of land for crop or livestock production, or expansion of human settlements and illegal activities such as gold mining or logging which affect traditional territories [202]. This process brings people, livestock and wildlife into closer proximity, increases the risk of spillover and spread of zoonoses [203,204] and has been linked to specific emerging infectious diseases, e.g. Nipah virus [112]. Global expansion of livestock farming has been linked to the emergence of influenza, salmonellosis and bovine tuberculosis [205]. Intensive livestock or poultry production can act to reduce overall animal-human contact because of lower number of workers per animal, however intensive production systems are linked to outbreaks of some diseases (e.g. influenza, Nipah virus) and dense animal populations can amplify these outbreaks [68,94,206]. The trade-offs between low intensity production (larger area used, more connectivity, lower density) and high intensity (smaller area, higher density) are important but are often disease-specific. Reduction of this risk in the short term will likely rely on better surveillance and biosecurity around intensive farms, and efforts to distance domestic animals from wildlife. Longer term policy options that involve reducing consumption and expansion of livestock production are addressed in section 5.

Figure 5: Drone photo of an oil palm plantation in Sabah, Malaysian Borneo. Trees are removed periodically for re-planting, revealing the monoculture nature of palm oil production. Land use change for palm oil in Borneo is linked to the emergence of zoonotic malaria [129] (Photo: EcoHealth Alliance).

Urbanization and emerging diseases

More than 50% of humanity now resides in cities, and by 2050, this may rise to 70% of the human population [207]. Urban dwelling, a form of land use, provides technological, social and economic advantages to people, yet cities – no matter how protected, wealthy and powerful they seem - may be particularly vulnerable to disease and climate impacts. Urban heat islands, exacerbated by climate change, provide high-risk habitats for mosquito vectors of dengue in Southeast Asia, Africa and Latin America and have driven cycles of significant outbreaks [208-212]. In northern latitudes vertebrate reservoirs in city parks and gardens such as hedgehogs, rats and squirrels usually live in high densities in close proximity to people and present known zoonotic disease or other health risks [213-220]. In South America, urban areas represent a high risk for autochthonous canine and human visceral leishmaniasis due to the presence of both the sand fly vectors and large feral populations of dog hosts [221]. Overlapping distribution of urban and forest mosquitoes at the park edge increases the risk of arbovirus exchange via multiple bridge vectors in Brazilian urban forest parks [222], perhaps explaining the local expansion of disease in urban parks and more regional expansion [223]. These risks are often countered by enhanced disease control systems to protect, treat and help urban residents to recover from infectious diseases in urban regions. However, despite this, the high density of people in urban centers represents an intrinsic risk for disease outbreaks. For example, city apartments and hotels in South China (including Hong Kong) became superspreading centers during SARS [224], urban centers became a focus of rapid amplification of Ebola virus infection in West Africa [225], and cities emerged as the central focus of outbreaks and impact of COVID-19 in the USA (e.g. New York City), Europe (e.g. Madrid, Stockholm, Prague) and other regions.

Climate change as a driver of emerging infectious diseases (EIDs)

The Intergovernmental Panel on Climate Change (IPCC) concluded that human influence on climate has been the dominant cause of observed warming since the mid-20th century, which is unprecedented in rate and scale [174]. Human and animal movements in response to climate change [226] are likely to allow microbes to make contact with new hosts, to potentially invade new niches [227] and to infect even relatively unrelated hosts [228-231]. Microbial species' capacity to colonize new hosts (ecological fitting) may facilitate the rapid expansion of host range even by ecologically specialized pathogens under climate change [232-234]. Such climate change-driven changes to microbial biogeography may have driven historical microbial evolutionary diversification [234]. Despite a lack of evidence that reports of emerging disease events from the 1960s to the early 2000s correlate significantly with measures of climate change [11,13], continued climate change and the development of research focused on identifying long term trends in disease cases will likely identify future impacts [234,235]. Climate change is projected to cause shifts in host and vector ranges, alterations to life cycles of vectors and hosts under altered climatic conditions and migration of people and domestic animals. Shifts in precipitation may alter abundance of crop plants and affect population cycles of herbivores such as rodents, with potential for shifts in reservoir distribution, population density and pathogen risk [236]. Simulations of climatically determined geographic range loss under global warming for >100,000 plant and animal species indicate that warming of 2°C by 2100 would lead to projected bioclimatic range losses of >50% in 18% (6–35%) of insect species, 8% (4–16%) of vertebrate species and 16% (9–28%) of the plant species studied [237]. Predicted shifts of this magnitude will also likely have impacts on disease emergence.

Examples of diseases that have emerged due to climate change are few, likely because of the intensive long-term ecological research needed to demonstrate this. Climate change has driven latitudinal and elevational shifts of biomes in boreal, temperate and tropical regions [238]. This likely led to the recent spread of bluetongue disease throughout Europe due to climate-induced migration of its biting midge vector [239,240], the expansion of some species of ticks and tick-borne diseases, e.g. the northern migration of tick-borne encephalitis in Scandinavia [69,70,229,241-244], and migration to higher altitudes in mountains [245]. Range expansion of several North American tick species has also been observed, including the recent genetic evidence of the northern expansion of the most important vector species for Lyme disease, the blacklegged tick (*Ixodes scapularis*) [246,247]. Climate change has also been implicated in increased hantavirus incidence in Western Europe [248] and South America [249].

Temperature changes also allow occasional immigration of vectors to lead to persistence of disease. For example, tick vectors of Crimean-Congo Haemorrhagic Fever virus, often carried by migrating birds from Africa and Mediterranean countries to temperate Europe [213] and Scandinavia [250] have been observed for the first time developing to adult stages in northern Europe, likely due to milder winters [242,251]. In tropical and temperate regions, rising temperatures can lead to increased vector abundance, density, biting rates and decreased time between new generations of vectors maturing, all driving increasing disease risk [252-254]. The tick *Ixodes ricinus* (the vector of Lyme disease and tick-borne encephalitis) has increased its rate of development (oviposition, moulting and incubation rates) in northern Europe since the mid-20th century [255]. Changes in climate have also been implicated in the increasing impact and emergence of some wildlife diseases [256-258].

Land use change can act together with climate change to exacerbate disease emergence

Both land use and climate change will likely create novel wildlife communities [259], new relationships among wildlife, human and livestock populations and increased potential for cross-species transmission [184]. Arthropod vectors such as mosquitoes and ticks have been shown to extend their geographical range as a consequence of both changing climate and land use. They can enhance transmission of pathogens locally, lead to diseases spilling over, and help spread them globally when mosquitoes are transported by ships and planes [260]. The identification of geographic regions, degraded ecosystems and species assemblages where these drivers overlap [40], may provide a strategy to monitor for indicators of biodiversity change that could lead to disease emergence [234]. Shifts in host species ranges due to land use and climate change could also be monitored to help better predict outbreaks.

Ecological restoration, land planning, green spaces and trade-offs among conservation and health

Conservation programs that aim to conserve intact habitat, reduce land use change by sustainably managing land and reverse ecosystem degradation by restoring forest and other intact habitats may reduce the risk of disease emergence if they also reduce contact among people, livestock and wildlife. However, analysis of spatial patterns of emerging infectious disease (EID) origins demonstrates that both deforestation and reforestation are correlated with heightened disease emergence risk globally [13], suggesting that it is the *disruption* of landscape ecology that drives changes in pathogen transmission dynamics and leads to disease emergence across landscapes [184]. Restoration programs that are designed to increase wildlife movement among patches of landscape (e.g. formation of wildlife corridors), or to create 'mosaic' landscapes of wildlife, livestock and human communities, could increase zoonotic disease risk by increasing contact and microbial transmission among animals and people [163,168,169,261]. This is supported by modelling studies of corridor building and forest fragmentation

[165,262,263], as well as empirical studies of fragmented habitat mosaics [13,38,264,265]. However, detailed empirical research on specific conservation programs is largely lacking, and urgently needed [266,267]. It may be that the increased risk as habitat is lost, is due to the loss of predators and the dominance of synanthropic species that also are reservoirs for specific diseases (e.g. Lyme disease) [24,40,268,269]. It may be possible that efforts to introduce previously-extirpated predators as part of conservation programs, may have beneficial effects on disease risk by reducing reservoir abundance [269,270]. Analyses of the trade-offs and synergies between infectious disease risk and conservation in these landscapes need to be undertaken urgently [163,271]. The risk of infectious disease spillover could be addressed substantially by increased healthcare provision and community education around behavioural risk of spillover in these landscapes. Conservation programs could also be designed to include disease testing and monitoring to help reduce risk of negative impacts through disease emergence.

The creation of green spaces in urban and peri-urban zones afford people areas for recreational activities, help regulate climate and reduce the urban heat island effect, in some cases regulate floods, and benefit welfare and mental health [272-274]. These areas may also provide habitats that support increased types and, or, prevalence of pathogens. Examples include urban hedgehogs and ticks maintaining several tick-borne pathogens in a Budapest city park [213,214], ticks in southern England which may support urban *Borrelia* transmission cycles and urban landscapes with more aquatic plants and water in eastern China have higher mosquito densities [275,276]. Mosquito assemblages in species-poor urban green spaces in São Paulo, Brazil, are composed largely of species considered vectors of human pathogens [277]. Finally, there is substantial evidence that suburban forest fragmentation in the USA, in the absence of top predators of the vertebrate reservoir hosts for Lyme disease, has led to increased disease risk for people [24,269,278]. Analysis of trade-offs may provide strategic guidance to maximize the benefits of green spaces, and heightened disease surveillance and public health education programs may help reduce risk.

Economic assessments of ecosystem services related to the maintenance of human health may allow analysis of trade-offs that help achieve the UN 2030 Agenda for Sustainable Development commitment of balancing "the three dimensions of sustainable development: economic, social and environmental." [279,280]. The COVID-19 pandemic demonstrated that societal impacts of a disease are driven by urban and suburban planning and individual space available to socially distance while accessing greenspace [281]. Some countries have already begun to witness a move out of cities to escape perceived risk of COVID-19 transmission. As countries recover from this pandemic, land use planning, adaptive management of ecosystems and adequate conditions for human life may become a key to preventing disease spillover in the future [282].

There is a critical role for scientists to identify possible precautionary steps for decision makers to prevent novel EID outbreaks including by standardized protocols to document, assess, monitor and act to reduce risk [234]. A cooperative effort of Indigenous Peoples and local communities, citizen scientists, ecologists, virologists, physicians, veterinarians, social scientists and decision makers is needed to switch from reactive to proactive behaviour. This is, in essence, the approach called for by advocates of One Health **(Figure 10)** which aims to foster close collaboration among human, animal, environmental health agencies, researchers and practitioners [156,283-286]. Some key organizations have begun the process of coordinating their programs around a One Health theme, including: the 'Tripartite' comprising WHO (World Health

Organization), FAO (Food and Agriculture Organization of the United Nations) and OIE (World Organization for Animal Health) [93,287]; the CBD (Convention on Biological Diversity) [288,289]; the World Bank [152,285]; and a wide diversity of civil society organizations [172,290-297]. There have also been calls for a One Health approach to COVID-19 control and response [290,298]. However, a great deal of further work is required to mainstream this approach [297,299].

Section 3: The wildlife trade, biodiversity and pandemics

The consumption of wild animals has occurred throughout human history, and is a critical source of nutrition and welfare for Indigenous Peoples and local communities and many rural communities in developing countries[300-303]. It is also a source of wild meat for consumption and of acquisition of animal products (fur, trophies etc.) in many developed countries [304,305]. Regulation of and governmental support for sustainable harvesting of wild products have been successfully used as a way to alleviate poverty in many countries and increase the sustainability of the wildlife trade (https://www.cites.org/eng/prog/livelihoods). Sustainable trade has led to better living conditions, welfare and health in some cases [306]. There is significant evidence that the wildlife trade is involved in the emergence of a range of diseases, particularly where the trade is poorly regulated, and concerns mammals or birds (the most important reservoir hosts for emerging zoonoses) [5,307-310]. The legal regulated trade in wildlife has also led to the spread and emergence of diseases and there is little comparative data with the health risks of the illegal trade to date [311-313]. For these reasons, and because of the links between COVID-19 and live animal markets [10], there is a great deal of current interest in policy measures to reduce risk of infectious disease in the wildlife trade. This section reviews existing information about trade (legal, illegal, international and domestic) in live wildlife and wildlife commodities (including farming of wildlife) in relation to their role in disease emergence and spread. It lays out evidence that can be used by decision makers in assessing trade-offs between the clear conservation, economic and welfare benefits in supporting a well-regulated and sustainable trade in wildlife, with the risk of disease spread and emergence via trade pathways. Where available, scientific analyses of data on the relative roles of legal and sustainable trade, versus unregulated and illegal trade in the emergence of disease are provided. The goal is to inform a discussion of trade-offs that may be timely and important given ongoing calls for, and effort to, change policy on the wildlife trade following the emergence of COVID-19 [314-321].

Trends in the wildlife trade

The trade in wild animals, their parts and products is common around the world through local networks (e.g. a hunter trading directly with restaurants), through transport to urban centres (e.g. live animal markets), via trade routes that cross national borders, or distribute to global destinations (e.g. the international trade in wildlife as pets, driven largely by markets in Europe and North America) [309,322]. In line with the increase in land use change **(Section 2)**, the wildlife trade has expanded significantly in the last few decades. Although data are not fully available for domestic trade, the international legal wildlife trade has increased 500% in value since 2005, and 2,000% since the 1980s [322,323] **(Figure 6)**, albeit that a proportion of this increase may reflect enhanced sustainable captive breeding or ranching [324]. This information, case study data and analysis of trends suggest that the legal wildlife trade is, in many cases, unsustainable and a continuing threat to biodiversity conservation [325,326]. About a quarter of all wild terrestrial vertebrate species are traded globally [327]. Although data are incomplete, it has been estimated that the global illegal trade in wildlife is worth ~$7–23 billion per year, equivalent to nearly 25% of the value of the legal market [328], (https://www.traffic.org/about-us/illegal-wildlife-trade/)[329] [327,330]. This may be an underestimate because illegal wildlife trade data are based on customs seizures that do not account for domestic trade [331,332]. Finally, the continued globalization of trade routes, lack of sufficient reporting [333], the links between poverty and illegal hunting [334] and insufficient or inadequate regulation throughout many trade pathways, suggest that the wildlife trade will become more unsustainable in future [335].

Regulation of the wildlife trade is challenging due to its breadth, scale and the myriad species and products involved. Since 1975, international trade in many wild species has been regulated by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) [336], a multilateral treaty with 183 signatory Parties (182 countries and the EU) that provides a mechanism to regulate the legal trade of about 36,000 species of animals and plants. CITES has had demonstrated success in reducing wildlife trade, driving up value of sustainably traded species and products and promoting captive-breeding, ranching or farming as alternatives to wild capture (https://www.cites.org/eng/prog/livelihoods). For example: CITES listing of seahorses (*Hippocampus* spp.) led to reduced trade and an increase in their value in the trade [337]; CITES listing of eels (*Anguilla* spp.) and an EU ban dramatically reduced the trade, although it then shifted to Indonesia [338] and North Africa [339]. However, the international trade in a large number of wild species – principally fisheries and forestry resources – are not regulated under CITES, while the domestic use and trade of wildlife falls outside the purview of the Convention.

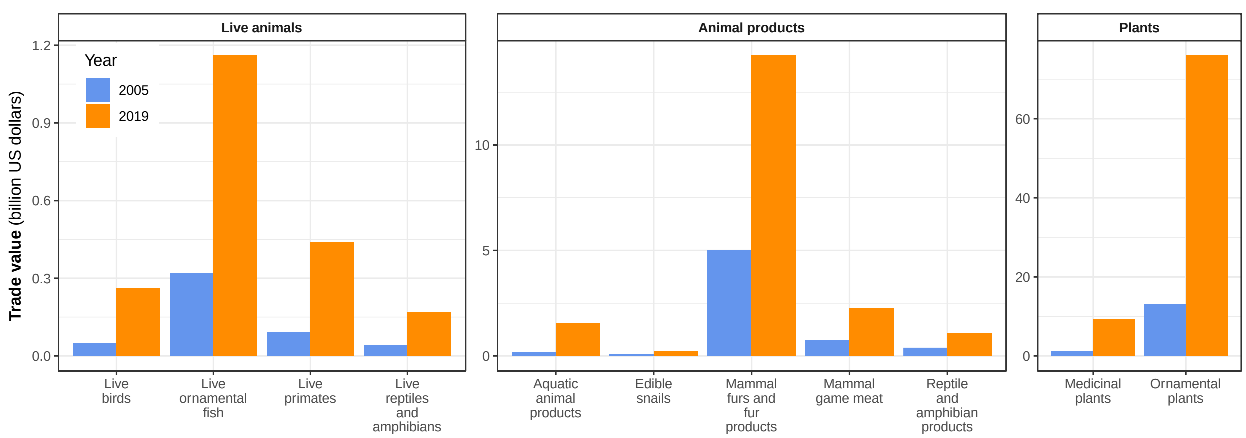


Figure 6: Monetary value of legally traded wildlife commodities has increased more than 500% between 2005 and 2019 for all categories. Figures above bars = values in billions of US dollars. Data for 2005 from [322]; for 2019 from [323]. Data for frog legs ('reptile and amphibian products' category) are from 2014. Data for plants included for comparison, and because trade in plants has led to introduction of disease vectors (e.g. tiger mosquitoes into USA, Netherlands [340,341]). Data do not include timber or commercial fisheries.

A number of countries have additional measures to regulate trade in wildlife—particularly exports. National or regional (e.g. the European Union – EU) level controls for trade in native and exotic species have been enacted for conservation purposes (e.g. the US Endangered Species Act); to promote animal welfare (e.g. EU import bans on young Harp Seal *Phoca groenlandica* and Hooded Seal *Cystophora cristata* skins, and on species trapped in ways that do not meet “international humane trapping standards”); for public or agricultural health concerns (e.g. EU ban on wild bird imports to reduce spread of high pathogenicity H5N1 avian influenza); and to reduce the risk of invasive alien species [322]. The Balai directive (https://lawlegal.eu/balai-directive/) has been enacted in the European Union to deal with some health risks for some of the international trade in wildlife. However, law enforcement, legislation and policing efforts are challenged by a rise in e-commerce [342-344], expansion of trade routes [335,343,345] and apparently increasing involvement of violent criminal elements in the illegal trade [346-348].

Wildlife consumption patterns vary markedly among countries, with North America, Europe and some parts of Asia being net importers and consumers, whereas countries in South America, Africa, Southeast Asia and Oceania tend to be net suppliers, or may have a large domestic trade, added to traditional consumption patterns [349-352]. Domestic trade dominates in some regions, e.g. West and Central Africa [302,353,354], the Neotropics [355-357] and some Southeast Asian countries [301,358]. Demand in Europe and China includes products for fashion (e.g. fur, leather). In China, a growing wealthy middle class is often the main consumer of fashion products, of wildlife for traditional Chinese medicine or of food with perceived health benefits [359,360]. The EU and USA are leading consumers of legally traded wildlife for pets [312,342,351,361]. The USA is one of the largest legal importer of wildlife globally with 10-20 million individual wild animals imported each year, largely for the pet trade [309,312]. The number of shipments rose from around 7,000 to 13,000 per month from 2000 to 2015 [361]. This trade has led to the introduction of monkeypox virus **(See Box 2)** and the tick vector and causative agent of heartwater disease of cattle [362], among other emerging disease threats.

In many regions, rural communities have traditionally depended on wild animal protein to supplement their diet. In some regions, increased demand from the international trade, coupled with poverty have resulted in growth of hunting and trade in illegal or legal wildlife [300,312,334,363-368]. Increased domestic trade in some countries is driven by rapid human population growth, growing wealth, migration to urban centres, increased connectivity and transportation routes, appreciation of wild meat for its taste, cultural connotations and as a luxury item and globalization. Links have been reported between the illegal wildlife trade with Asia-driven organized crime in South America in the last decade [369]. In the USA, the legal wildlife trade doubled between 2000 and 2013 [312], and wild meat seizures in passenger baggage are common in airports in the USA and Europe [312,367,368,370].

Wildlife farming

Wildlife farming is defined as the captive breeding of traditionally undomesticated animals in an agricultural setting, for profit, to produce: animals to be kept as pets; commodities such as food and traditional medicine; and materials like leather, fur and fibre [371] [372,373]. Wildlife farming may offer an alternative source of wildlife products, particularly wild meat, economic development in rural areas and biodiversity conservation by reducing hunting pressure on free-living populations. This has led to a reduced consumption of wild individuals in some cases (e.g. American alligators), and has alleviated poverty and improved health and welfare (https://www.cites.org/eng/prog/livelihoods). However, surveys have reported that in many regions wildlife farms are stocked repeatedly with wild-caught individuals that are largely indistinguishable from those that are captive-bred, record keeping is often lax or non-existent and enforcement of laws often poor [373,374]. The increased availability of wild animals due to captive breeding may increase consumer demand, put pressure on free-living populations for founder stock because breeding capacity is unable to meet demand [373,375] and create opportunities for laundering illegally-caught animals [376]. A 2014 census in Vietnam documented over four thousand wildlife farms producing nearly one million individuals of 182 wildlife species. However, many farms had a high proportion of wild-caught animals (e.g. doves and bears) or their stock was nearly all wild-caught (e.g. tiger, rabbit, squirrel) [377]. Wildlife farming has expanded substantially in China [378], where 'non-traditional animal' farming generated US$77 billion dollars and employed 14 million people in 2016 [141,379].

The wildlife trade has led to a series of high-profile emerging diseases

The hunting and consumption of wildlife has been integral to human survival throughout history and has developed as part of most community's cultural heritage. The hunting, trading, butchering and preparation of wildlife for consumption has led to a significant proportion of known zoonoses, EIDs and pandemics such as Ebola virus disease, HIV/AIDS, Monkeypox, SARS and COVID-19 **(Box 2)**. These likely include many of the zoonoses now endemic in the human population [308,380]. The trade in wildlife is a particularly important risk factor for disease emergence because it provides intimate contact among wildlife, livestock and humans, facilitating the spillover of novel or known pathogens, their amplification and spread. Increased numbers and density of farmed animals (both domestic and wild) allow infections to spread more easily and drive bigger outbreaks. Increased volume of trade and efficiency of long-distance transport along the wildlife trade supply chain drive the movement of pathogens across large distances to contact populations that may not have had prior infection by them.

The logistics involved in the wildlife trade supply chain may be a risk for increasing the prevalence (percentage of animals infected) and the diversity of microbes, and allowing viral recombination in animals that are in transit [381]. A ten-year study of pangolins (*Manis javanica*) seized at the country of origin revealed a complete lack of potentially zoonotic viruses [318], whereas two different groups seized at the end of the trade route were found to contain coronaviruses with genetic elements closely related to SARS-CoV-2, and others likely of pangolin origin [315,382,383]. Analyses of viral genetic data suggest that these animals were infected with recombinant viruses that may have evolved due to contact with other species during prolonged trade pathways [6,318]. Detailed studies have not been conducted, but transmission studies on captive animals demonstrate that many of the necessary logistical demands of the wildlife trade likely enhance disease risk. For example, at different stages of a trade supply chain, individual animals may be held at unnaturally high densities, which can increase the risk of microbial transmission among them. Individuals from different geographic locations are often housed together or close to each other in holding pens and containers, some in mixed species assemblages, all of which increases the opportunity for microbial transmission. Stress due to handling and the many other unnatural conditions in the trade, are likely to reduce fitness, increase the likelihood of infection (i.e. prevalence), increase the shedding of microbes and increase the risk of illness which may lead to enhanced transmission. All of these are inevitable aspects of the logistics of trading animals, and likely can't be completely eliminated by guidelines on care, hygiene and welfare considerations. The factors that enhance likelihood of pathogen shedding, transmission, cross-species spillover and illness are intensified in live animal markets, where animals are often held for long periods of time in overcrowded conditions, with poor hygiene practices, mixed with diverse species and in close contact with large groups of people who travel regionally to purchase often live animals [301,384,385] [358,381,386,387]. Thus, when SARS emerged from a likely bat origin through the live animal markets of southern

China in 2002, it infected a range of other wild mammal species (raccoon dogs, civets, etc.) as well as people [10].

Figure 7: Masked palm civets (*Paguma larvata*) were farmed for sale as a food item in the live animal markets of South China. Civets were found to be infected with SARS-CoV at the live animal markets where some of the earliest known human cases of SARS were identified, in Guangdong, China, 2002 (Right photo: EcoHealth Alliance).

The wildlife trade may also lead to increased human activity in rural or uninhabited regions to capture often increasingly rare species, driving new contact among people, animals and their microbes. These activities are linked in many cases to land use change and the processes of deforestation and forest degradation, timber extraction, mining, settlement and agricultural expansion [50 388]. The industrialization of the trade also puts increasing pressure on Indigenous Peoples and local communities who have nutritional dependence on wildlife, when hunting pressure to supply the trade reduces populations to unsustainable levels. Because live animal markets are often a place where people congregate, the emergence of SARS-CoV-2 appears to have been amplified among people within a live animal market in Wuhan, suggesting that live animal markets may provide a mechanism for wildlife-to-human spillover of previously undescribed pathogens and also their amplification [10].

The increasing complexity of wildlife trade networks, including wildlife farms, live animal markets with mixed livestock and wildlife, long-distance bulk transport and international trade will likely increase future risk of disease emergence. The industrialization of the wildlife trade provides substantial opportunity for cross-species microbial transmission when diverse wildlife species and livestock are held in close confinement for significant periods of time, with often little surveillance, poor regulatory framework and poor law enforcement [389]. Despite few studies of the mechanisms that drive risk, recent data demonstrate that the percentage of bamboo rats infected by coronaviruses increases through the wildlife trade value chain in Vietnam, from 6% in rat farms, to 21% in large live animal markets, to 56% at the point of slaughter in restaurants [381]. Similarly, the trade appears to have enabled SARS-related coronaviruses to recombine among species, leading to infections in pangolins by viruses with genes closely related to SARS-CoV-2 [315,318,382,383]. These studies, taken together, suggest a role for the wildlife trade in Southeast Asia in driving the emergence of SARS, COVID-19, and potentially a growing number of future zoonotic coronaviruses and other zoonotic pathogens. Some bat-origin CoVs are known to infect both people and livestock, e.g. MERS-CoV (bats, camels, people), SARS-CoV (bats, farmed raccoon dogs and civets, people), SARS-CoV-2 (bats, people, farmed mink, raccoon dogs) and SADS-CoV (bats, pigs, high potential for human infection) [99,117,130,390,391]. Some elements of the wildlife trade also increase the risk of emergence of diseases that affect animals farmed for food, highlighting their potential impact on food security as well as public health.

Figure 8: Carcasses of confiscated frozen pangolins illegally imported into Indonesia in 2015 are buried for safe disposal. Pangolins, which are threatened with extinction due to the illegal wildlife trade, have recently been identified as hosts of coronaviruses closely related to SARS-CoV-2 (Photo: Earth Tree Images).

Box 2: Five emerging infectious diseases linked to wildlife trade and consumption

Ebola virus disease

Since its discovery in 1976, several epidemics of Ebola virus have been reported in Central and West Africa, the largest of which began in Guinea in 2014 and lasted until 2016 [225]. Some Ebola outbreaks are thought to have begun with an infected wildlife host (e.g. a gorilla, chimpanzee, duiker, or fruit bat) that was either killed for food or harvested after dying of the disease [392]. Community transmission among people is associated with intimate contact with infected individuals or bodily fluids during burial practices, caregiving, or habitation [393]. Many Ebola virus outbreaks have been limited to rural communities and therefore have remained small, usually involving less than 400 cases [225]. In the 2014 outbreak, failure to control transmission in the early phases led to large numbers of infected people in two adjacent countries because of high population mobility, strong connectivity of distant rural communities and densely populated urban centres in the region [225]. Hospital care and burials were important amplifiers of transmission [394]. The identity of the wildlife reservoir host of Ebola virus is uncertain. However, based on partial sequences of Ebola virus genome detected in tissue samples and on antibodies to Ebola virus in blood, the likely original host reservoirs are one or more bat species

[66,395,396]. This is supported by the fact that a related filovirus, Marburg virus, has a fruit bat species (Egyptian rousette, *Rousettus aegyptiacus*) as original host reservoir [397].

HIV/AIDS

HIV-1 and HIV-2 were identified as causes of HIV/AIDS in 1983 [398,399] and 1985 [400], respectively. Their origin is thought to be hunting and butchering a chimpanzee or gorilla (HIV-1) or sooty mangabey (HIV-2) infected by related viruses in Central or West Africa [401]. Such infections have likely happened repeatedly throughout human history, and this is supported by analysis of sequence data comparison from HIV and the related simian immunodeficiency viruses. However, in the late 19th or early 20th century, human communities in central and west Africa were expanding and becoming more connected due to land use change and road construction. These circumstances probably allowed rapid spread within the region [402]. Global spread was facilitated by increased airline and ship travel and the outbreak achieved pandemic status [403]. Analysis of viral gene sequences suggests the date of transmission that led to the pandemic is the early years of the twentieth century for HIV-1 [404] and the middle of the twentieth century for HIV-2 [405].

Monkeypox

Monkeypox is caused by a poxvirus originally described in a colony of captive non-human primates, and is endemic in West and Central Africa where it causes serious outbreaks with a case fatality rate as high at 10% [406,407] . In 2003, 71 cases of human monkeypox were reported in five states of the USA [311]. This was the first known report of monkeypox in the Western Hemisphere. The virus was imported into the US within a shipment of Gambian pouched rats (*Cricetomys gambianus*) for sale as pets, and these also infected captive prairie dogs, an endemic USA rodent, although the disease did not become endemic in the USA [408,409]. No deaths were reported. No human-to-human transmission was found, although it is known in Africa [409,410]. All cases involved direct contact with infected prairie dogs. The presence of this potentially serious infection within the wildlife trade led to the USA Centers for Disease Control and Prevention using emergency authority to ban the trade in rodents from African countries and the USA Food and Drug Administration to ban the sale of prairie dogs, despite there being uncertain legal authority to do either [411]. The ban on African rodent importation into the USA is still in place (https://www.cdc.gov/poxvirus/monkeypox/african-ban.html).

SARS

SARS emerged in the Guangdong province, China, in November 2002. That province had shown 38% population growth in the previous 10 years (the most rapid in China) and a 138% increase in GDP per capita in previous 10 years (5th highest in China). As a result, consumption of wildlife had increased in the province in the previous 20 years, with 95% of the inhabitants of the major city in Guangdong province, Shenzhen, having eaten wildlife, and wild-caught or farm-raised masked palm civets (*Paguma larvata*) being a popular meal. The first case clusters included restaurant owners and chefs who bought wildlife from large live animal markets in Guangzhou [412,413]. Evidence of infection was found in masked palm civets (*Paguma larvata*), Chinese ferret badgers (*Melogale moschata*) and raccoon dogs (*Nyctereutes procyonoides*) in one live animal market [414]. However, these animals were likely infected during transit in the wildlife trade, and the true reservoir hosts are insectivorous bats (*Rhinolophus* spp. and others) that are commonly eaten in South China, and were traded widely in live animal markets at the time [415]. Initial spread was mainly to family members and to medical staff at hospitals where they were cared for [412], then via an infected doctor to Hong Kong [416]. Subsequent global spread resulted in just under 8,000 confirmed cases, about 10% of whom died. Due to strict public health measures and most viral transmission occurring after noticeable symptoms, the pandemic was stopped by July 2003 [417]. A temporary ban of wildlife hunting and trade in southern China was issued, with particular focus on the quarantine of farmed or traded civets. Additionally, some of the larger live animal markets were temporarily closed. In January 2004, when new SARS cases were diagnosed again and linked to the wild animals in Guangzhou [418], the authorities ordered culling of wildlife in the markets[419]. In total, 838,500 wild animals were reported being confiscated from the live animal markets in Guangzhou city [420]. These measures were relaxed months following the outbreak.

COVID-19

The timing, geography and source of infection for the first human cases of COVID-19 are still not fully known, but the earliest known cases occurred in November 2019 in Hubei province, China. The majority (27/41, 66%) but not all of an initial cluster of infected people visited a seafood market in Wuhan and it is probable they either were infected by wildlife traded there, or from other people who were already infected in another part of China [10,421,422]. The animal species from which people contracted the causative agent, SARS-CoV-2, is not known, but the closest relatives are found in horseshoe bats (*Rhinolophus* spp.) from Yunnan province [6]. SARS-CoV-2 spread among family members and hospital staff in Wuhan and disseminated rapidly to other provinces in China, partly due to extensive travel for Chinese New Year and because Wuhan is a major transport hub [423]. Subsequently, it spread by travellers to Southeast Asia, then the Middle East, Europe, the USA and elsewhere. COVID-19 has since become a very significant pandemic, largely because of its relatively high mortality compared to seasonal flu or recent outbreaks of pandemic flu (e.g. H1N1, 2009) [424].

The live animal market that was considered being associated with the first cluster of cases was closed down in December 2019 [425], and Chinese authorities issued national urgent notices to strengthen wild animal market supervision, enforce the law on illegal wildlife trade and prohibit the trade of wild animals in January 2020. In February 2020, the central government issued a permanent ban on wildlife consumption for food [314]. As a result, many wildlife farms across the country were closed, and animals were ordered to be culled, transferred to be used for medicine, or released into the wild as instructed by the government. Revisions of major state laws for wildlife protection and animal epidemic prevention are also undergoing. A survey among 74,040 Chinese citizens (largely from urban centers) after the main outbreak of COVID-19 in China showed 94% were supportive of more stringent policy and legislation on wildlife trade, and the majority of respondents intended to cease wildlife consumption for food [316]. Similar public opinion was reported in Japan, Myanmar, Thailand and Vietnam [317]. Similar changes in attitude were observed in China after outbreaks of SARS and avian influenza during 2002-2004 [426], however there is no published evidence that this led to a long term reduction in the number of live animal markets or to a change wildlife consumption patterns. A deeper understanding of cultural incentives for wildlife consumption would likely be required to implement long-term behaviour change and successfully reduce wildlife trade [427].

There are significant gaps in policies to control disease emergence through wildlife trade

The World Organisation for Animal Health (OIE) is the primary international agency with a remit to protect animal health globally by providing a mechanism to reduce risk of disease spread through animal trade **(Box 3)**. OIE has established a list of notifiable terrestrial and aquatic animal diseases that are considered as specific hazards to livestock health, human health and the environment. The OIE list is the reference for international sanitation for animal diseases by the World Trade Organization under its Agreement on Sanitary and Phytosanitary Measures (SPS), making adherence to trade measures based on this list internationally enforceable [428,429]. OIE member countries are obliged to report semi-annually and annually on OIE listed diseases and immediately on the new occurrence of an OIE listed disease or an unusual epidemiological event in animals, regardless of the species affected, whether domestic, wild, captive wild or feral, and on the measures taken to reduce risk. Between 1900 and 2014, 73 OIE-listed terrestrial animal diseases were reported in wildlife (defined as wild animals, captive wild animals and feral animals [313]), with 528 wild animal species that are documented hosts of at least one of these [313]. These include zoonotic diseases caused by Japanese encephalitis virus, Nipah virus, *Coxiella burnetii,* Rift valley fever virus, *Francisella tularensis* and West Nile virus. Trade in wildlife has been cited as causing the spread of OIE-listed pathogens responsible for zoonoses or livestock outbreaks in 30 peer-reviewed papers [430]. This included spread through the wild meat trade, the introduction of non-native or invasive alien species, human encroachment or habitat alteration, migration or expansion of habitat, trade in wild animal parts, or a combination of these [430]. Despite the OIE's proven reporting system and legal framework, regulatory responsibility for wildlife is often unclear [313]. In many countries, wildlife is regulated by agencies dedicated to the management of natural resources and is not under the purview of human or agricultural health officials. This leads to lack of health expertise in managing wildlife and exotic animals, making it difficult to organise appropriate health surveillance and risk assessment protocols. Most trade in wildlife had no veterinary oversight, compared to that for domesticated animals and their diseases (e.g. foot and mouth disease) [309,312]. As a result, there is a lack of organization and funding for wildlife health policy in many countries, and policies that are reactionary rather than precautionary, leading to increased risk and costs of mitigation and control [308,309].

Box 3: International mechanisms and organizations of potential importance in regulating the role of wildlife trade in zoonotic disease spread

The World Organization for Animal Health (OIE)

The OIE was originally created as the Office International des Epizooties through an international Agreement signed in 1924. It was renamed in 2003 as the World Organisation for Animal Health but kept its historical acronym OIE. OIE is the intergovernmental organisation responsible for providing a mechanism and guidelines to track, monitor and control disease threats to animal health that arise through trade in animals and their products. It is focused primarily on livestock trade and health but has a remit to include diseases that threaten the environment and covers many diseases that are zoonotic by nature. OIE is recognized as a reference organisation by the World Trade Organization (WTO) and its 182 Member Countries (2018 data) and has regional and sub-regional offices on each continent.

OIE operations are managed through headquarters based in Paris, that implement resolutions passed by an international committee and developed with the support of Commissions elected by OIE Delegates. Work is supported by annual contributions from Member Countries, supplemented by voluntary contributions.

The OIE provides the rationale, and detailed mechanism for countries to monitor and control the risk of disease spread in wildlife trade via the setting up of groups of experts. These groups assess whether a disease should be 'notifiable' by countries due to the threat it represents to the trade, to animal health (primarily livestock, captive-bred or ranched species) in a country and to the environment. Signatory countries are then mandated to report annually on the presence of the disease in the country, whether the disease is absent within their country and on measures they are taking to control the disease. At the time of writing (2020), it is mandatory to report on 117 animal diseases, infections and infestations, and voluntary to report on another 55 diseases that affect wild animals. Countries can designate disease-free zones within their national boundaries that they can trade from and into, but trade is restricted or blocked for notifiable diseases outside these zones.

The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)
CITES is a multilateral treaty that provides a mechanism for countries to monitor and control international trade in species covered by the Convention. Its aim is to ensure that international trade in specimens of wild animals and plants does not threaten their survival. It entered into force in 1975 and is legally binding for all 183 signatory Parties (182 countries and the EU). CITES regulates international trade in species covered by the Convention and requires Parties to enforce the provisions of the Convention by requiring them to adopt measures that prohibit trade that would violate the Convention, penalize illegal trade and the possession of illegally traded specimens; and provide for the confiscation of such specimens. International trade is managed by the national management authority, designated by each Party to the Convention, typically a ministry or agency responsible for environment, forests, wildlife or agriculture. The trade is monitored through the submission of annual reports to the Secretariat by each Party. CITES secretariat activities are supported by national contributions. The Review of Significant Trade monitoring mechanism monitors the sustainability of international trade. CITES does not conduct the monitoring of domestic (within-country) trade, and this is funded and organized by national governments, usually working through their wildlife, environment or forestry ministries or agencies. Procedures for addressing compliance matters have been established under the Convention with the Standing Committee responsible for overseeing such matters by adopting recommendations, aimed to assist the Party to come into compliance. As a last resort, the Committee may recommend that trade be suspended with the concerned Party until the Party has addressed the matter.

CITES Parties agree to controls (both export and import) on international trade in species that are listed in one of the Convention's three Appendices: Appendix I species are considered to be threatened with extinction and international trade for primarily commercial purpose is always prohibited; non-commercial trade can be allowed for certain purposes under certain conditions only (e.g., zoos, scientific research, movement of personal effects), and the trade in sport-hunted trophies is allowed because it is considered not primarily for commercial purposes. Appendix II species are species that are not necessarily threatened but may become so unless trade is subject to strict regulation. It also includes species that are so similar when traded to other CITES-listed species, that their trade must also be regulated. Appendix III species are those that require the co-operation of other countries to prevent unsustainable or illegal trade in native species [322]. CITES Appendix I currently lists 687 animal species (325 mammals, 155 birds) and 395 plant species; Appendix II contains 5,056 animal species (523 mammals, 1,279 birds) 32,364 plant species; and Appendix III lists 202 animal species (46 mammals, 27 birds) and 202 plant species [431]. A number of pandemics and emerging diseases have originated in species that are included in the Appendices of CITES **(Table 1, appendix)**. At the time of writing, CITES Parties have not yet discussed how the Convention may contribute in reducing risks posed by zoonotic diseases, but this could include the adoption of dedicated Resolutions and Decisions and new or strengthened partnerships with relevant organizations.

Unsustainable and illegal wildlife trade has multiple implications for health

The loss of biodiversity due to unsustainable or unregulated wildlife trade may directly affect the health of communities who rely on wildlife as a source of food, nutrition and traditional medicine [432]. Indirect health effects may also occur due to replacement of declining species by others that may carry disease risks, or with processed food. Analyses of how sustainable the wildlife trade is depend on the quantification of its impacts on wild populations. However, data are lacking, particularly for domestic trade. For example, in Brazil, commercial hunting is illegal and subsistence hunting, hunting for controlling wildlife populations, hunting for scientific purposes, and recreational/sport hunting are regulated and require a permit, which is costly and time-consuming to obtain [433]. Most non-commercial hunting therefore occurs without license, and 70% of wild animals are traded domestically [434], through informal networks and not documented or captured in government statistics [363]. Secondly, data on shipments and annual reports submitted by member states to the CITES Secretariat concern only species listed in the appendices, which comprise a small percentage of traded wildlife. Data for importation of non-CITES listed species are often incomplete, for example rarely including the species name or number of specimens shipped [435]. Over 50% of live wildlife imports and exports in the USA between 2000 and 2006 were identified only to animal class (e.g. birds, fishes) [309,436]. Thirdly, most of the importation data available for analysis do not account for illegal trade, which has been documented as a risk for importation of zoonoses [437,438]. Illegal trade intercepted by enforcement officials provides a crude and unreliable measure of overall illegal activity [439]. Finally, there have been significant reported discrepancies between data reported to different agencies and with survey data [440-442].

It is challenging to assess how sustainable the global trade in wildlife is, because the population dynamics of many traded taxa are understudied, and there is a lack of coordinated, systematic data collection within the trade [443]. In Southeast Asia for example, ~30 million individuals of ~300 wild-caught species were traded over a 10-year period, while population numbers for many taxa were lacking [333]. The effectiveness of CITES is undermined by non-compliance, overreliance on regulation, lack of knowledge and monitoring of listed species, challenges from overwhelming market forces, and influence among CITES stakeholders [336,444]. Consideration of the totality of wildlife trade, including domestic and international, legal and illegal trades suggests that much of it is unsustainable, i.e. with demonstrated evidence that it is driving the loss of abundance, biodiversity and increasingly threatened status of traded species. For example, analysis of CITES and IUCN databases show that traded wildlife species are in higher threat categories than non-traded species (especially among mammals and birds) [327]. Of those listed as threatened or near-threatened, 72% (6,241) have been over-exploited for commerce, recreation or subsistence [125]. This has occurred historically throughout much of North America and Europe and other regions that were deforested and modified over the preceding centuries [445]. More recently, hunting has led to documented local extirpations and ecological extinctions in West and Central Africa, Southeast Asia and Neotropical forests [303,333,446,447]. Hunting for meat alone has placed 113 wildlife species at risk in Southeast Asia (13% of all threatened mammals occur to the east of India and to the south of China), 91 in Africa (8%), 61 in the rest of Asia (7%), 38 in Latin America (3%) and 32 in Oceania (7%) [447]. Hunters are now increasingly targeting smaller species, following declines in nearly 60% of larger biomass mammals [447], that has led to ecosystem-wide effects in Central African rainforests [448], with impacts particularly significant among primates [449,450]. African elephants have declined by 30-fold over the last century (from 12 million to ~400,000), with more than 100,000 elephants killed by poachers between 2010 and 2012 [451,452]. Rhino poaching in South Africa increased 77-fold between 2007 and 2013 (https://www.worldwildlife.org/threats/illegal-wildlife-trade), and seizures of pangolin scales increased 10-fold between 2014 and 2018 [453]. The rapid expansion of the Belt-and-Road Initiative that links China through land and sea trade routes to Europe, the rest of Asia and Africa, has led to calls for strengthening of biodiversity safeguards [454], and strategies to reduce risk of microbial spread [455]. In a study of wildlife seizures in Central and South America representing 1,038 individual wild felids, the numbers of jaguars seized annually increased by an estimated 200-fold between 2012 and 2018 [456]. In Latin America, the illegal wildlife trade is considered the primary threat to the survival of several endangered large felids, parrots, primates and other taxa [365]. Increasing numbers of confiscations of high-value neotropical species such as jaguar, Andean bear and anteater have been reported [365,456].

Programs to reduce wildlife trade demand may also reduce disease risk

The majority of interventions implemented to combat illegal wildlife trade and support sustainable trade in wildlife are conservation-driven. However, some measures specifically target public health risk. For example, research demonstrates that live animal market closure effectively reduces the risk of zoonotic transmission of highly pathogenic avian influenza [457,458]. A temporary ban was imposed on hunting, trading and transporting wild animals in South China after the SARS outbreak, and quarantine procedures have been proposed for the wildlife trade following the emergence of COVID-19 to reduce risk of zoonotic pathogen emergence, and to improve biosecurity in live animal markets [459]. Designing effective policies is hindered by the diversity of motivating factors behind wildlife trade and consumption and the complexity of zoonotic disease emergence [319]. A blanket ban in a country or region is unlikely to stop the spillover of zoonotic pathogens, because it may stimulate the trade in bordering countries, or encourage illegal trade and consumption. Blanket bans may also threaten food security, nutritional welfare and the livelihood and economic development of local communities reliant on wildlife, which are often Indigenous Peoples and local communities[460].

Targeted interventions to reduce disease risk in the wildlife trade value chain have been designed mainly for farms and live animal markets to reduce avian influenza risk from poultry [457,458]. Measures include increased numbers of days with live animal market closures, increased cleaning out of live animal cages, increased testing at intensive farms and backyard production facilities and promotion of other sanitation measures [93,94,206]. Few programs to specifically target interventions around wildlife trade have been implemented, despite numerous calls for research, intervention design and policy measures [308,358,389].

Efforts to reduce unsustainable trade include programs to identify underlying motivating factors in culture and tradition and use these to promote behaviour change [427]. Campaigns against overconsumption or illegal wildlife trade have been implemented globally, regionally and nationally (e.g. a relatively successful campaign to combat the ivory trade in China [461,462]). However, their impact on changes of consumption behaviour or species conservation has been evaluated for only a few of these [463]. Furthermore, the lack of detailed understanding of incentives for wildlife consumption likely undermines their efficacy [464]. Even with demonstrated success and effectiveness, community engagement programs face challenges in engaging high-level policy for implementation [465]. Community-based ecotourism that uses a “Payments for Ecosystem Services” approach has successfully reduced local wildlife trade in Laos and Cambodia [466,467], but outcomes were mixed in other contexts that required improved institutional basis for implementation [468,469].

Section 4: Controlling pandemics relies on, and affects, biodiversity

An understanding of the biodiversity of microbes in nature is critical to controlling pandemics

Substantial aspects of the development of modern medicine are historically and currently dependent on biodiversity. The 3.5 billion years of evolution of life on Earth have led to tens to thousands of genes, each producing proteins that serve specific functions [470,471]. Microbial diversity is extraordinary [472]: for instance, it moderates infection in plant ecosystems [473] and free-living viruses drive species composition dynamics in marine ecosystems [474]. Microbes compete among each other for space and nutrition, leading to selection for strategies to kill or inhibit other microbes, replicate, and respond to chemical and physical stimuli, all of potential benefit to fighting infection. Natural or naturally derived compounds account for around 75% of approved antimicrobial drugs [475]. For example, there may be 12 million fungal species [476], one of which was the source of penicillin used to control bacterial infections and revolutionize medicine [477]. The antiparasitic drug ivermectin was derived from the bacterium *Streptomyces avermitilis* and the antimalarial artemisinin from the plant *Artemisia annua*, sweet wormwood [478]. Diagnosis of infectious agents with polymerase chain reactions (PCR), now being used to detect hundreds of thousands of SARS-CoV-2 infections daily, is dependent on the heat-resistant Taq polymerase enzyme discovered in a thermophilic bacterial organism *Thermus aquaticus* from hot springs [479]. CRISPR (clustered regularly interspaced short palindromic repeats) is a family of DNA sequences discovered in bacterial and archaeal genomes [480]. These sequences are derived from bacteriophages, viral parasites of bacteria, and used to detect and destroy subsequent bacteriophage infections along with Cas-protein enzymes. CRISPR-Cas systems are now utilized to engineer probiotic cultures for yogurts, to improve crop yields and drought tolerance, and to produce malaria-resistant mosquitoes [481]. CRISPR has been used for diagnostic testing with high levels of sensitivity [482,483], including for SARS-CoV-2 [484].

The health sector also uses digital sequence information on genetic resources, for example, for the design of diagnostic tests for infectious disease agents, detection of pathogens in contaminated food for disease prevention and discovery of new therapeutics [485]. Given that less than 1% of known species have been utilized by people, discovery of further compounds that help develop therapeutics and diagnostic agents is highly likely [486]. Genomic advances are now bringing insights into how other species, such as bats, may resist or tolerate infections, potentially leading to mechanisms of infection control [487-489]. Biodiversity is therefore a fundamental resource for health. However, it is difficult to predict which genes, species, or ecosystems will become valuable for bioprospecting in the future [490] highlighting the need to conserve as much biodiversity as possible [491]. Similarly, the rapid and comprehensive scientific sharing of the wide array of pathogens found in animals and humans is crucial for public health preparedness [492]. However, there is limited capacity to predict which pathogens may cause outbreaks and may be used in the development of necessary life-saving (and, potentially commercially valuable) countermeasures, such as vaccines [14].

Therapeutics to fight pandemics have their origins in biodiversity and have been identified through indigenous and local knowledge and traditional medicine

Indigenous Peoples and local communities have had a long relationship with nature that has had a lasting impact on the landscapes people live in today [493-495]. They have also demonstrated that nature can provide a source of medicines with significant benefits to public health [496]. Common therapeutics, such as aspirin, can be dated back to traditional knowledge in ancient Egypt [497]. The first effective modern treatment for malaria came from quinine from the bark of the cinchona tree [498]. Tu Youyou's Nobel winning artemisinin malaria discovery was possible because *Artemisia annua* is an herb employed in traditional Chinese medicine [478,496,499]. Traditional medicine products are being used as potential therapeutics against COVID-19 [500] and the pandemic has increased demand for traditional medicine. Traditional knowledge systems highlight the importance of equitable "access and benefit sharing" (ABS) [501]. Of around 270,000 known terrestrial plants, 10,000 are used medicinally [499,502]. There are many potential benefits (medicinal and others) that remain to be discovered within plant species [475], and the genetic information present in wild species thus represents substantial 'future opportunity'. Natural products have been the source of more than 50% of therapeutics approved by the USA Food and Drug Administration (FDA) over the past three decades [503]. Given that only a fraction of the world's biodiversity has so far been tested for its biological activity, the challenge remains how to access this natural chemical diversity and how to do so ethically, equitably and sustainably.

Understanding access and benefit sharing policies is critically important to the supply of vaccines and therapeutics that rely on sampling the diversity of pathogens in the wild.

The sharing of the benefits from biodiversity must be equitable, but equally, if such benefits are to be realized globally, frameworks for sharing benefits need to also protect nature and enable access to genetic resources. The development of diagnostics, drugs and other therapeutics, and vaccines from biological resources, including pathogen and cell cultures and genetic or tissue samples from people, livestock and wildlife all typically require international material transfer agreements to source and move. The accessing and transfer of these genetic resources are also governed by international law, in particular, the Convention on Biological Diversity and its Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization (The Convention on Biological Diversity of 5 June 1992 (1760 UNTS 79)) [504]. The CBD and the Nagoya Protocol both recognize states' sovereignty over the genetic resources within their borders and were adopted to address the inequitable exploitation of biodiverse countries' genetic resources [492]. The Convention and the Nagoya Protocol provide for states to require prior informed consent to accessing their genetic resources and, through bilateral arrangements negotiated on mutually agreed terms, aim to ensure that state receives the equitable sharing of benefits from the use of such resources. In addition, the Nagoya Protocol contains provisions to ensure prior informed consent for accessing genetic resources held by Indigenous Peoples and local communities, and equitably sharing the benefits of Indigenous Peoples and local communities' genetic resources and their traditional and local knowledge [504].

With the exception of resources covered by specialized international instruments, such as the International Treaty on Plant Genetic Resources for Food and Agriculture, the CBD and Nagoya Protocol both default to bilateral arrangements for access and benefit sharing. However, the time required to negotiate these agreements has led to the unintended consequence of sometimes hampering research in biodiversity hotspots [505], while the evidence of financially significant benefits to local and traditional owners is lacking [505]. Furthermore, this has led to reported delays in the sharing of pathogens for outbreak response [506].

With the exception of pandemic influenza (discussed below), there is no specialised international instrument that streamlines accessing pathogen samples and the equitable sharing of benefits arising from their use. The WHO's International Health Regulations (IHR) [507] require states to notify the WHO within 24 hours of events that are a potential Public Health Emergency of International Concern (PHEIC), and following notification, must continue to share timely, accurate and sufficiently detailed public health information relating to the notified event. However, neither pathogen samples nor their genetic sequences are expressly included in the definition of public health information required to be shared under the IHR [492]. While the CBD and Nagoya Protocol expressly acknowledge the IHR, and the Nagoya Protocol contains provisions for special considerations such as public health emergencies, the sharing of genetic resources for therapeutic development, including compounds and pathogens, is subject to the bilateral arrangements, with one notable exception. In 2011, WHO Member States adopted the Pandemic Influenza Preparedness (PIP) Framework [508], to ensure access to influenza viruses with human pandemic potential and the sharing of benefits arising from their use, including vaccines. The PIP Framework is a nonbinding resolution adopted while parallel negotiations under the CBD's Conference of Parties for the Nagoya Protocol were occurring, and it expressly acknowledges state sovereignty over genetic resources and incorporates access and benefit sharing [492]. Although the PIP Framework has not yet been formally recognized as a specialised international instrument, there is ongoing formalised collaboration between the WHO and the CBD Secretariat on these issues.

Increasingly, the development of diagnostics, therapeutics and vaccines relies upon the use of genetic sequence data from biological materials. However, the CBD, Nagoya Protocol, and as noted above, the IHR, do not currently expressly cover genetic sequence data (digital sequence information) [509]. Increasing reliance on sequence data will reduce the need to access physical samples of biological materials, which may undermine the equitable sharing of benefits from biological resources, while imposing similar access and benefit sharing arrangements on sequence data has been criticised as potentially imposing unnecessary and inefficient burdens [510]. Despite the lack of clear legal obligation, China publicly shared full genomic data for SARS-CoV-2 within two weeks of the reported date of sample acquisition (https://virological.org/t/novel-2019-coronavirus-genome/319). There are public and voluntary initiatives to encourage immediate sharing, such as GenBank and the Global Initiative on the Sharing of All Influenza Data (GISAID). However, it is clear that issues relating to intellectual property (IP), access and benefit sharing, microbial genomes and therapeutic and vaccine development have and may further hamper pandemic control efforts if they lead to delays in data sharing **(Box 4)**.

Box 4: Intellectual property, biodiversity and global vaccine development and distribution

Intellectual property (IP) rights are critical to any discussion about benefits arising from the use of genetic resources, as research and development (R&D) based on genetic resources and associated traditional knowledge may eventually be subject to some form of IP protection, such as patents. While ABS regimes recognize states' sovereign rights over genetic resources, intellectual property rights recognize inventors' rights to exclusively control the use of an invention for a period of time. IP rights may be expressly included as benefits shared in mutually agreed terms under Nagoya Protocol compliant material transfer agreements, or they may be asserted completely separately to any sovereignty claim. This may result in conflicts between claims and perceptions of ownership over genetic resources, delaying access to genetic resources or products developed using them.

IP laws such as patents purport to incentivise R&D by granting inventors exclusive rights to control the use of a product or method developed for specific period of time, typically 20 years depending on domestic laws. However, this exclusivity may limit the amount of a product available and its affordability. While the patentability of genetic resources may differ between jurisdictions, patents may claim genetic resources or a part of their composition, including as part of a therapeutic, diagnostic, or vaccine. This may prevent or delay vaccine development from genetic resources, while cost may make distribution inequitable between and within countries.

Domestic laws may also permit governments to issue compulsory licenses over patented medicines, so that additional manufacturers can produce the medicine. Under the World Trade Organization's Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS) these flexibilities are codified as minimum standards, however there are additional processes that generally must be first fulfilled. These flexibilities were reaffirmed in the Doha Declaration on the TRIPS Agreement and Public Health, recognizing the importance of access to essential medicines, including during emergencies.

Scientists may facilitate keeping technology and medicines "open" without IP restrictions by sharing their research and data openly. The voluntary uptake of open science around a COVID vaccine has been immense, with many global companies having pledged to keep their science free and open (https://opencovidpledge.org/). Other initiatives facilitate the sharing of IP through pooling and licensing to permit certain uses while retaining underlying IP rights. The World Health Organization (WHO) has launched the COVID-19 Technology Access Pool (C-TAP) to compile pledges of commitment made under the Solidarity Call to Action to voluntarily share COVID-19 health technology related knowledge, intellectual property and data.

Vaccines
The political, economic and social demands on vaccine development and manufacture during pandemics highlight the fragility and discriminatory nature of vaccine development [511,512]. Prior to the Ebola Virus Disease epidemic in West Africa in 2013-2016, the existing R&D environment delayed manufacture of vaccination because of a perceived lack of profitability [513]. This delay in manufacturing is particularly critical when the affected population is largely within developing countries[513-515]. In 2003, more than 95% of the world's influenza vaccines were produced in only nine countries and more than 65% of all doses came from five Western European countries. Overall, the nine vaccine producing countries used 62% of the world's vaccines, yet they accounted for only 12% of the world's population. The remaining 38% of all doses were used in countries that have little or no capacity to produce influenza vaccines on their own [516]. There is no global organisation responsible for financing or organising vaccine manufacture for any communicable disease leading to barriers to development [512], including during a pandemic [514]. This inequality is mirrored in other areas, such as OIE Reference laboratories that characterise wildlife-related infections [517].

The Coalition for Epidemic Preparedness Innovations (CEPI) is a public-private partnership focused on selecting and funding vaccine R&D projects in an effort to prevent outbreaks of infectious diseases. In January 2020, CEPI entered into agreements to provide financial support for the development of three different types of vaccines for SARS-CoV-2 (COVID-19). The financial commitment came less than two weeks after Chinese scientists first made a sequence of COVID-19 available through a public database. CEPI supports the Access to COVID-19 Tools (ACT) Accelerator, a consortium organized through WHO that has raised US$58 billion.

Even if a vaccine or a number of vaccines were to be manufactured, it is unclear if supply will meet demand at low and sustainable prices. Mobilizing public funds for pharmaceutical development has not yielded clear pricing guidelines [518]. These issues are compounded by other global inequalities including the lack of manufacturing plants in developing countries and, in some cases, unequal access to constant refrigeration and temperature control [519]. The pharmaceutical industry appropriately states that the high price of new therapeutics reflects the cost of R&D for those and the other candidates that failed during the many, expensive stages of research, clinical trials and manufacturing. However, the inequities between developing countries and the countries that pay for R&D in the availability and affordability of vaccines and therapeutics are striking, and have relevance for biodiversity when samples collected in developing countries ultimately lead to novel lines of R&D.

Policies implemented to control outbreaks can directly affect biodiversity conservation

Infection control policies have the potential to benefit or harm biodiversity and conservation. Some historical measures to reduce disease risk to people or livestock have led to substantial, global impacts on biodiversity. Wetland drainage has been a long-used method of infection control, despite its detrimental environmental impacts [520,521]. To control sleeping sickness in Africa in the 1950s and 60s wildlife was killed, including endangered black rhinoceros (*Diceros bicornis*) [522]. However, control methods were not only physical: the application of Dichlorodiphenyltrichloroethane (DDT) provides a classic example of the impacts of chemicals used to control insect vectors for infections like malaria. DDT and its metabolites not only ultimately had human health issues, but seriously impacted aquatic systems and bioaccumulated in animals to cause the massive decline of many birds, causing serious population declines in species such as the iconic bald eagle (*Haliaeetus leucocephalus*) [523].

Identifying the wildlife reservoir of an emerging viral disease, for example, may lead to efforts to control them as pests, ultimately leading to population declines and biodiversity loss. Bats are hosts to a high diversity of coronaviruses, including the closest relatives of SARS-CoV, SARS-CoV-2 [6,415] and other highly pathogenic zoonotic viruses [64,66,395,524]. Evidence has emerged of bats being targeted for roost removal or culling in an effort to prevent the spread of SARS-CoV-2, despite the virus spreading globally among people [525-529]. There is a substantial literature that suggests culling is usually ineffective in reducing, and may actually increase disease risk to people or livestock (e.g. bovine tuberculosis and badgers [530-532]), may lead to immigration of animals from nearby populations, or otherwise increase the transmission or prevalence of pathogens, leading to increased risk to people and livestock [533,534]. Bats play a critical role in ecosystems, including providing ecosystem services such as pollination and pest control [535], and these services are under pressure from anthropogenic change [536]. Culling of vampire bats occurs regularly in Peru in an effort to control rabies and *Rousettus* spp. fruit bats have been culled to control Marburg virus, a relative of Ebola virus, in Uganda, both leading to increased viral prevalence and risk of disease transmission [96,537]. Similar disturbance, habitat destruction and killing have been reported for birds after influenza outbreaks, including wetland drainage and killing of nesting birds [538,539].

Disinfection of environmental surfaces was used in the first few months of the COVID-19 pandemic, to attempt reduction in transmission and spread of SARS-CoV-2 via contaminated surfaces. As a result, countries across the world have extensively used disinfectants on "high-touch" surfaces in non-health care settings, both in indoor and outdoor spaces, and in urban and rural areas, including homes, schools, businesses, streets. However, disinfection has also included public beaches and disinfectants are used in biodiversity rich areas such as urban parks, wetlands and green spaces. This approach to disease control often takes place without guidelines for monitoring its effects on either human or environmental health and with limited evidence for its efficacy. Based on available evidence, WHO clearly advises that in indoor spaces, routine application of disinfectants to environmental surfaces by spraying or fogging is not recommended for COVID-19, nor is it recommended to spray or fumigate outdoor spaces, such as streets or marketplaces, to kill the SARS-CoV-2 virus or other pathogens [540]. Nevertheless, many countries continue to spray disinfectants not following the scientific evidence. The overuse of disinfectants poses a significant threat to the urban environment and wildlife. There are documented toxicological effects of disinfectants on terrestrial and aquatic animals [541], potentially contaminating food and water resources [542] or roosting habitats of free-living animals [543,544]. However, limited information exists on the ecological consequences of disinfectants in urban environments and on biodiversity [545].

Finally, there is evidence that poor control of pandemics can impact biodiversity. For example, HIV/AIDS has led to increased poaching, morbidity and death of park rangers and conservation workers and reduction of funds for conservation [546]. The impact of disease on households can lead to food insecurity and increased reliance on and use of natural resources [547-549]. Similarly, non-pharmaceutical interventions adopted to combat COVID-19 such as social distancing and travel restrictions have significantly reduced ecotourism demand, leading to lay-offs of park rangers and guides and anecdotally reported increase in poaching.

Pandemic diseases can move from people into wildlife

Microbes or pathogens of people have been reported to cause disease in wildlife, leading them to be called anthroponoses or reverse zoonoses [550]. These can have significant impact [551]. The global pandemic of H1N1 influenza virus in 2009 involved a strain derived from a recombination among human, pig and avian strains, indicating regular movement of influenza strains among people and these groups of animals [95,552]. During the H1N1 pandemic, there was virus spread from humans to farmed pigs, turkeys, and mink, to pet dogs, cats, and ferrets, and to both captive and free-living wild animal species, including cheetah, American badger, giant panda and striped skunk [553,554]. Human respiratory infections have infected great apes, leading to significant illness [555,556]. Yellow fever virus has spread from wildlife in Africa to people and back to wildlife in South America, causing regular outbreaks and die-offs in primates [557-560]. Cross-species transmission is not limited to viruses, for example a *Salmonella* subtype in New Zealand infected multiple species, including wild birds [561]. Wild non-human primates have also been infected by parasites of human origin [562,563]. Thus, failure to control human disease can lead directly to wildlife health issues. The panglobal spread of COVID-19 has led to concerns that it may spread to and possibly become endemic in other animal species. SARS-CoV-2 has caused die-offs in farmed mink, which have in turn infected people, leading to largescale culling [116,117]. The virus has also been reported from domesticated and zoo animals, all thought to be infected by close contact with people [116,564,565]. It is also possible that SARS-CoV-2 will be able to infect bats outside its natural host range, leading to measures to reduce human-bat contact in the USA and other countries [566]. There have also been concerns about potential infection by COVID-19 of wild rodents, [567], non-human primates [568], following infection of related species in the laboratory.

Measures to control outbreaks can indirectly affect biodiversity conservation

The response to COVID-19 has led to a global “pause” in human activity, as a partial or full movement restriction for large parts of the world are being imposed [569]. Like previous disasters, the impacts on biodiversity can be many and complex [570]. On a macroeconomic scale, the global economic slowdown has decreased the demand for many industrially produced commodities and thus reduced direct extractive pressures on the environment [570]. In Peru commercial fishing dropped 80% following the onset of the pandemic [571]. High seas commercial fishery landings were reduced by just 6.5%, with the highest impact on small scale fisheries, potentially affecting livelihoods of more poor people [572]. Reduction in travel and pollution may have increased turtle breeding success [569], and anecdotally have allowed increased abundance and short term population recovery for some wildlife species [573]. Environmental pollution may have declined by up to 30% due largely to travel restrictions and reduced oil demand [574]. Limitations to social and economic activities [575] improved air quality noticeably in China [576], and by 30-60% in India [577], Malaysia [578], Italy [579] and Brazil [580], although these are likely temporary effects. Continued restrictions in power demand from industry, aviation, transport and residential activities may lead to measurable reduction in global CO_2 emissions trends [581]. However, these changes are likely temporary, with the advent of a vaccine likely to allow relatively full employment and industrial production [576]. They are also likely to lead to a negligible decrease in global climate change, albeit that an economic recovery tilted towards green stimulus and reductions in fossil fuel investments could avoid future warming of 0.3 °C by 2050 [582]. The restrictions also highlight the human value of green space in cities, essential for physical and mental health and wellbeing of people [583,584] and that rapid behaviour change are possible if people are convinced of its value to their health and wellbeing.

On the other hand, movement and work restrictions, as well as illness-related work absences, have reduced conservation work and enforcement against illegal resource extraction [585,586], severely reduced incomes and employment, leading to increased hunting and poaching of wildlife, including of endangered species like tigers and leopards [587]. The global economic impact of H1N1 on tourism was around US$55 billion [588]. The Ebola virus disease epidemic reduced tourism to East Africa for over two years after the epidemic ended [589]. Tourism fees are the principal source of funding for national parks worldwide [590]. They are also particularly important for low-income countries where, for example, $142 million of park fees were paid in Africa alone in 2013 [590]. Indeed, low-income countries with high biodiversity tourism and hotspots are particularly vulnerable. Nature-based tourism represents more than 10% of the economies of Kenya, Tanzania, South Africa and Namibia [570], while nineteen small island nations source more than 20% of their GDP directly from tourism [591]. The sudden loss of income has forced the loss of employment of rangers in Zimbabwe and other countries [586,592]. Loss of tourism has been linked to increased illegal logging in Tunisia [593], and poaching in India [594] and Africa, including rhinoceros and elephant poaching [595,596]. The use of dried bear bile for COVID-19 as having potential health benefits is untested by appropriate clinical trials and, even if farmed, has ethical and conservation implications [598].

Preventive measures to control the spread of infectious diseases include the use of disposable masks and gloves and other equipment. During the COVID-19 pandemic, global surges in the use of disposable plastic equipment has led to a rise in medical waste [599]. This represents a significant source of microplastic fibers in the environment [600] that threatens wildlife and contaminates the human food chain [601]. The increase in plastic waste with the temporary relaxation on use of single-use plastic may also alter consumer behaviour on recycling and banning single-use plastics [602]. Proper medical and plastic waste management treatment during and after COVID-19 crisis, along with social responsibility and corporate action will be critical [603].

Strategies to recover economically from COVID-19 could have significant effects on biodiversity

Efforts to stimulate national and global economies and trade after COVID-19 shutdowns [570] may reinforce the activities that drive pandemic emergence and spread, such as air travel, construction and road building [604-606]. Governments have so far deployed US$9 trillion globally in financial support to compensate for financial losses during the pandemic, including stimulus packages [607]. Funds could be used to support communities affected by COVID-19 in biodiversity hotspots. For example, the EU recovery plan was agreed on 21 July 2020, comprising €1,824.3 billion to help to rebuild societies and economies in the region and will support investment in the green and digital transitions. Of this budget, €750 billion is allocated for recovery efforts [608]. The biodiversity strategy, in line with the European Green Deal, is a central element of this recovery plan and provides immediate business and investment opportunities for restoring the EU's economy post COVID-19 crisis [609].

Building 'green' and resilient economic systems in which the value of nature is included, will be a vital element for human health and wellbeing as well as environmental health. To achieve this, several international organizations and the IPBES Global Assessment recognized the role of nature-based solutions for contributing to biodiversity conservation and overall climate change adaptation and mitigation effort in addition to providing other substantial benefits to people and nature [124]. Nature-based solutions are defined by the IUCN as "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" [610]. Nature-based solutions have been included in the draft of the post-2020 Global Biodiversity Framework to be considered by the Parties to the Convention on Biological Diversity at its 15th meeting, with measuring the trend and use of nature-based solutions suggested as part of nationally determined contributions [611]. The role of nature-based solutions in the prevention of pandemics has not yet been calculated, but is likely to be significant, through informed environmental management and dedicated conservation efforts that reduce pandemic risk.

Impact of COVID-19 control policies on women and Indigenous Peoples and local communities

Women are disproportionately affected by climate change, environmental degradation and biodiversity loss, lowering their ability to adapt–in particular in developing countries where it is often their responsibility to provide water, food and fuel for their families, usually from the surrounding environment. Pandemic control measures also have a higher negative impact on women, who are already at greater risk of COVID-19 impact. Women represent 70% of health care and social workers globally, exposing them to a greater risk of infection from COVID-19, and increasing societal reliance on them in the workforce during this pandemic [612]. Additionally, COVID-19 has exposed layers of social, political and economic vulnerability and intensified pre-existing inequalities and discrimination confronted by women [613]. Non-pharmaceutical interventions (restriction on movement, social distancing etc.) mean that women face multiple challenges including accessing reproductive and sexual health services, and bigger risks for labour and domestic abuse and gender-based violence [614]. Women also encounter increased burden of care work for household and childcare duties due to school and workplaces closure [615] that may negatively affect their ability to work from home and influencing their academic productivity [616]. Seventy percent of the world's poor are women, and many women live in crowded spaces with poor ventilation, or have limited or lack access to clean water and food, which puts them at elevated risk of COVID-19 infection in developing countries and within marginalized communities in high income countries [613].

Pandemic control policies and recovery programs to be transformative should be gender responsive and inclusive and ensure women are equally represented in decision making processes, so that gender is not neglected and that decisions made adequately address the impediments women face in pandemics.

Indigenous Peoples and local communities are under particular threat from COVID-19 [617,618]. Past pandemics and emerging disease outbreaks have had a disproportionately higher impact on Indigenous Peoples, often because, due to geographical isolation, there is a lack of herd immunity to diseases that emerge in urban centers of Europe and other developed countries [619]. The 1918 influenza pandemic killed Māori at seven times the rate of Europeans [620], and this disproportionate impact has been repeated through history, with the 2009 H1N1 influenza pandemic causing four-times greater mortality in Native Americans (including indigenous Alaskans) than the general USA population [621]. Much of this imbalance is due to health and social inequity that are a legacy of invasion and colonization, driven by intergenerational concentration of poverty, transport and housing inequities, domestic and family violence and poor access to healthcare and in particular to culturally-relevant healthcare [617]. This precariousness is amplified by the frequent brutality of contacts with national society, inappropriate policies such as the distribution of food or financial aid that have led the Indigenous Peoples and local communities to travel to the cities where they are infected, and the sharp distinctions between their community-based model of life and social distancing measures that help avoid infection. These impacts are heightened by travel restrictions under COVID-19, wherein smaller communities, separated from urban centers and living in remote, rural settings are at even higher risk due to reduced access to primary healthcare clinics. These impacts on Indigenous Peoples and local communities demonstrate the interconnectedness of pandemic causes and impacts: Pandemics are driven largely by unsustainable consumption of richer developed and emerging countries, but their impacts are particularly felt by the Indigenous Peoples, and those living in poverty who cannot afford to avoid work to social distance.

Pandemic control measures and human values

Human dimensions research is essential for managing biodiversity and understanding the societal consequences of pandemic control and response [622,623]. In some respects, the current pandemic has had a positive impact on people's values towards nature. For example, it has been estimated that outdoor recreational activity increased by 291% in Norway during lockdown [624], and there has been anecdotal evidence of similar increases around the world. Time in nature can increase a person's understanding of human interconnectedness with all other living things ('Nature Relatedness') and contribute to positive values towards nature and biodiversity [625]. However, numerous reports have been published of reduced physical activity due to closure of schools, universities and offices [626,627]. This has resulted in efforts to increase access to green spaces and countryside during the pandemic [628,629]. Human dimensions research for zoonoses of pandemic potential is sparse [622]. Values vary geographically, so that pandemic control and response polices may have unpredicted impact on people's attitudes towards biodiversity [630]. On the other hand, top-down laws and policies prioritizing conservation can perpetuate negative attitudes towards biodiversity, decreasing meaningful implementation [631-634]. Lack of trust can reduce compliance with management strategies and disease risk alone may be insufficient to foster behaviours that promote compliance [622], and enforceable laws may not be complied with when they are implemented with little community support [635]. Such an approach can also create knowledge gaps and other discrepancies on the ground. Top-down policies can, particularly in developing countries, ignore local conditions around poverty, food insecurity, drought and other issues that affect local ability to implement policy. Policies that make the human-environment connection to zoonotic transmission and pandemics clear can increase support for biodiversity conservation, especially for emotive subjects like the commercial trade in wildlife and deforestation [636]. For example, surveys conducted during the COVID-19 pandemic in China showed that the desire to eat wild meat in the future was significantly reduced among respondents, particularly younger cohorts [637].

Figure 9: Drone photo of deforestation in the Bolivian Amazon. Forest has been cleared for the production of soybeans. There has been a significant increase in demand for soybeans as part of a globalized system of livestock production and trade (photo: Rhett A. Butler).

Section 5: Policy options to foster transformative change towards *preventing* pandemics

Transformative Change: *Preventing* Pandemics

Throughout the COVID-19 pandemic, the term 'pandemic preparedness' has been highlighted as a critical approach for governments to deal with the threat of pandemics. However, despite its forward positioning, pandemic preparedness in most countries involves traditional public health measures, e.g. building surge capacity in hospitals, stockpiling personal protective equipment, bulk purchasing of antibiotic and antiviral therapeutics. These are all actions that involve *responding* to a pandemic after it has emerged. Yet, the research reviewed in sections 1-3 suggests that there is growing knowledge available that provides **a pathway to *predicting and preventing pandemics***. This includes work that predicts geographic origins of future pandemics [11,13], identifies key reservoir hosts and the pathogens most likely to emerge [307,638-641] and demonstrates how environmental and socioeconomic changes correlate with disease emergence [13,40,42,178,232,380]. Pilot projects, often at large scale (e.g. PREDICT [14], VIZIONS [642], ProMED [643-645]) have demonstrated that this knowledge can be used to effectively target viral discovery, surveillance and outbreak investigation. The urgency of the public health impact of COVID-19, and of HIV/AIDS, Ebola, Zika, influenza, SARS and many other emerging diseases; suggest a **critical need for *policies that will promote pandemic prevention***, based on this growing knowledge.

In this section, potential policy options are put forward that represent **fundamental transformative change to address the Pandemic Era by *preventing pandemics***. These build on the evidence from sections 1-3, and therefore *many of the citations and data are not repeated here*. Scientific proof-of-concept for some of the policy options is also cited here, and in the preceding sections. In some cases, agencies and organizations are identified that already conduct some of the activities or that might be involved in these policy options. In most cases, a **One Health approach** is used as a guiding principle for pandemic prevention policy options. One Health leverages work across the animal health, human health and environmental health landscapes **(Figure 10)**. The goal of this section is to identify solutions that could take us beyond the business-as-usual approach to pandemics, so that even while still in the throes of COVID-19, **the hard work can begin to *prevent* the next pandemic.** Furthermore, these policy options should be considered in light of all dimensions of health and cognizant of the multiple interlinkages between biodiversity and health [288,289]. The section begins with policy options that could: **1)** provide critical high-level enabling mechanisms to assess, set targets for and reduce pandemic risk; **2)** increase sustainability and reduce pandemic risk due to land use change and agricultural expansion; **3)** reduce pandemic risk through the wildlife trade; **4)** bridge critical knowledge gaps; and **5)** foster the involvement of all sectors of society in reducing pandemic risk.

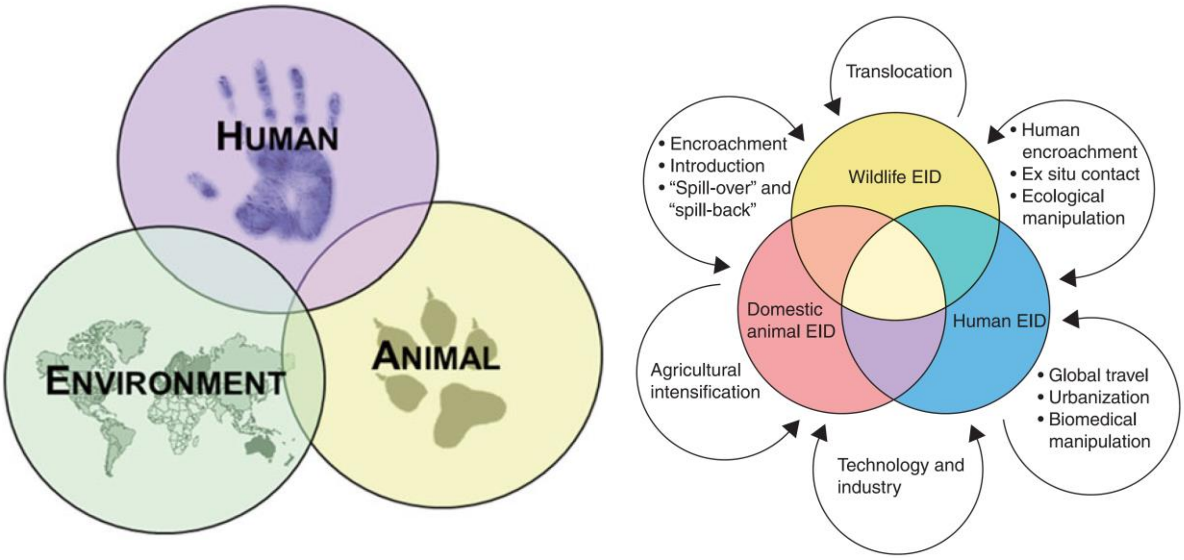


Figure 10: One Health is a system of tackling key health issues (e.g. the emergence of pandemics) by recognizing that the health of people, animals and the environment are often inextricably linked; and by leveraging work in all three sectors to better address the proximal and underlying causes of health issues. Figure **left** from [646]. Figure **right** shows how disease emergence across wildlife, livestock and people are linked through anthropogenic drivers that involve global environmental changes which also drive biodiversity loss, from [53].

1) Enabling mechanisms

Launching a high-level intergovernmental council/panel on pandemic prevention: Pandemic prevention is a complex and multidisciplinary One Health challenge that will likely require coordination and collaboration among sectors and agencies nationally and internationally. However, these agencies are separated by their mandates and their funding mechanisms, which may fragment efforts to coordinate pandemic prevention. One option to enhance such coordination could be the establishment of a high-level intergovernmental council or panel that would provide for cooperation among governments to: **1) provide policy relevant scientific information** on the emergence of diseases, predict high risk areas, evaluate economic impact of potential pandemics, highlight research gaps; and **2) coordinate the design of a monitoring framework, and lay the ground work for an agreement on goals and targets** to be met by all partners for implementing the One Health approach [283], and reducing the activities that drive pandemic risk such as land use change, unsustainable consumption, expansion and intensification of livestock production and the wildlife trade.

A high-level coordinating structure that is stable over time, funded by country contributions, and with a clear mandate to use One Health approaches to prevent pandemics, could ensure the necessary synergies to institutionalize a global strategy to break free of the

Pandemic Era. This "high level council" could work at the crossroads of the activities and actions of the three Rio conventions, while having strong links with the other biodiversity conventions, including CITES and the Ramsar Convention on Wetlands of International Importance especially as Waterfowl Habitat. An international registry of commitments and actions taken by countries to reduce pandemic risk could help drive common action. This council could act as a focal point to alert governments, the private sector, and civil society, on near-term pandemic risks to human, livestock and environmental health. It could act as a central coordinating mechanism or clearing house of information to identify critical changes that forecast pandemic risk and inform the targeting of pandemic prevention, outbreak investigation and intervention and control measures. It could provide annual One Health assessments that include evaluation of the economic impact of potential pandemics, the cost of prevention programs and data on how One Health has leveraged actions, providing a key incentive for support. It could provide a pathway for work on antibiotic resistance, endemic zoonoses like rabies and known threats like avian influenza.

Over a longer timeframe, this approach might lead to **countries setting mutually agreed goals or targets within a multilateral framework, similar to the Paris Agreement**. A broad intergovernmental agreement on pandemic prevention and the underlying drivers of pandemics, could provide benefits for humans, animals and ecosystems.

Nascent intergovernmental One Health collaborations have been formed, e.g. the WHO-OIE-FAO tripartite, the OIE Wildlife Working Group and the WHO-CBD partnership. However, true complementarity has not been fully achieved, and a clear mandate for pandemic prevention not given. The Global Health Security Agenda (GHSA) initiated Joint External Evaluations (JEE) of a country's capacity to achieve goals of the WHO International Health Regulations [647,648]. However, a possible high-level intergovernmental council could provide a more specific focus on risk reduction programs that address environmental change and socioeconomic drivers and go beyond the animal-human health agenda of the JEE. The high-level council could work in conjunction with multilateral environmental agreements and intergovernmental platforms, and bring together key intergovernmental organisations for each One Health sector (e.g. WHO and the Global Health Security Agenda for human health; OIE, FAO, IUCN Wildlife Health Specialist Group for animal health; UNEP for environmental health), UNDP, with those of relevance for trade (e.g. CITES, OIE, WTO), land use change (e.g. the Global Environment Facility, World Bank), pandemic control (e.g. WHO R&D blueprint) and biodiversity (e.g. CBD). It could act to raise awareness of policy recommendations already adopted under the CBD (on, among other things, promoting interagency cooperation, health impact assessments, monitoring) and help advance their implementation. Financing could be through earmarked contributions to participating organizations or via a special fund directly supplemented by voluntary contributions.

<u>Institutionalizing One Health within national governments:</u> The One Health approach calls for cooperation among human, wildlife, livestock health and environmental sectors. Within national governments, agencies tasked with each of these are usually separate and funded by separate budgets. This has led to poor uptake of the One Health approach in most countries. Notable exceptions exist, and One Health platforms are active in Rwanda [649], Bangladesh [650], Bhutan [293], Uganda [651], Tanzania [652], Guinea, Sierra Leone, Liberia [653] and others. National governments could form One Health taskforces or cross-cutting working groups focused on pandemic prevention, that foster collaboration among ministries of health, agriculture, and environment, with strong interaction with ministries of finance. They could have a key role in alerting national agencies to upcoming pandemic threats, identifying research gaps, liaising with the private sector to ensure appropriate supply of diagnostics, acting as national focal points for an intergovernmental high-level taskforce or council on

pandemic prevention (above). Critically, they could build capacity within the agencies for practical, on-the-ground surveillance and outbreak investigation in the face of an emerging disease. Coordination of One Health pandemic prevention could be managed at the central government level, to ensure effective collaboration.

Mainstreaming the economic cost of pandemics into consumption, production and government policies and budgets: Integrating the externalities from future pandemics into consumption, production and government budgets could also be an important way to reduce future pandemic risk. For example, mainstreaming pandemic costs within the finance sector, via assessments of dependencies, could help to reduce risks and subsequent costs. Mainstreaming pandemic costs into government budgets and policies across a range of economic sectors could ensure co-benefits which result in increased resources for biodiversity. Mainstreaming pandemic costs into national development plans could provide a strong argument for achieving greater policy coherence and correspondingly higher efficiency of resource use.

Generating new green corporate or sovereign bonds: New investment tools like green corporate or sovereign bonds, and blended finance to support resource mobilization for biodiversity conservation and pandemic risk reduction could increase fund allocation for biodiversity and pandemic risk. These bonds could link the cost of the debt to progress in protecting biodiversity and reduce pandemic risk. They could help reduce the economic impact from the crisis produced by Covid-19 and simultaneously be consistent with environmental and health global ambitions. It has been noted that zoonotic outbreaks also threatened the stability of the financial system. Central banks could therefore target and buy debt that supports biodiversity conservation and pandemic risk reduction programs as part of their objectives [654].

Designing a green economic recovery from COVID-19**:** Emerging infectious diseases are not easily contained by borders. More efficient global mechanisms could help to provide the necessary funds to invest not only in recovery response after disease outbreaks (e.g. the Pandemic Emergency Financing Facility) [655] but also in increasing capacity for disease prevention based on global risks (e.g. the Global Environment Facility) [656]. These global mechanisms could serve as an insurance to provide an immediate response during outbreaks while mobilizing more resources to developing countries. Investing in post-COVID-19 economic and social recovery efforts in low-income countries could be a priority, and these funds would help to lower the risk and economic impact to high-income countries from future pandemics.

2) Increasing sustainability and reducing pandemic risk due to land use change and agricultural expansion

While the global community concentrates its efforts on the immediate health and economic threats from COVID-19, it is critical to take into account the long run risks and economic costs arising from future pandemics. To date many of the economic policies launched to recover from COVID-19 have not included synergistic biodiversity conservation or climate change goals [657]. A good starting point could be to include in any recovery efforts the necessary investments in biodiversity conservation and sustainable use to reduce the risk and build human and economic resilience from future pandemics [658]. In order to accomplish this, support for a new post-2020 global biodiversity framework that promotes a transition to One Health, and implementation of an ambitious strategic approach that includes the efficient allocation of funds and resource mobilization would be vital [659]. The following measures are identified as having potential to generate benefits for both pandemic prevention, economic development and biodiversity conservation:

Incorporating considerations of health impacts into protected area policies, restoration programs and land use planning: Programs to conserve intact habitat, reduce land use change by sustainably managing land, and reverse ecosystem degradation by restoring forest and other intact habitats may also affect disease transmission dynamics by altering wildlife-livestock-human contact. This is both a risk and an opportunity. Where planning specifically identifies a likely reduction of disease risk, these positive linkages to human health could be used to identify added societal and economic value to the policy. These benefits could inform the work under multilateral environmental agreements, such as the United Nations Convention to Combat Desertification (UNCCD), the United Nations Framework Convention on Climate Change (UNFCCC) and its associated agreements, the Convention on Biological Diversity (CBD) and the Ramsar Convention on Wetlands [288,660]. Some have already incorporated ecosystem health reviews, e.g. Ramsar Convention on Wetlands[77,661,662]. Ambitious global targets have been set to restore degraded ecosystems (e.g. 350 million ha of forest restoration by 2030), and these may leverage the public health benefits of reduced EID risk to promote their uptake. Similarly, efforts to drive sustainable agricultural practices, reduce negative impacts of conventional agriculture practices on biodiversity and improve the provisioning of ecosystem services could be leveraged to balance the needs of food security for local communities and improve human, animal and ecosystem health.

More directly, the consequences of programs that restore habitat, create corridors, or otherwise alter landscapes include changes in human-livestock-wildlife contact that may promote or reduce disease emergence [41,77,154,178,184,280]. Such programs could include efforts to monitor disease prevalence and the potential for emergence of novel pathogens. This is particularly relevant for protected area policies that include “mosaic” strategies that encourage juxtaposition of agriculture and conservation zones, green corridors to enhance wildlife movement, patterns of land use that allow increased human activity in or near protected areas and others [267]. Where large programs are planned, resources to build healthcare provision, and community education around behavioural risk of spillover in these landscapes could reduce risk. They could also be designed to include health surveillance and disease monitoring in wildlife, livestock and people in these landscapes to enable modifications that reduce disease risk and increase conservation benefits. Surveillance could be considered one of the benefits of conservation programs to local communities, offsetting perceived loss of capacity to develop land. Enforcement of regulations that avoid human encroachment would likely also have a benefit in reducing disease risk, as recommended by the CBD [288,289].

Reforming financial aid for land use so that benefits to health are recognized and explicitly targeted: The Global Environment Facility (GEF), Green Climate Fund (GCF), World Bank, Asian Infrastructure Investment Bank (AIIB), other multilateral development banks and relevant international financing funds and agencies could incorporate in their current programs measures to simultaneously reduce pandemic risk and biodiversity loss. Grantees, contractors and national focal points could work with these agencies to encourage programs that affect land use to be redesigned to reduce pandemic risk among wildlife, livestock and people (e.g. by better enforcement of hunting bans or reducing encroachment of settlements in protected areas). National governments could consider removing subsidies for activities that involve deforestation, forest degradation and land use change.

Mandating pandemic risk health impact assessments for major development projects: Major development projects often require environmental impact assessments, and some require health impact assessments before being allowed to begin. Agencies, national governments and international organizations could draft guidance on pandemic risk impact assessments, and enforce a requirement for projects greater than a certain size, cost or geographic range, to conduct this assessment, roll out measures that would simultaneously reduce pandemic risk and biodiversity loss, and monitor and evaluate disease emergence risk and biodiversity maintenance throughout the life of the project. This could be considered a high-priority issue, considering the continued expansion of agricultural land, human settlements, urban sprawl, coupled with exponential growth of road-building, high-speed rail connections, air travel and shipping trade. EID risk assessments could also determine the risk for impact on wildlife and livestock, providing a One Health approach that might give a greater return-on-investment due to the potentially high cost of agricultural and environmental health impacts.

Enabling transformative change in the types of consumption, globalized agricultural expansion and trade that have led to pandemics: Unsustainable patterns of global consumption drive globalized agricultural expansion and trade, and are linked to pandemic risk, as well as land use change, biodiversity loss and climate change. Increasing available knowledge on the economic benefits of more sustainable consumption and agricultural development could be used to drive an added incentive in a shift to agriculture that focuses on provisioning of ecosystem services, while responding to the needs of food security for local communities and encouraging human, animal and ecosystem health. Developing a better understanding of the specific links between consumption patterns in developed and developing countries; demand for meat, products of mining and expansion of agriculture in EID hotspots; and the risk of disease emergence, could drive transformative change to reduce pandemics. Efforts could include:

- Identifying, ranking and labelling high pandemic risk consumption patterns to provide incentives for alternatives
- Designing certification programs for low-pandemic risk consumption, e.g. programs to label products that reduce dependency on land use change from agriculture to re-established natural ecosystems
- Steps to increase efficiency of agricultural processes, while balancing with sustainability, to meet food requirements from currently available land and subsequently reduced land areas
- Promoting a transition to healthier and more sustainable and diverse diets, including responsible meat consumption.
- Promoting food security to reduce the ad hoc consumption of wildlife
- Where there is a clear link to high pandemic risk, consideration of taxes or levies on meat consumption, production, livestock production or other forms of consumption, as proposed previously by the USA Institute of Medicine Committee [118], UK Royal Institute of International Development [122], academic reports [119-121] and others [123].

These activities will need to balance the commitments of developing countries for economic development, the nutritional requirements for Indigenous Peoples and local communities that depend on natural food sources, the need to maintain, restore, or sustainably use biodiversity and the need to protect global health by reducing pandemic risk.

3) Reducing pandemic risk due to the wildlife trade

Building a new intergovernmental health and trade partnership to identify zoonotic disease risks in the international wildlife trade: Despite examples of domestic and international trade in wildlife driving known (e.g. monkeypox introduction to the USA in the pet trade) and novel (e.g. emergence of SARS) zoonotic diseases, surveillance for potentially zoonotic or other threatening pathogens in the wildlife trade is woefully inadequate to protect against future disease emergence. The task of conducting disease surveillance in animal trade (e.g. livestock) falls on agencies within the importing nation, unless pre-border surveillance protocols have been agreed. For livestock, countries' ministries of agriculture usually have a clear mandate and budget for disease testing, shipment seizure, quarantine and control measures including culling during outbreaks. For wildlife, there is often no mandate for ministries of environment, forestry, or fish and wildlife, to conduct health tests on animals within a shipment of wildlife, whether for the pet trade or consumption.

Two international mechanisms have been used effectively for different aspects of this challenge: CITES has raised the profile of the wildlife trade as a threat to biodiversity, enabled a system of checks and balances to identify species that should not be traded, that should be traded under a quota system, or are free to be traded. The system works and has been widely adopted. However, the convention does not currently provide a mechanism for health testing. In fact, CITES requirements may delay the movement of emergency diagnostic samples from Appendix I & II species, thus preventing timely identification of causes of disease outbreaks and response activities [663]. Detailed proposals on how CITES could be amended to monitor the risk of disease spread through the wildlife trade have been published (https://endwildlifecrime.org/cites-amendments/), and other papers have proposed an expansion of CITES to cover health issues [141,664]. The OIE provides assessments of pathogens in animals in the context of the health of animals, humans and the environment as well as the distribution and potential spread of the pathogen. Diseases that threaten animal or human health, or the environment, can be listed as 'notifiable', whereby the OIE member countries are mandated to then report semi-annually and annually on OIE listed diseases and immediately on the new occurrence of an OIE listed disease or an unusual epidemiological event in animals. They are also requested to identify measures of its impact and plans for its control. Importantly, OIE provides for countries to designate internal regions as 'disease-free' so that trade into and out of these regions is allowed. This mechanism might have relevance for monitoring disease risk to domestic trade in wildlife that otherwise is not covered by existing rules under CITES.

Effective surveillance for known and potential zoonoses (and diseases that threaten livestock and wildlife) in the wildlife trade is crucial. The building of strong national wildlife health programs would increase surveillance capacity and enhance reporting to OIE [665]. For international trade, a strong partnership between OIE and CITES could provide a legal mandate to inspect shipments, take biological samples, and test for presence of high-risk pathogen groups in internationally traded species. Nations could expand their protocols for inspections currently conducted under CITES and use the reporting mechanisms in place through the OIE to report annually on the level of disease importation found. For wide surveillance to control pandemics, this could include species listed in CITES appendices as well as all other traded species, and measures they are taking to reduce it, as is mandated for OIE notifiable diseases. An expert group set up as an ad hoc group under the OIE could be established, which could provide guidelines on monitoring and testing. This partnership could provide a legal basis for seizure, culling or quarantine during outbreaks and for banning the trade in high-risk species. It could be linked to the WTO through OIE. An umbrella partnership among representatives of OIE, CITES, the International Air Transport Association, the United Nations Conference on Trade and Development, the IUCN Species Survival Commission Wildlife Health Specialist Group, CBD, WHO and other agencies of relevance, could provide expert guidance and act as a key intergovernmental focal point.

Funds would need to be raised, likely from country contributions, for the work that the partnership would do, and for the expanded mandates for OIE, CITES and others. To effectively contribute to pandemic risk reduction, this partnership would need to include coverage of species not regulated by CITES. In addition, funds would be required for staff, logistics and materials for the sampling, testing and reporting of infectious disease monitoring programs. While these would represent new expenditures for countries, the cost savings when outbreaks are prevented, are likely to be substantial, perhaps with an order of magnitude or higher return on investment, as calculated recently [141]. A similar proposal to designate a global authority for wildlife disease that would have a remit to include traded species has been made by the IUCN SSC Wildlife Health Specialist Group co-chairs (https://www.iucn.org/crossroads-blog/202009/it-time-a-global-wildlife-health-authority).

Reducing the volume of high EID-risk wildlife in the trade: Birds [666], mammals [11,667], and in particular bats, rodents and primates are a key risk for viral spillover [307,668]. Reducing their traded volume or banning specific high-risk taxa from the trade could be considered as a simple and rapid way of reducing risk. Defining these high-risk taxa would need to be based on expert advice, but they would likely include species known to harbour high diversity and prevalence of potentially or known zoonotic RNA viruses that are a high risk for potential zoonotic emergence [307]. Reducing the overall diversity of animals within live animal markets could also reduce the risk of future disease emergence, but further research is needed on how diversity in the trade relates to risk, and how policies to increase biosecurity could work synergistically with selective bans to reduce risk and provide for sustainable trade.

Enhancing welfare and sanitation in farms, traders and live animal markets: A range of tactics are available to reduce disease transmission risk at live animal markets, and have been proposed in reports by FAO, WHO and OIE. They include combinations of live animal market closure and clean-out days, education programs to highlight the risk of pathogen exposure to workers butchering and handling meat, improving and increasing sanitary regulations at all stages of the supply chain, separating butchering and sale of meat to consumers, biosecurity enhancements in wildlife trade like the testing of wildlife hunters, farmers, traders for known and novel pathogens. Disease surveillance of high-risk people like wildlife traders would likely provide information on viruses currently in the process of beginning to spill over.

Analysing incentives to consume wildlife, designing behaviour change programs: Educational activities to reduce consumption of wildlife or domestic animals that is unsustainable or has a high risk of leading to zoonotic spillover depend on understanding the incentives that lead people to consume wildlife. Analyses of these incentives are needed to provide baseline data to develop behaviour change programs that nudge towards adoption of more sustainable use of wildlife, and the avoidance of consumption patterns that have a particularly high-risk of zoonotic spillover. These could be co-designed with the support of local communities, based on scientific principles and data and an understanding of cultural practices and norms.

Reducing high-risk international wildlife trade: Efforts to better regulate international trade from the point of view of pandemic risk are urgently required. While CITES focuses solely on species that are, or may, become threatened by international trade, the OIE has a partial mandate, and the experience, to include international risk assessment of the emergence of diseases from wildlife.

Providing cold chain infrastructure: One perceived rationale behind the habit of purchasing live animals at market to be taken home and butchered, is to maintain freshness in the absence of adequate cold storage. The development of cold chain infrastructure that leads to largescale refrigeration at wildlife markets may help foster a cultural shift from live to killed and refrigerated/frozen meat, and a significant reduction in pandemic risk. Potential impacts of refrigeration on climate change could be offset by using Liquified Natural Gas cold chain facilities. Educational programs that push and nudge behaviour change away from the purchase of live animals or those killed and butchered at point of sale, could begin with the younger generation in some countries where they have been found to be less interested in wildlife consumption.

4) Bridging knowledge gaps

There are fundamental knowledge gaps on the linkages among biodiversity, anthropogenic environmental changes, and pandemic risk that will be critical to enacting policy changes to prevent pandemics. These are compounded by uncertainties due to the inherent complexity of the socio-ecological systems through which diseases emerge, and the value laden and stakeholder dependent nature of solutions. This section proposes some of the key knowledge gaps but does not consider health research goals such as data on prevalence of disease, spillover rates and disease incidence, that are already addressed in this report around enhancing surveillance, for example.

Social sciences and humanities:

Assessing economic cost and benefits of preventing pandemics: Efficient policy decisions could be enabled by measures of how much a specific policy would cost, how much it would reduce disease risk, the savings in morbidity, mortality, days off work or school these would lead to, as well as reductions in economic impact. National agencies could support analytical research supported by field-based ground truthing of assumptions for economic damages during outbreaks. Trials of policies/measures could be set up to test their efficacy, cost and the savings and then scaled up for an estimate of return-on-investment. Measurable health indicators could include reduction in disease incidence or seroprevalence of spillover pathogens in a high-risk cohort over time.

Analyzing behavioral risk in communities, co-designing programs to reduce risk: Key drivers of disease spillover are activities and behaviors that provide opportunities for increased contact among people, wildlife and livestock. The risk for spillover varies widely within all communities, with some exposed more heavily than others due to occupation, habits and behaviours (e.g. wildlife market workers [358,669]). These are often deeply embedded in cultures around the world, particularly around food or medicine (e.g. butchering of wildlife [670], drinking of uncooked blood as a health measure [671]). They represent not only a pathway for disease emergence, but also an opportunity for risk reduction. Qualitative and quantitative social science research into these behaviours would help to identify the incentives that drive high risk activities, so that programs to reduce risk can be designed, trialed and rolled out.

Valuing Indigenous Peoples and local communities' engagement and knowledge in pandemic prevention programs: EID hotspots are primarily in countries with relatively high biodiversity, often in remote regions that may also be managed by Indigenous Peoples and local communities. The development of successful strategies and policies may therefore benefit from collaboration with Indigenous Peoples and local communities to bridge the knowledge gap across cultures. There is an extensive accumulated knowledge in these communities that can play a much bigger role in the future prevention and prediction of pandemics [672]. Collaborating with Indigenous Peoples and local communities in the development of strategies and policies in the respect of equitable "access and benefit sharing" (ABS) or other instruments as the Consultation Protocols established by the Indigenous Peoples and local communities, would enhance their success. Linking the different levels of management (from international organizations to national governments, local authorities, NGOs, research institutions, citizen scientists, local communities etc.) is also considered crucial. Developing effective pandemic prevention programs in these regions will be enhanced by efforts to enhance secure land tenure and ownership rights for Indigenous Peoples and local communities.

Biological, ecological and evolutionary sciences:

Increasing knowledge of microbial diversity in wildlife: Pandemics emerge due to the spillover of diverse microbes in wildlife reservoirs, driven by anthropogenic change. Estimates of microbial diversity suggest less than 0.1% of microbes available for future emergence have been discovered to date [22]. Discovery of the background microbial diversity in wildlife is urgently needed, particularly for viruses and antimicrobial resistant microbes. National agencies from EID hotspot countries could work with donor countries to fund programs that aim to identify, triage, characterize, and monitor the high-risk microbes in wildlife that have high potential to act as zoonotic reservoirs. A series of programs to identify country-level viral diversity in wildlife ("National Virome Projects")[22] could be coordinated to assess the global potential for future disease emergence, and target funds to the regions, communities and pathogens of highest risk. These programs would need to be matched with research projects that assess the risk of emergence for newly discovered viruses, as was done for SARS-related coronaviruses prior to COVID-19 [640,641]. While much of the work on microbial diversity has focused on their risk for disease, there have been repeated calls for conservation programs that include microbial biodiversity in their goals [673-675]. Microbial diversity surveys could enhance their effectiveness by assessing which microbes should be prioritized for conservation.

Mapping within-country EID hotspots: The risk of disease emergence has been mapped at a global scale [13], but within-country production of risk maps are hindered by unequal surveillance and reporting, and are currently lacking. Accurate, high-resolution mapping of risk would allow resource allocation to the regions and communities most likely to be at the frontline of a novel emerging disease. Efforts to quantify fine scale hotspots of disease emergence could be supported by donor countries, the WHO and others, to identify regions for enhanced surveillance.

Analyzing the role of pathogen evolution in disease emergence: Research to better understand the evolutionary underpinnings of host shifts that are involved in zoonotic disease spillover and the adaptation of emerging pathogens to new host species may provide key strategies to predicting patterns of spillover risk. Prior work on viral emergence in particular could be enhanced and used to better focus viral discovery, research and surveillance [20,21,676,677].

Analyzing EID risk within freshwater and marine ecosystems: As people turn to marine ecosystems in the future for food and energy resources, tourism, and transportation pathways, people will likely come into increasing contact with aquatic species, leading to disease emergence that could affect public health and food security. Examples include influenza strains in seals with zoonotic potential, diseases of marine fish driven by human activity, or conservation threats due to livestock diseases moving into aquatic ecosystems, including antimicrobial resistant pathogens.

Analyzing the importance of vector-borne disease risk and migratory species in disease spread: Emerging disease spread across continents can be enhanced by the mobility of arthropods (including their capacity for anthropogenic spread due to air travel and climate change) and by migratory species. Risk analyses of potential for future spread of arthropod-borne pathogens and those carried by migratory species would provide potentially critical information in pandemic prevention. This is particularly important because of the relatively recent international spread of West Nile and Zika viruses and avian influenza through these mechanisms.

Identifying evidence of climate change impacts on disease emergence: There is a paucity of evidence that climate change has already driven the emergence of infectious diseases, and this is often limited to vector-borne diseases that have clearly shifted in range, rather than increased in incidence. Policies to build knowledge on further incursions of novel diseases or expanding cases of known diseases due to climate change would help drive policy changes to anticipate and reduce further health impacts.

Transdisciplinary knowledge:
Obtaining and disseminating critical data on the wildlife trade and disease risk: There is a striking paucity of data on certain important aspects of the wildlife trade that could be used directly to enable policies to reduce risk of disease emergence and spread, including:

- The relative risk of disease emergence and spread in illegal, unregulated and regulated trade in wildlife
- The relative risk of disease emergence and spread in international vs. domestic (within-country trade)
- The relative importance of farmed wildlife in the emergence and spread of infectious diseases
- How the wildlife trade supply chain alters disease risk, from capture through to market and slaughter, and how this differs depending on diversity of wildlife and livestock, and density of animals in the trade
- Species, number, diversity and time spent for each species in the wildlife trade
- Analysis of how risk alters across the value chain
- Maps of live animal markets within countries
- Volume of trade within-country
- Volume of illegal wildlife trade
- Attitudes to consumption of wildlife among different age classes and social structures and over time

Analyzing trade-offs between biodiversity conservation and disease transmission within landscape conservation and restoration programs: There is a paucity of empirical data on how large-scale conservation programs that restore habitat, create corridors, or otherwise alter landscapes affect disease transmission, despite evidence from limited studies and modelling that they can promote or reduce disease risk [41,77,154,178,184,280]. Long term studies of how changing land use patterns in conservation programs affect host-microbe species assemblages, and transmission among species and into humans and livestock may provide vital knowledge that could be used to better assess the impact of corridors, mosaic landscapes, and other conservation tools on health. It will be critical to conduct studies at multiple scales, relevant to the transmission dynamics, ecological changes and behaviors and activities that drive emergence, as well as the scales targeted by conservation and restoration programs.

Supporting One Health science: The promotion of One Health science would provide an overarching mechanism to enable closing of knowledge gaps. This would likely need to begin with transdisciplinary academic training in faculties of medicine, veterinary medicine, public health, and social, ecological and environmental sciences, both in develop and developing countries. In many countries, an overwhelming proportion of the infectious disease research budget is allocated to vaccine and therapeutic development, rather than preventative approaches that involve collaboration among animal, human and environmental sectors. A One Health framework could be considered to provide research and collaboration among programs on ecological interactions of wildlife, livestock and people across gradients of land use; social science of behavioural risk for pandemics; pathological analyses of wildlife disease outbreaks to identify potential zoonotic pathogens in wildlife. This work is particularly important in biodiverse countries which are often relatively resource-poor. Donors from developed countries could support research in these key EID hotspots.

5) Foster a role for all sectors of society to engage in reducing risk of pandemics

Sharing knowledge among all communities in EID hotspots of the health risks associated with some wildlife trade: Culturally sensitive knowledge sharing and behaviour change programs could be co-designed by the communities that are engaged in occupational risk of exposure (e.g. wildlife traders) and other experts, based on the behavioural risk surveys described in the knowledge gaps section. Trials of specific, targeted, single issue behaviour change programs could be enacted to measure success. For example, programs to share knowledge with hunters on the risk of Ebola by picking up dead primates for consumption, or on how to reduce contact with bats. Programs could begin with information on how important wildlife is in driving contributions to people's welfare and other ecosystem services in the local region.

Enhancing a focus on education and communication with the next generation on the drivers of pandemics: It is essential that future leaders understand the importance of biodiversity and the risks that anthropogenic activities have on this diversity and the ecosystem services it provides, and how these if left uncontrolled can lead to more recurrent pandemic episodes. International organizations such as UNESCO, UNEP, IUCN and the International Science Council (ICS) could, with the necessary resources, lead and coordinate education strategies in countries that have the fewest resources and are often at the frontline of disease emergence. Education and public awareness campaigns in developed countries could be targeted around the consumption practices that drive pandemic risk, as laid out in section 2 and 3. Education programs in all countries could tackle the growing misinformation and conspiracy theories around the origins, impact and treatment of infectious diseases, including racially-motivated accusations around the geography of pandemic origins and the cultural or ethnic identities of the people first affected.

Building partnerships among the public, private sector and civil society to reduce anthropogenic change that drives pandemics: Many of the companies involved in land use change in EID hotspots (e.g. mining, palm oil producers, timber extraction, agricultural development) have a global customer base that could be leveraged to push for corporate social responsibility by engaging in public, public-private and civil society partnerships. Another leverage point would be those commercial sectors most directly affected by pandemic risk either positively (e.g. information technology (IT), pharmaceutical, insurance) or negatively (airlines, tourism, hotels). Programs to reduce risk, increase profits in the face of pandemics, or identify key risks to specific industries would help provide economic incentives for the private sector to support resilience and sustainability. Transformative change in agriculture and food systems, health research and development and consumer needs will require strong involvement of the private sector. Goal 17 of the SDGs actively advocates for countries to "Encourage and promote effective public, public-private and civil society partnerships, building on the experience and resourcing strategies of partnerships" [678]. Some partnerships have successfully addressed agricultural [679,680] and health challenges [681]. Unitaid is a hosted partnership of WHO and has leveraged over US$3 billion since 2006 for HIV/AIDS, tuberculosis and malaria innovations for prevention, diagnosis and treatment. Funding for Unitaid has come mainly from the solidarity levy on airline tickets implemented first by France and later several other countries [682].

Reducing high pandemic-risk consumption in developed countries: Unsustainable consumption of palm oil, sugar cane, tropical forest hardwood, rare earth elements for electronic equipment, meat and other livestock products, wildlife products (e.g. fur for the fashion industry) and wild animals for the pet trade, all play a role in driving land use change and the wildlife trade, and increasing pandemic risk. More sustainable consumption in developed countries could be promoted by better labelling of products, and campaigns to raise awareness of the connections between consumption and emerging disease risk, biodiversity loss, and climate change. For example, labelling fur trims in the fashion industry with the species name and origin may provide a nudge towards alternative consumption. Likewise, governments could enforce the labelling of captive wildlife for sale as pets as either "wild-caught" or "captive-bred" with information on the country it was bred or captured in. Campaigns for shade-grown coffee, sustainable palm oil, and deforestation-free beef, have been successful in driving sustainable consumption, and could be adapted for pandemic risk. A significant step could be to establish internationally accepted and required processes for tracing the sources of these consumer-driven products. Success in this area could eventually eliminate clandestine, illegal and environmentally destructive activities which threaten biodiversity as the market and trading platforms supporting these would eventually not be viable.

Raising global awareness of the nexus between biodiversity, health and pandemic risk: Concerted efforts could reinforce the findings of this report that anthropogenic environmental change drives pandemics. This may encourage reduced consumption, use of sustainable alternatives and reduction in people's global ecological footprint as a way of combatting pandemic risk. Individual behaviour could be leveraged through media campaigns, for example by highlighting the major role of tourists in consuming wildlife. During the COVID-19 pandemic, trusted voices in many countries such as medical doctors, civil and religious leaders have led the campaign to gain public support for health measures. These leaders could play a role in heightening awareness of the linkages to global environmental change and biodiversity loss and help promote pandemic prevention programs.

Concluding comments

Pandemics represent an existential threat to the health and welfare of people across the planet, and their emergence, impact and control are deeply embedded in biodiversity and the major causes of biodiversity loss. New diseases emerge largely in tropical or subtropical countries with high wildlife biodiversity. The first people to be infected are often from communities in remote or rural regions, in developing countries with lower capacity to rapidly diagnose and treat novel diseases, and control and contain pandemic spread. Land use change and the wildlife trade (especially unsustainable, illegal or poorly regulated wildlife trade) are key drivers of pandemic emergence, including the recent emergence of COVID-19. Pandemics, such as COVID-19, underscore both the indivisible interconnectedness of the world community and the rising threat posed by global inequality to the health, wellbeing and security of all people: Exponential growth in consumption of products from land use change and globalized trade, often driven by developed countries, have led to the repeated emergence of diseases from developing countries with high biodiversity, and thus conditions that increase potential for zoonotic emergence. Mortality and morbidity may ultimately be higher in developing countries, due to economic constraints affecting healthcare access. However, for largescale pandemics such as COVID-19, economic impacts can be severe in the developed countries that depend on globalized economies. Furthermore, without effective vaccines or therapeutics, per capita mortality rates from COVID-19 appear to be highest at this point in some of the developed countries such as the USA and others in Europe, perhaps reflecting data inconsistencies as well as differences in the abundance of predisposing conditions [683].

Pandemics are becoming more frequent, driven by a continued rise in the underlying emerging disease events that lead to them [13,56]. The continued rise in human population density, consumption, encroachment into wildlife habitat, degradation of ecosystems, industrialization of the wildlife trade, climate change and intensification of agricultural production are driving the current Pandemic Era. Without predictive and preventative strategies, pandemics will emerge more often, spread more rapidly, kill more people and crash the global economy more often and with more devastating impact than ever. The current pandemic strategy relies largely on responding to pandemics after they have emerged with public health measures and technological solutions, in particular the rapid design and rollout of novel vaccines and therapeutics. However, the COVID-19 pandemic has progressed along a slow and uncertain path, and as the world waits for vaccines to become available, true pandemics cost societies dearly, in lives lost, sickness endured, unemployment and economic collapse. All of these affect the global poor and Indigenous Peoples and local communities far greater than most.

Reducing the frequency and impact of pandemics will require the types of transformative changes called on for conservation and restoration of nature (biodiversity and ecosystem processes) and its benefits to people [124]. These include shifts in societal paradigms, goals and values that replace unsustainable consumption and overuse of biodiversity and strategically reduce the underlying drivers of pandemics. The IPBES Global Assessment of Biodiversity and Ecosystem Services concluded last year[124] that such transformative changes were necessary to reach global biodiversity conservation and sustainability goals for 2030. While many of these potential policies are costly, difficult to execute, and their success uncertain, their cost is dwarfed by the impact of just the current COVID-19 pandemic, let alone the rising tide of future diseases. In fact, the cost of implementing these measures is likely to be between $22 and 31.2 billion, reduced even further ($17.7 to 26.9 billion) if benefits of deforestation on carbon sequestration are calculated, while the annualized cost of emerging diseases (including COVID-19) is likely to exceed $1 trillion of dollars annually [141]. All of the evidence in this report demonstrates that the spillover of novel pathogens is accelerating, just like the impacts of climate change. For both issues, there is an optimal time to initiate new global policies for prevention, after which it becomes extremely difficult to mitigate. Research demonstrates that the optimal time is now [56], and **that these policy options may provide a pathway for transformative change to prevent pandemics.**

Appendix

Table 1: Animals identified as hosts of pathogens that have emerged through the wildlife trade in **Box 2**, with their CITES [1] or IUCN [2] status

Animal Host	IUCN Red List **	Threats	CITES List	Zoonotic pathogens
Chimpanzee *Pan troglodytes*	EN	Poaching, habitat loss and degradation, disease	Appendix I	HIV-1; Ebola virus
Gorilla *Gorilla gorilla;* *Gorilla beringei*	CR	Poaching, disease, habitat degradation and destruction, climate change, civil unrest	Appendix I	HIV-1; Ebola virus
Sooty mangabey *Cercocebus atys*	VU	Poaching, habitat loss	Appendix II	HIV-2
Gambian pouched rat *Cricetomys gambianus*	LC	None known	None	Monkeypox virus
Prairie dog *Cynomys spp.*	LC	Some species endangered due to habitat loss	None	Monkeypox virus
Duiker *Cephalophus spp.* *Philantomba spp.* *Elaphodus cephalophus*	EN (2); VU (2); NT (4); LC (10);	Poaching, habitat loss	Appendix I (1); Appendix II (5)	Ebola virus
Fruit bats *Myonycteris spp.;* *Hypsignathus monstrosus;* *Eidolon helvum*	EN (1); LC (3) LC NT	Habitat loss, hunting and trapping	None (only *Acerodon spp.* and *Pteropus spp.* on the list)	Ebola virus
Masked palm civets* *Paguma larvata*	LC	Overharvest, habitat reduction	Appendix III (India)	SARS-CoV
Raccoon dog* *Nyctereutes procyonoides*	LC	Hunting and trapping	None	SARS-CoV; Rabies virus
Pangolin *Manis spp.*	CR (3); EN (3); VU (2)	Hunting and poaching	Appendix I	SARS related-CoVs
Horseshoe bats *Rhinolophus spp.*	CR (1); EN (13); VU (4); NT (9); LC (57); DD (15)	Habitant loss, in-cave disturbance	None	SARS related-CoVs

**Animals that are known to be captive and/or bred for commercial use.*
***IUCN Categories (from most to least threatened): Extinct (EX); Extinct in The Wild (EW); Critically Endangered (CR;) Endangered (EN); Vulnerable (VU); Near Threatened (NT); Least Concern (LC); Data Deficient (DD).*

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Annex I – Scientific Steering Committee

The Scientific Steering Committee of the workshop was composed of the following members of the IPBES Multidisciplinary Expert Panel:

- **Luthando Dziba** (Co-Chair of the Multidisciplinary Expert Panel, South African National Parks, South Africa)
- **Isabel Sousa Pinto** (University of Porto, Portugal and Interdisciplinary Centre of Marine and Environmental Research (Ciimar)
- **Judith Fisher** (Fisher Research Pty Ltd and Institute of Agriculture, University of Western Australia, Australia)
- **Katalin Török** (Centre for Ecological Research, Hungary)

Procedural oversight was provided by members of the IPBES Bureau **Douglas Beard** (United States of America) and **Hamid Custovic** (Bosnia and Herzegovina).

Annex II – List of participants

EXPERTS				
Name	**Role**	**Nominating Government / Organization**	**Nationalities**	**Affiliation**
Peter Daszak	Workshop Chair	United States of America	United States of America	EcoHealth Alliance
John Amuasi	Expert	Ghana	Ghana	Kwame Nkrumah University of Science and Technology SPH & Kumasi Centre for Collaborative Research in Tropical Medicine
Peter Buss	Expert	South Africa	South Africa	South African National Parks
Carlos Das Neves	Expert	Norway	Portugal	Norwegian Veterinary Institute
Heliana Dundarova	Expert	Bulgaria	Bulgaria Czechia	Institute of Biodiversity and Ecosystem Research, the Bulgarian Academy of Sciences
Yasha Feferholtz	Expert	Chile	Chile	Resource Mobilization Panel of the Convention on Biological Diversity (CBD), EcoHealth Alliance
Gabor Foldvari	Expert	Hungary	Hungary	Institute of Evolution, Centre for Ecological Research, Hungary
David Hayman	Expert	Massey University	United Kingdom of Great Britain and Northern Ireland	Massey University, New Zealand
Etinosa Igbinosa	Expert	University of Benin, Nigeria	Nigeria	University of Benin, Benin City, Nigeria
Sandra Junglen	Expert	Germany	Germany	Institute of Virology, Charité Universitätsmedizin Berlin, Germany
Thijs Kuiken	Expert	Netherlands	Netherlands	Department of Viroscience, Erasmus University Medical Centre, Rotterdam, The Netherlands
Qiyong Liu	Expert	China	China	Chinese Center for Disease Control and Prevention
Benjamin Roche	Expert	France	France	French National Research Institute for Sustainable development (IRD)
Gerardo Suzan	Expert	Mexico	Mexico	School of Veterinary Medicine and Husbandry (FMVZ), National Autonomous University of Mexico (UNAM)
Marcela Uhart	Expert	University of California One Health Institute	Argentina United States of America	University of California, Davis, United States of America

EXPERTS				
Name	**Role**	**Nominating Government / Organization**	**Nationalities**	**Affiliation**
Chadia Wannous	Expert	Future Earth	Sweden Syrian Arab Republic	Towards A Safer World Network (TASW) and Future Earth Health Knowledge Action Network
Katie Woolaston	Expert	Queensland University of Technology	Australia	Queensland University of Technology, Australia
Carlos Zambrana Torrelio	Expert	Bolivia (Plurinational State of)	Bolivia (Plurinational State of)	Institute of Molecular Biology and Biotechnology, Bolivia; Bolivian Bat Conservation Program, Bolivia; EcoHealth Alliance
Paola Mosig Reidl	Liaison expert	IPBES Sustainable use of wild species assessment	Mexico	CONABIO, Mexico
Karen O'Brien	Liaison expert	IPBES Transformative change assessment scoping process	Norway	University of Oslo, Norway
Unai Pascual	Liaison expert	IPBES Values assessment	Spain	Ikerbasque (Basque Foundation for Science), Basque Centre for Climate Change, Bilbao, Spain
Peter Stoett	Liaison expert	IPBES Invasive Alien Species Assessment	Canada	University of Ontario Institute of Technology, Canada

RESOURCE PERSONS		
Name	**Role**	**Affiliation**
David Cooper	Resource person	Convention on Biological Diversity Secretariat (CBD)
Tom De Meulenaer	Resource person	Convention on International Trade in Endangered Species of Wild Fauna and Flora Secretariat (CITES)
Hans-Otto Poertner	Resource person	Intergovernmental Panel on Climate Change (IPCC)
Cristina Romanelli	Resource person	World Health Organisation Secretariat (WHO)
Nichole Barger	Resource person	United Nations Convention to Combat Desertification Secretariat (UNCCD)

BUREAU and MULTIDISCIPLINARY EXPERT PANEL (MEP)			
Name	**Role**	**Nationality**	**Affiliation**
Douglas Beard	Bureau	United States of America	U.S. Geological Survey, National Climate Change and Wildlife Science Center
Hamid Čustović	Bureau	Bosnia and Herzegovina	University of Sarajevo, Faculty of Agriculture and Food Science - Institute of Soil Science, Bosnia and Herzegovina
Luthando Dziba	MEP	South Africa	South African National Parks (SANParks)
Judith Fisher	MEP	Australia	Fisher Research Pty Ltd/Institute of Agriculture University of Western Australia, Australia
Isabel Sousa Pinto	MEP	Portugal	University of Porto, Portugal and Interdisciplinary Centre of Marine and Environmental Research (Ciimar)
Katalin Török	MEP	Hungary	Centre for Ecological Research, Hungary