INTERNAL SCIENCE BRIEF

Beyond Boundaries

Insights into emerging zoonotic diseases, nature, and human well-being

May 6, 2020

Authors
Rebecca Shaw, Christa Anderson, Christo Fabricius, Louise Glew, Brent Loken, Shauna Mahajan, Nasser Olwero, Jeff Opperman, Pablo Pacheco, Linwood Pendleton, Dave Thau, and Chris Weber

Editors
Alex Batka and Kimberley Marchant

Design
Sylvia Weir

Acknowledgments
We are grateful for the critical input and review from the following: Zach Abraham, Laura Bloomfield, Kerry Cesareo, Kate Cooke, Winnie De'Ath, Andy Dobson, Katie Gough, Ginette Hemley, Claire Jones, Sam Myers, Robin Naidoo, Catherine Power, Nik Sekhran, Annika Terrana, Adele Turzillo, and Mark Wright

Purpose
This science brief represents a deep dive into the rich contemporary academic literature on the ecological, cultural, social, and economic determinants of increasing frequency of zoonotic disease emergence globally. This rapid internal review is intended to provide input into the design of conservation interventions that decrease the risk of zoonoses. The factors that give rise to zoonoses vary with differing natural, cultural, social, and economic systems across the planet, which must be taken into account when developing targeted solutions in a systems context.

Publication details
This document is an internal science brief released in April 2020 by WWF. Any reproduction in full or in part of this publication must be in accordance with the rules below, and mention the title and credit the above-mentioned publisher as the copyright owner.

Recommended citation
WWF Global Science. (2020). Beyond Boundaries: Insights into emerging zoonotic diseases, nature, and human well-being. Internal science brief. Unpublished.

WWF

Beyond Boundaries

Insights into emerging zoonotic diseases, nature, and human well-being

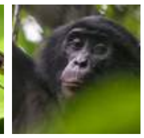
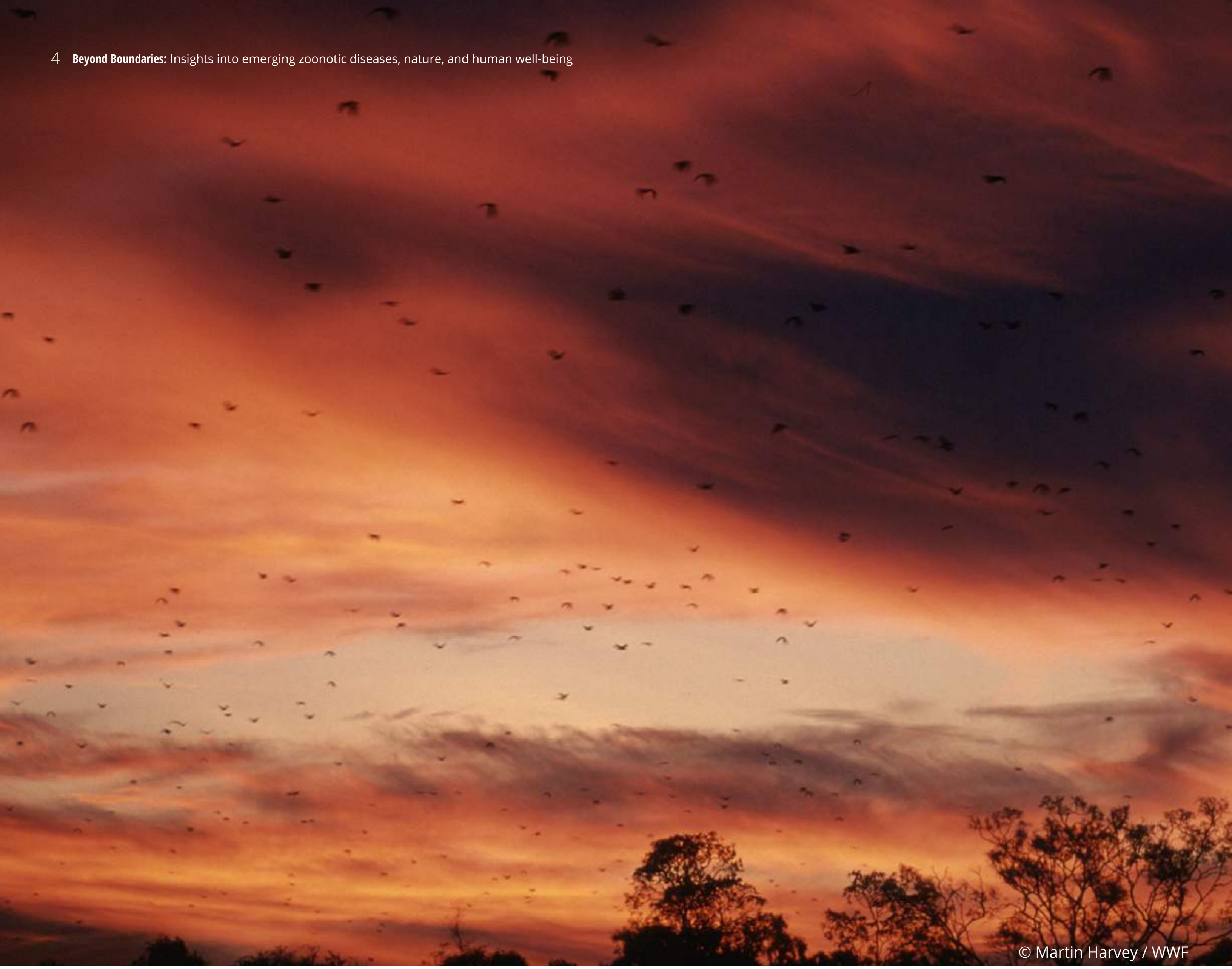
    

Table of Contents



Executive summary

What we do to the natural world often comes back to affect us and not always in ways we would expect.

The devastating human and economic losses resulting from the COVID-19 pandemic are now central in the lives of people throughout the world. Beyond the immediate challenge of rebuilding lives and the global economy looms a sense of uncertainty about the future. Yet, there is also an opportunity to reimagine a new and better world.

This is not the first time a new and deadly virus has emerged, and it will not be the last. Although we cannot always foresee and prevent diseases, if we continue to destroy the natural world, these events will likely become more frequent and severe.

For this science brief, WWF's Global Science team reviewed the scientific literature to identify the key drivers influencing the risk of novel zoonotic disease emergence. Finding that the drivers of zoonotic pandemic events are shared with both climate change and biodiversity loss, we propose a systems approach to guide targeted and coordinated interventions that deliver a future where emerging infectious diseases are less likely to become a recurring threat to our health and economic prosperity. This brief provides the reader with a background on zoonoses, the evidence needed to understand the drivers of zoonotic events (i.e., when a pathogen jumps from animal to humans), and a systems framing for the design of effective, regionally appropriate conservation interventions.

The emergence and spread of zoonotic disease

There is considerable speculation about the origins of COVID-19 with some evidence pointing to a live animal market in China. From RNA analyses, we do know its original animal source was a bat. Regardless of its origins, scientists and public health officials have been warning for years that humans are creating the ideal conditions for more frequent spillovers of increasingly virulent pathogens with the potential for a zoonotic disease outbreak of pandemic proportions.

The warnings of a potential pandemic are partially based on the fact the rate of emergence of novel zoonotic infectious diseases has been increasing in recent decades (Figure ES.1), with spillovers from both wild and domestic animals (Table ES.1). Although the COVID-19 pandemic is devastating, it could be far worse and serves as a strong warning. Its fatality rate is much lower than other zoonotic diseases like Ebola and Nipah. If a zoonotic emerging infectious disease was to combine high transmission rates during the asymptomatic phase of the disease with higher fatality rates, the consequences would be even more devastating.

Figure ES.1 The cumulative discovery of virus species known to infect people. In recent decades, approximately three to four new infectious diseases have emerged each year and the majority of these are zoonotic and originating from wildlife (Woolhouse 2008 with interpretation by A. Dobson pers. comm).

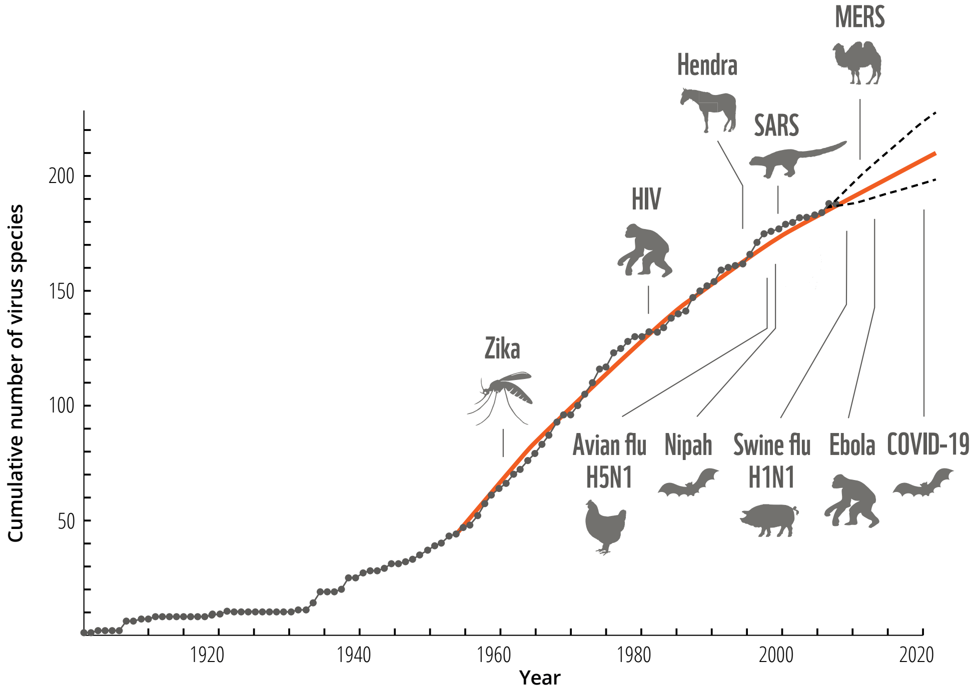


Table ES.1 A typology of zoonotic emerging infectious diseases with respect to pathogen transmission pathways from animals to people. We identify seven pathogen transmission types (on the left), the steps in each transmission pathway, and the drivers of change (e.g., land-use change, agricultural intensification including livestock production, permanent live animal markets, wildlife farms & wildlife trade, and wild meat hunting & consumption). We focus attention on the diseases that have the potential to be pandemic due to their human-to-human spread (#4, 6, 7).

Zoonotic Pathogen Types	Host/Reservoir	Vector/Intermediate Host	Human Infection	Primary Drivers
1. Vector-borne zoonotic Example diseases: West Nile virus, Lyme disease				
2. Vector-borne with zoonotic origin; now restricted to people Example diseases: malaria, dengue fever				
3. Direct transmission from animal host; no secondary transmission Example diseases: hantavirus pulmonary syndrome, rabies				
4. Pathogens with reservoirs of both wild and domestic species Example diseases: avian influenza			Respiratory droplets	
5. Paramyxoviruses Example diseases: Hendra, Nipah				
6. Filoviruses Example diseases: Ebola, Marburg			Bodily fluids	
7. Coronaviruses Example diseases: SARS, MERS, COVID-19			Respiratory droplets	

Land-use change

Climate change

Agricultural intensification

Wild animal hunting, butchering, and consumption

Permanent live animal markets, wildlife farming, and wildlife trade

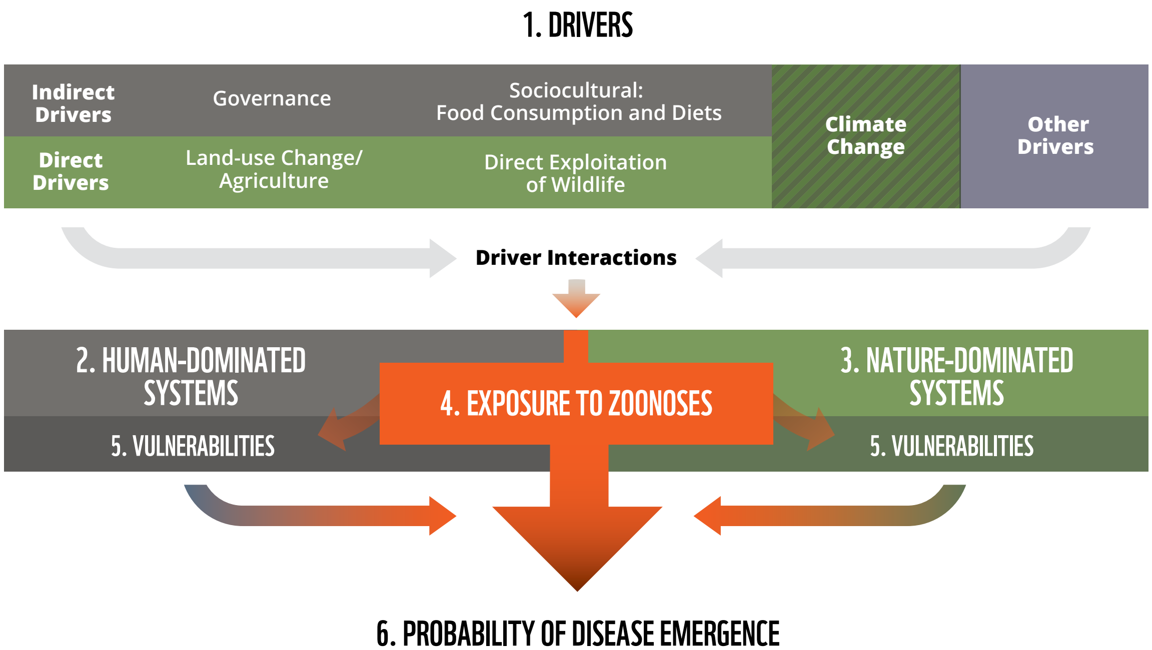
We should also remember that while the scale of the current crisis is unprecedented, the greatest zoonotic disease burden in low-income countries is still from well-known endemic diseases such as brucellosis, Rift Valley fever, dengue fever, and malaria (Table ES.1, #1–2).

The conceptual approach

A given zoonotic disease has a specific mechanism of transfer from animal to human (Table ES.1). Some diseases can only be transmitted to a human by a vector such as a mosquito, with no subsequent human-to-human transmission. Others can move from an original host to an intermediary host to humans and then commence human-to-human transmission. This type, which includes COVID-19, is the most dangerous to people because it can lead to rapid spread and global pandemics. Because of the different types of transmission and spread, different zoonotic diseases can have very different drivers and risks.

To make sense of this complexity for conservation, we provide a simple causal diagram that describes the direct and indirect drivers of change in human- and nature- dominated systems that increase the risk of novel disease emergence by increasing the exposure and/or the vulnerability of humans to novel pathogens (Figure ES.2). We employ a simplified model of the risk to help us organize information and communicate how the drivers interact to affect the probability of emerging zoonotic diseases and to help us make strategic decisions regarding our interventions.

Figure ES.2 Conceptual diagram of zoonotic disease. Drivers (1) include governance, the primary indirect driver that affects land-use change and agriculture; human behavior and consumption; and climate change. These causal factors and their interactions influence vulnerability of human-dominated systems (2) as well as nature-dominated systems (3). The more vulnerable human-dominated systems or nature-dominated systems become (5), and the greater people's exposure to zoonoses (4) becomes, the higher the probability of disease emergence (6). Adapted from Wilcox & Gubler 2005; Gortazar et al. 2014; Hosseini et al. 2017.



From a conservation perspective, we need to understand the range of transmission pathways of different types of zoonotic diseases (Table ES.1), how the direct and indirect drivers of change alter transmission of these diseases, and the impact of this change on the risk of zoonotic disease emergence. We focus this science brief on those diseases that have the potential for human-to-human spread, and therefore, the potential to become a pandemic (Table ES.1, #4,6,7). For example, diseases that rely on transmission to humans through vectors such as mosquitoes are likely to be influenced by climate change because climate change affects the disease vector's geographic range (e.g., West Nile virus). In contrast, diseases that require direct transmission of pathogens between wildlife, domestic animals, and people are more likely to be influenced by drivers that bring people and animals together in close proximity (e.g., land-use change, exploitation of wildlife).

Because the intention of this brief is to understand the opportunities for conservation interventions to help in preventing the next pandemic, we focus on the direct and indirect drivers responsible for the emergence of zoonotic diseases that can give rise to pandemics. We also highlight the conditions that increase the likelihood of exposure to a disease, increase the vulnerability of human- and nature-dominated systems, and ultimately allow for the successful transmission of the disease itself. We find, as many have before us, that the probability of zoonotic disease emergence increases dramatically when humans, wildlife, and domestic animals are in close proximity to one another for long durations of time, increasing the risk of novel disease emergence.

Drivers of zoonotic disease exposure

The direct and indirect drivers that affect the emergence of infectious disease are numerous and interacting, and their relative impact on the emergence of new disease differs geographically with natural, cultural, social, and economic conditions. In this science brief, we focus on the direct and indirect drivers with the greatest influence on zoonotic disease emergence that give rise to pandemics.

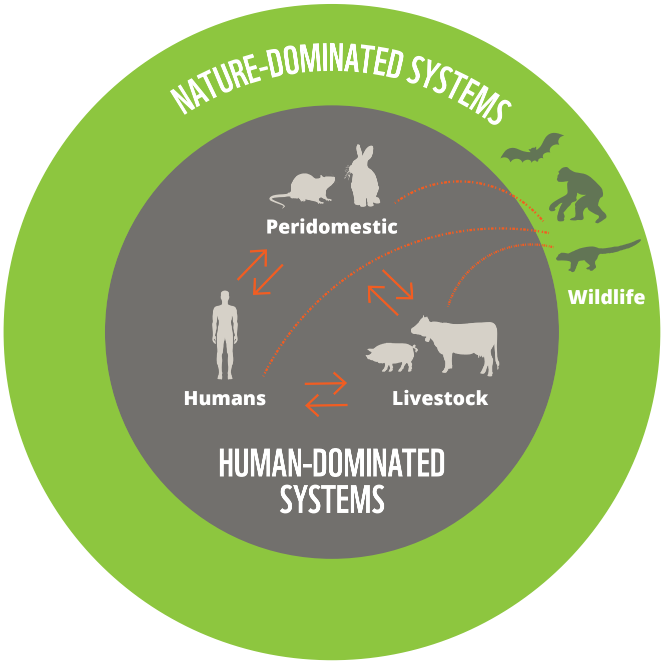
Land-use change. The risk of a zoonotic disease event is exacerbated by the expansion of human activities in natural ecosystems which increases human-wildlife-domestic animal interactions that enable cross-species transmission of pathogens (i.e., spillover). There are many indirect drivers of land-use change, but there is a sequence of change we see across geographies. The expansion of road networks, including local unpaved roads, facilitates access to natural ecosystems, often triggered by logging and/or mining activities. This stimulates the growth of human settlements which is followed closely behind by agriculture—both subsistence and commercial—which is the most important direct driver of habitat conversion globally. These activities bring humans, livestock, and wildlife into close proximity at high densities, creating ripe conditions for spillover of previously unknown pathogens into livestock or humans by wildlife. Chances of spillover are expected to increase with population growth and continued land conversion for food and livestock production, thus increasing the human-livestock-wildlife contact rates.

Intensification of agriculture, particularly domestic livestock production. The expansion and intensification of agriculture promotes encroachment into wildlife habitats, bringing humans and livestock into closer proximity to wildlife and potential zoonotic pathogens across the globe in varied settings. In the last 50 years, as the growth in the human population increased, the demand for animal protein and wildlife products increased, intensifying human-animal and human-wildlife-livestock interaction through livestock production, wildlife farming, and live wildlife trade across the globe (Figure ES.3). This intensification has facilitated pathogen spillover from wildlife to livestock and increased the likelihood that livestock become intermediate hosts in which pathogens are transmissible to humans. Many wildlife species have thrived in this transitional landscape and have become reservoirs for disease in livestock and humans.

When we couple this closer proximity of wildlife with intensive livestock operations, the right conditions are created for increased spillover of previously unknown pathogens into livestock and/or humans. Producing food for an expected population of 10 billion people by 2050—and the associated increase of land converted to food and livestock production—will create even greater human-livestock, human-wild animal, and livestock-wild animal contact rates, increasing the likelihood of spillover events (Figure ES.3).

Figure ES.3 Pathogen flow at the wildlife–livestock–human interface. Arrows indicate direct, indirect, or vector-borne pathogen flow. If a pathogen is also transmissible in a new host species, then a new transmission cycle or pathway may be established. The rate and direction of pathogen flow will depend on the nature and intensity of interaction between humans-wildlife, livestock-wildlife, and humans-livestock (Jones et al. 2013).


© Luis Barreto / WWF-UK



The increasing demand for and consumption of animal protein increases the risk associated with the emergence of zoonotic diseases. This increased demand leads to changes in the proximity and relationship to domesticated animals and wildlife which increases exposure to potential emerging infectious diseases. Given that approximately 70% of emerging infectious diseases and almost all recent pandemics originate from animals, there is a growing call to reevaluate how animal source food is produced.

Exploitation of wildlife: markets, trade, and farming. Live wildlife trade is big business. The volume of reported wildlife trade rose from 25 million whole-organism equivalents per year in 1975 to 100 million in 2014. The increase was mostly due to trade in captive species, many of which are sold in live animal markets that may serve as fertile ground for spillover. The wildlife trade has played a role in the emergence of zoonotic diseases in and out of live animal markets. In addition, a growing proportion of trade in some wildlife species is captive-bred animals from wildlife farms. Like live animal markets, wildlife farms concentrate people and 'wild' animals which increases exposure to potential zoonotic pathogens. With wildlife farming on the rise to meet the demand for wildlife products in the face of increasing scarcity of wild animals, there is increased potential of disease transmission. While wildlife farms should be regulated to decrease the potential for disease transmission within, the few studies that exist suggest the problem lies with the transportation, sale, and consumption within the live animals markets that commingle people, domestic livestock, wildlife, and farmed wildlife in high densities.

In many areas across the globe, wild meat is harvested from primary habitat and wild meat consumption plays an essential role in food security and livelihoods. Spillover of pathogens from wildlife to humans can happen directly due to wild meat consumption (e.g., Ebola) or through direct interaction with live wildlife such as primates, rodents, and bats. Spillover can happen indirectly through intermediate hosts such as civets, antelope, and deer (e.g., SARS) or through domestic animals such as camels, cattle, swine, and poultry (e.g., avian influenza; Table ES.1). Apart from contributing substantially to food security, wild meat consumption is linked to wild meat trade, much of which takes place illegally. Trade of wild meat not only provides income streams in regions where few alternatives exist, but it also supplies local and proximate urban markets where wild meat is sold and consumed. Wild meat consumption is also linked to wildlife trade that feeds wider market networks beyond national boundaries. This also puts pressure on wildlife population decline, such as the one linked to the pangolin trade in Myanmar.

For COVID-19, it is possible that the zoonotic origin was an infected animal or group of animals that came into the marketplace to be sold. It is also possible that the zoonotic event happened prior to arrival at the market and that someone infected on a farm brought the disease into the market. This person could have been infected during the capture, production, transportation, or handling of wildlife or domesticated animals and later brought the disease into the market. While the market is at the center of the spread, it may not be where the spillover event occured. Given this uncertainty, closing live animal markets in response to a zoonotic event might not prevent the next zoonotic event. However, it may prevent many from accessing nutritional foods. Regulations should target species that are most likely to be problematic and have identified several important risk factors, including genetic similarity to humans and taxonomic richness within a group. Several wildlife groups—rodents, bats, shrews and shrew-like relatives, primates, carnivores, and ungulates—have been identified as high concern. Regulations that require disease surveillance, veterinary care, controlled transport, sanitary market conditions, and control of the source of traded animals would also need to be implemented.

Governance. Governance of the direct drivers discussed above—land use, wildlife trade, and agriculture—acts as an important indirect driver of emerging zoonotic disease. Governments can play an important role in preventing zoonotic disease outbreaks, through education, outreach and training, to give people the practical knowledge needed to minimize exposure and transmission. Governments can also guide land use through planning, zoning, tenure reform, and enforcement to minimize risk of transmission. Governance issues are also critical post-emergence in dictating whether an emerging disease reaches epidemic or pandemic state. Post-emergence governance concerns include issues around transparency, trust in governments and institutions, and the regulation and reactions of markets and trade.

Climate change. Strong scientific evidence suggests that climate change will increase the occurrence of many endemic zoonotic infectious diseases by expanding their geographic ranges. It is possible that zoonotic emerging infectious diseases involving novel pathogens that lead to pandemics will increase with climate change as a result of changes in pathogen evolution and ecology, but the existing scientific evidence is mixed.

© Luis Barreto / WWF-UK

Conservation interventions to reduce risks

Based on a scientific review of zoonotic diseases and the drivers of novel zoonotic infectious diseases, we explore a systems approach to identifying leverage points through which conservation interventions can reduce the risks of emerging zoonoses, both in the short- and long- term. The list of interventions we provide is not intended to be exhaustive, but instructive in the way to use a systemic approach for sustained outcomes.

Crucially, there are substantive risks for people, nature, and climate when poorly designed interventions, intended to address the link between zoonotic emerging infectious diseases and conservation, are rapidly implemented. Risks include market closures and regulations creating a hard-to-monitor illegal wild meat trade, the rapid expansion of land conversion for livestock production in regions where wild meat is currently an important source of dietary protein, adverse impacts on the food security of marginalized and vulnerable communities, and the potential alienation of local stakeholders where the links between biodiversity conservation and zoonotic disease are overstated. Evidence-informed strategy design should help mitigate many of these risks.

Conclusion

The scientific evidence indicates that three direct drivers of change result in the greatest risk of emerging infectious disease exposure and vulnerability. They include:

- land-use change which results in the loss and degradation of nature,
- expansion and the intensification of agriculture and animal production, and
- the sale and consumption of high-risk wild animals in and out of live markets.

Underlying these direct drivers is the indirect driver of increasing demand worldwide for animal protein and wildlife products. As people, wildlife, and domestic animals are coming into close contact more intensively in farming, transport, and market settings across the globe, we are creating the ideal mixing vessels required for pathogen evolution and spillover. These drivers of change are some of the same drivers that result in climate change and biodiversity loss. Addressing the root causes of drivers offer the potential for 'win-win-win' solutions for conservation and human health. Potential interventions should focus on reducing the risk of spillover, not just in live animal markets, but also where wildlife and domestic animals are raised, transported, and sold.

Section 1. Setting the scene

1.1 Context

COVID-19, a novel zoonotic emerging infectious disease (EID) caused by the SARS-CoV-2 virus, has led to severe global socioeconomic disruption, the largest global recession in history, and to the lockdown of one in two people worldwide. A zoonotic disease, or zoonosis, is a disease that originates in animals and can be transmitted to humans (Box 1.1). COVID-19 is believed to have originated in the Huanan Seafood Market in December 2019 in Wuhan, China (Wang et al. 2020a), but there is some evidence of its emergence earlier in 2019, 150 kilometers from Wuhan (Lu 2020).

The COVID-19 pandemic serves as a reminder that zoonotic diseases represent the majority (60%–76%) of EIDs worldwide and that zoonotic EIDs have been responsible for all recent outbreaks and pandemics that have threatened global health and economies, including HIV, Ebola, SARS (severe acute respiratory syndrome), MERS (Middle East respiratory syndrome), and now COVID-19 (World Health Organization 2020a).

Some scientists and policy actors have been providing advice about how to avoid outbreaks for years (Dobson & Carper 1996; Morse et al. 2012). However, their evidence-based arguments have not penetrated the arena of media, particularly social media, which has provided fertile ground for dissemination of misinformation regarding the processes which give rise to the emergence and spread of zoonotic diseases.

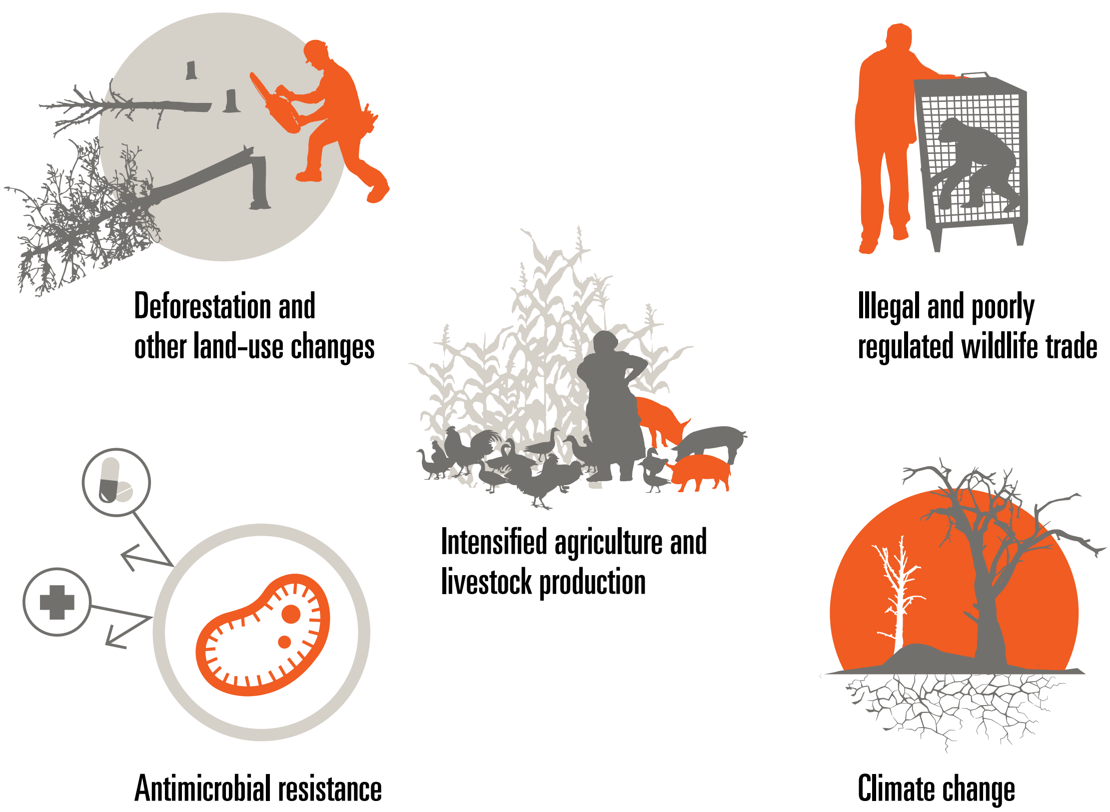
In this science brief, we synthesize the recent research evidence on the nexus between emerging zoonotic diseases and conservation with a goal of supporting WWF in designing and implementing conservation interventions where appropriate to reduce risk of future pandemics where appropriate. In exploring this nexus, we avoid the temptation to call out simple causes and solutions, but rather seek to inform decisions about the role of conservation in advancing human health. To be effective, we need to understand the direct and indirect drivers of the emergence of different types of zoonotic diseases in various contexts and to understand where and under what conditions conservation interventions can successfully benefit nature and people.

To accomplish this, we organize the report into six sections:

- **Section 1** provides the background to zoonoses and current debates and questions,
- **Section 2** lays out the status and trends of zoonoses, including pathways of transmission and biodiversity impacts,
- **Section 3** explains the conceptual approach we use to explore the intersection between zoonotic emerging infectious disease and conservation,
- **Section 4** assesses the direct and indirect drivers of the emergence of zoonoses,
- **Section 5** explores plausible futures for these drivers and the broader relationship between people and nature under a range of scenarios, providing a vision for a sustainable future,
- **Section 6** highlights leverage points for conservation interventions that could have positive impacts for nature and people, and
- **Section 7** provides conclusions from the findings of the report.

While our emphasis is on the links between zoonoses and conservation, we put this in a broader perspective by evaluating direct and indirect drivers and impacts of the emergence of zoonotic diseases that are not directly related to nature, but still touch upon the relationship between people and the natural environment (Figure 1.1).

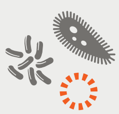
Figure 1.1 The direct drivers of zoonoses. Zoonoses are increased by amplifying direct drivers including land-use change, intensified agriculture and livestock production, illegal and poorly regulated wildlife trade, increasing microbial resistance, and climate change. This report focuses on the first three as they are the most important drivers of zoonotic events that lead to pandemics.



We look at the linkages and feedbacks between the direct and indirect drivers of change (governance, land use, agriculture, human behavior and consumption, and climate change) and how these affect people's exposure and vulnerability to pathogens that give rise to a zoonotic disease, further described in Section 2 (Hosseini et al. 2017; Di Marco et al. 2020). This science brief will focus on novel zoonotic EIDs but will also examine those aspects of endemic EIDs (i.e., a disease long established in a given region, such as West Nile virus) that share drivers or potential solutions with novel EIDs (Box 1.1). Our emphasis is on the emergent phase of zoonoses as this is where conservation interventions can be effective and where WWF has the greatest potential for influencing outcomes.

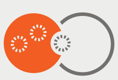
© Edward Parker / WWF

Box 1.1 Key terms. See glossary for complete list of terms.

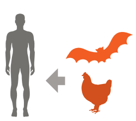


Infectious Disease – diseases caused by organisms such as bacteria, viruses, fungi, or parasites

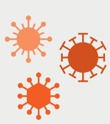
Endemic Infectious Disease – a disease that is always present in a certain population or region (e.g., malaria in Africa)



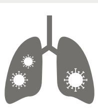
Emerging Infectious Disease (EID) – diseases that have recently appeared within a human population or those whose incidence or geographic range is rapidly increasing or threatens to increase in the near future



Zoonotic Disease or Zoonosis (plural zoonoses) – a disease transmitted to humans from other animals which can be caused by bacteria, viruses, fungi, or parasites; approximately half of all infectious disease—and 60%-76% of all EID—are zoonotic including recent outbreaks and pandemics that threaten global health and economies, including COVID-19, SARS, MERS, avian influenza, Ebola and HIV



Coronaviruses – a group of related viruses that cause diseases in mammals and birds. In humans, coronaviruses cause respiratory tract infections that can be mild, such as some cases of the common cold, and others can be lethal, such as the zoonotic diseases SARS, MERS, and COVID-19



COVID-19 – the coronavirus disease that emerged in 2019

SARS-coronavirus 2 (SARS-COV-2) – the virus that causes the current pandemic of coronavirus disease 2019 (COVID-19) that likely emerged in China in late 2019 and believed to have zoonotic origins

1.2 Relevance to WWF's work

Many questions have arisen across the WWF Network regarding the link between conservation and EIDs in general, and the immediate COVID-19 crisis (Appendix A). We address these questions through the use of a conceptual framework (Section 3) that allows us to assess the potential for leveraged conservation interventions to reduce both the exposure and vulnerability of people to zoonotic pathogens.

The link between zoonotic EIDs and nature is highly relevant to WWF's work and offers us the opportunity to:

1. **Understand the relationship between the prevalence/emergence of zoonoses and species richness.** Wild animals, particularly mammals, act as reservoirs and intermediate hosts of zoonotic diseases. This presents both an opportunity (e.g., preventing over-exploitation of threatened or vulnerable wild animals such as pangolin and bats) and a threat (e.g., when wild animals believed to be carrying these viruses are exterminated; Degeling et al. 2016). A key challenge is to distinguish between those situations where the relationship between undisturbed habitat (a proxy for biodiversity) and the incidence of human disease is either positive or negative (See section 4.1, Wood et al. 2014). Zoonotic diseases of various kinds interact differently with nature and people in varying contexts; nature can prevent a spillover event between animals and people but is also a reservoir of potential zoonotic viruses. It is therefore important to understand the conditions leading to the emergence and spread of zoonotic diseases to inform interventions (Allen et al. 2017) and the potential consequences of zoonoses for conservation (Corlett et al. 2020).
2. **Incorporate the relationship between emergence of zoonotic diseases, large-scale modifications of ecosystems, and human health into our strategies.** The connections between ecosystem loss and degradation and human health are central to WWF's mission. Zoonoses are just one outcome of the set of interactions and feedbacks that exist at the interface of nature and people. These largely determine whether exposure to nature has positive or negative impacts on our well-being (Hosseini et al. 2017). Zoonoses not only have impact on human lives and livelihoods but may also influence future conservation policies and strategies (Corlett et al. 2020).
3. **Contend with the relationship between wildlife, markets and their social-ecological contexts, and emerging zoonotic disease.** It is particularly important to identify taxonomic groups that present the greatest risks when traded or consumed (Olival et al. 2017). These are places that are risk hotspots for novel zoonotic disease emergence (Daszak et al. 2020), and the governance, land use, human behavioral, biological, and climatic factors which, when they collide, increase the likelihood of disease emergence (Di Marco et al. 2020).
4. **Highlight the consequences of public health interventions for nature and its contributions to people.** Public health interventions to curb the rise of EIDs may result in win-wins for nature and people when integrated approaches such as those adopted by the EcoHealth Alliance are used (Daszak et al. 2020). Researchers found a drop in wild meat sales and consumption in Nigeria during the 2014 Ebola disease outbreak which lasted for three months, whereafter sales and consumption returned to normal when Nigeria was declared free of Ebola (Onyekuru et al. 2018). Unintended consequences are possible. For example, when the culling of vampire bats to curb rabies threatened other endemic bat species through incidental poisoning (Aguiar et al. 2010). Lose-lose outcomes may also arise. Interventions could unintentionally harm both human health and nature. For example, when disease abundance and prevalence increase with culling, thereby reducing the likelihood of eradicating infections (Bolzoni & De Leo 2013). Messages about the risks of wild meat consumption, aimed at curbing Ebola outbreaks in West Africa, fueled resistance among the public to health campaigns by those who regularly ate wild meat without getting ill. Informal networks of wild animal trade and sale proliferated, making it very difficult to develop acceptable, evidence-based surveillance and mitigation strategies to prevent future zoonoses (Bonwitt et al. 2018).
5. **Communicate objectively about the links between nature and zoonotic EIDs.** In an era of misinformation and unsubstantiated advocacy, many of us want reliable information about root causes of zoonoses (Cinelli et al. 2020) and are expecting conservation NGOs, such as WWF, to provide clarity.

Section 2. Zoonotic disease: status, trends, and core concepts

Main points

- EID events constitute a major threat to global health and economies, with consequences for biodiversity conservation.
- The rate of emergence of novel zoonotic EIDs has been increasing in recent decades, with most coming from wildlife.
- Zoonotic diseases have direct and indirect impacts on wildlife.
- A range of direct and indirect drivers of nature loss and degradation—including land use, agricultural practices, climate change, and human-wildlife interactions—also increase the likelihood of human exposure to zoonotic pathogens and, therefore, conservation interventions can play a role in reducing the risk of future spillover zoonotic events.

We must realize that in our crowded world of 7.7 billion people, a combination of altered human behaviors, environmental changes, and inadequate public health mechanisms now easily turn obscure animal viruses into existential human threats.

(Morens et al. 2020)

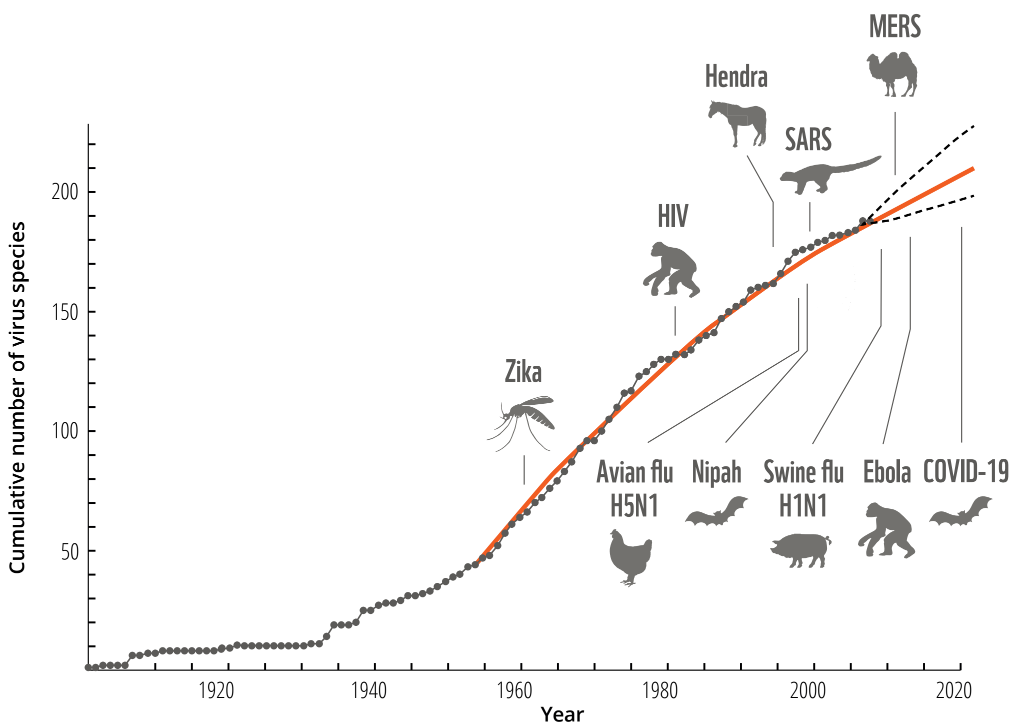
2.1 Zoonotic diseases: novel and endemic emerging diseases

2.1.1 Context

Infectious diseases—diseases caused by organisms such as bacteria, viruses, fungi, or parasites—are a leading cause of human mortality globally (Fauci 2001). More than half of all infectious diseases are zoonotic, meaning they originate from other animals. These include three of the most deadly pandemic diseases in human history—the bubonic plague, the Spanish flu, and HIV/AIDS (Lloyd-Smith et al. 2009).

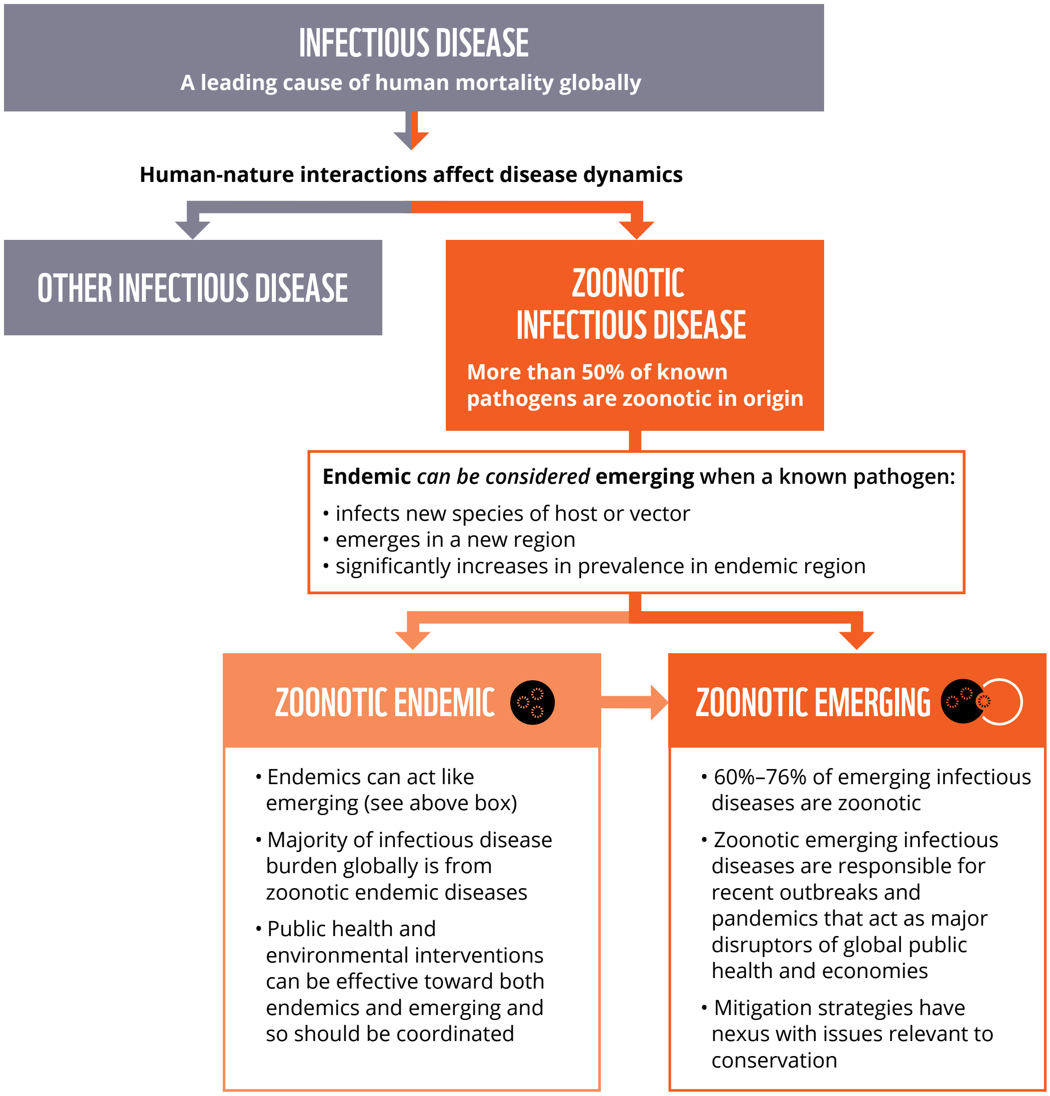
After a period of apparent success in reducing the public health impact of infectious diseases through the use of vaccines and improved sanitation, a set of novel diseases began emerging in the latter half of the 20th century (Figure 2.1), drawing attention to the growing threat of EIDs to public health (Cunningham et al. 2017). We define an EID as an unknown infectious disease classified for the first time (a novel EID, such as COVID-19) or a previously known infectious disease that appears in a new geographical area (e.g., West Nile virus appearing in the eastern United States), that rapidly increases with respect to the number of new cases in a population or appears in a new species (World Health Organization 2014). Sixty to seventy-six percent of recent novel EID events are zoonotic (Lloyd-Smith et al. 2009; Gortazar et al. 2014).

Figure 2.1 The cumulative discovery of virus species known to infect people. In recent decades, approximately three to four new infectious diseases have emerged each year and the majority of these are zoonotic and originating from wildlife (Woolhouse 2008 with interpretation by A. Dobson pers. comm).



A review of 335 EID events found that 60% were zoonotic, and the majority of these (72%) were from wildlife (Jones et al. 2008) even though many wildlife-origin zoonoses first travel through an intermediate host, such as domestic livestock, as a bridge to humans (Daszak et al. 2006; Hollenbeck 2016; UNEP 2017). The frequency of novel EID events and the proportion of those caused by wildlife appears to be increasing over time, suggesting that the threat of EIDs to human health is increasing, driven largely by zoonotic viruses (Jones et al. 2008). Morse et al. 2012 summarize this growing threat stating, “most recent pandemics, such as HIV/AIDS, severe acute respiratory syndrome, and pandemic influenza, are caused by zoonotic pathogens, are viral diseases, and originated in wildlife” and have the potential to dramatically endanger global public health and disrupt economies. Importantly, for conservationists, these new diseases generally emerge due to changes in ecosystems, human behavior, and socioeconomic systems. Our understanding of these interacting drivers is improving, offering the hope of improving our ability to predict and avoid or manage future pandemics (Morse et al. 2012). **Thus, this science brief will focus attention on novel zoonotic EIDs from wildlife origins and the direct and indirect drivers that influence the processes of spillover and transmission (Figure 2.2).**

Figure 2.2 The relationship between infectious disease types and their origins. This science brief focuses on novel diseases, while lightly addressing endemic zoonotic EIDs where appropriate.



It is important to note that even though novel zoonotic EIDs receive the most attention due to the uncertainty in their extraordinarily high transmission rates and their spread to countries of the Global North, the greatest zoonotic disease burden globally is from well-known endemic zoonotic diseases (e.g., brucellosis, rabies, Chagas disease, rickettsioses, and Rift Valley fever) or diseases that have a zoonotic origin but are now predominantly human diseases, such as malaria. For all of these, the disease burden falls primarily on poor communities in the Global South (Cunningham et al. 2017). Further, in certain situations, these endemic diseases behave in ways that can be classified as 'emerging' (World Health Organization 2014), and they share some similar drivers (e.g., land-use change). Relevant to this science brief and WWF's mission, some of the same interventions rooted in conservation, such as protection of intact habitat, can reduce risks from both novel zoonotic EIDs and intensification of endemic zoonotic diseases. Similarly, the public health interventions necessary to reduce risks from both, such as widespread monitoring programs, can and should be directed at both novel and endemic EIDs. For these reasons, we will also discuss endemic and novel zoonotic EIDs in this science brief, but we will strive to clearly differentiate between them as appropriate (Figure 2.2).

2.1.2 Zoonotic disease and the animal-human interface


© Luis Barreto / WWF-UK

Most pathogens of animals are not able to infect people. Some pathogens can only move from an animal to infect a human through a vector, such as a mosquito, with no subsequent human-to-human transmission (e.g., malaria, West Nile virus). Other pathogens lead to limited cycles of human-to-human transmission but do not persist, such as monkeypox. The most dangerous zoonotic pathogens are those that can infect people and sustain effective human-to-human transmission (Lloyd-Smith et al. 2009).

There are three barriers to animal disease becoming a human disease, or 'spillover' (Gortazar et al. 2014). All three barriers must be overcome for a disease to become established within the human population:

1. **interspecies barrier:** are people exposed to a zoonotic pathogen?
2. **intrahuman barrier:** can the zoonotic pathogen establish within a person and overcome their immune response?
3. **interhuman barrier:** can the zoonotic pathogen transmit between people, leading to outbreaks, epidemics, and pandemics?

This science brief focuses primarily on the first barrier which includes ecological processes driving animal and human population dynamics and interspecies contact, including changes in land use and land cover. We focus here as these are the processes that most closely align with conservation interventions. We include some focus on the other barriers because (1) some aspects of health that affect a person's vulnerability to infection—such as nutrition and burden of other diseases—can also be influenced by ecological processes relevant to conservation; and (2) some potential interventions reviewed in this science brief (e.g., closing wildlife markets) have been implemented to reduce transmission and spread after a novel zoonotic EID event has begun.

As described above, we will also discuss endemic zoonotic diseases where relevant. For these, the path from animal to human is already established, but many of the same environmental drivers relevant to the first two barriers are also relevant as drivers of incidence of endemic disease.

Gortazar et al. (2014) offers a conceptual model of the interspecies barrier, which can help understand and predict risks, and prioritize policies and interventions to minimize those risks. The model focuses on interactions between people and animals (and potentially vectors such as mosquitoes) and the direct and indirect drivers that influence the dynamics of those interactions. The key components of the model include:

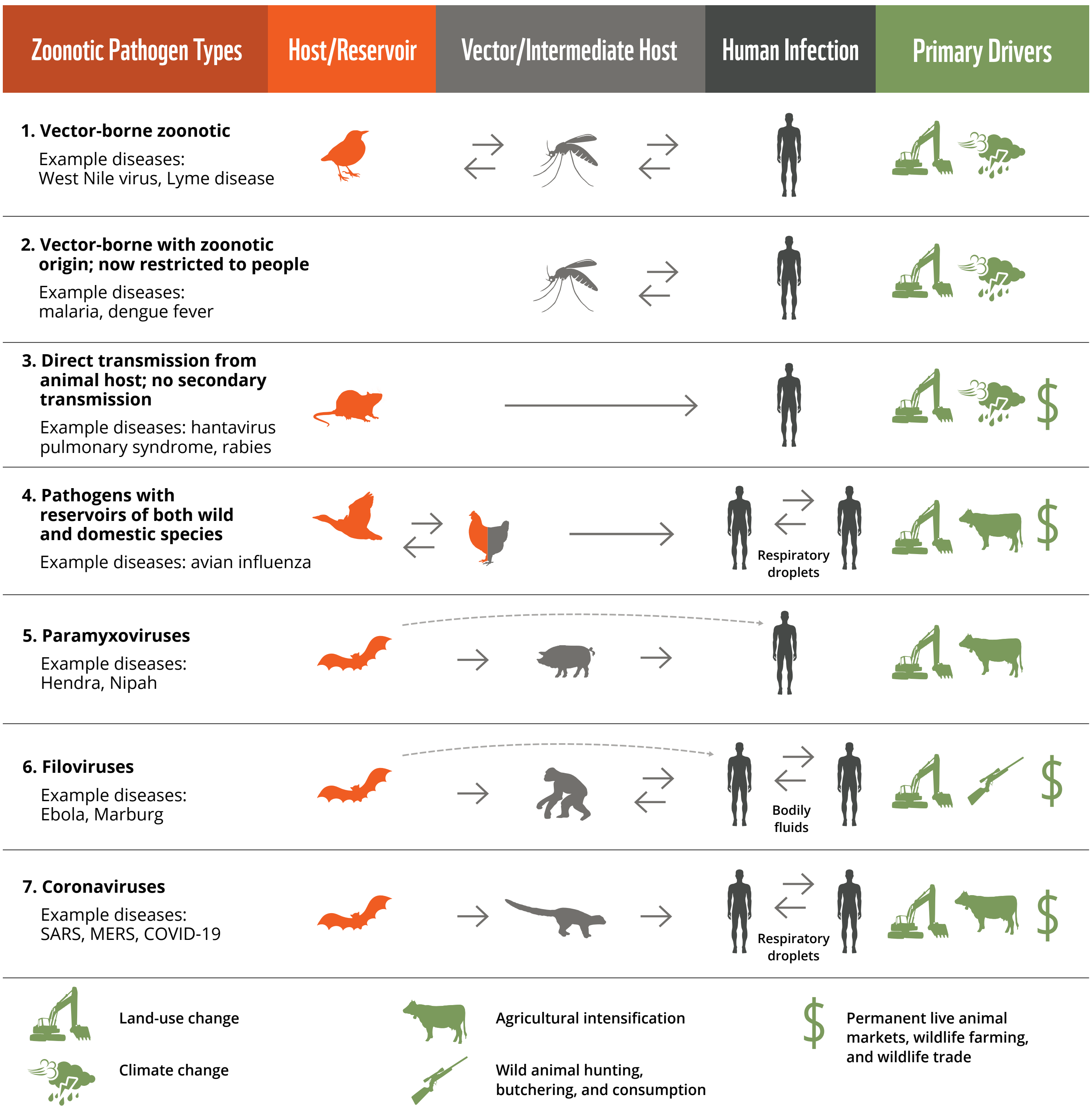
1. ***The extent of interactions between people and the animal host population,*** which is shaped by population dynamics of both people and animals, encompassing components such as range expansion, population growth, and behavior that influences interspecies contact;
2. ***Direct drivers of those dynamics,*** including changes in land use, the availability of habitat and resources, and migration; and
3. ***Indirect drivers,*** which occur at broader scales (regional to global) and can be anthropogenic or natural and include governance and climate change.

Subsequent chapters will focus on these drivers and associated leverage points, policies, and interventions that could reduce risk from zoonotic diseases.

2.2 Typology of zoonotic diseases

A given zoonotic disease has a specific mechanism of transfer from animal to human. Some diseases can only be transmitted to a human by a vector such as a mosquito, with no subsequent human-to-human transmission. Others can move from an original host to an intermediary host to humans and then commence human-to-human transmission; these, such as COVID-19, are the most dangerous zoonotic diseases to people because they can lead to rapid spread and global pandemics. Because of the different types of transmission and spread, different zoonotic diseases can have very different drivers and risks (Table 2.1).

Table 2.1 A typology of zoonotic emerging infectious diseases with respect to pathogen transmission pathways from animals to people. We identify seven pathogen transmission types (on the left), the steps in each transmission pathway, and the drivers of change (e.g., land-use change, agricultural intensification including livestock production, permanent live animal markets, wildlife farms & wildlife trade, and wild meat hunting & consumption). We focus attention on the diseases that have the potential to be pandemic due to their human-to-human spread (#4, 6, 7).



While this science brief focuses on zoonoses of terrestrial origin, researchers have found that marine mammals and birds are reservoirs for potential zoonotic pathogens, which they may transmit to people in coastal communities (Bogomolni et al. 2008).

© Shutterstock.com

Table 2.1 provides preliminary information on the potential drivers with a nexus to conservation, but these are explored more fully in subsequent chapters. The numbering below corresponds to the types of transmission described in Table 2.1.

1. **Zoonotic vector-borne pathogens.** These pathogens have an animal host and infection is transmitted to people via a vector, generally an invertebrate such as a mosquito. Examples include West Nile virus, carried by mosquitoes with birds serving as the reservoir, and Lyme disease, carried by ticks with mammals serving as the reservoir. For these diseases, people are often "dead-end" hosts, meaning there is no human-to-human transmission. Changes in land use can increase the population of hosts, such as how changing land use and land cover in the northeastern United States expanded habitat for the mammalian hosts of Lyme disease, including white-tailed deer mouse (Kilpatrick & Randolph 2012). Climate change can lead to range expansion of the hosts and vectors, as is happening with Lyme disease and the northward expansion of the white-footed deer mouse into the states of Wisconsin and Minnesota (Mills et al. 2010).
2. **Formerly zoonotic vector-borne pathogens.** Endemic diseases such as malaria and dengue fever are thought to have been zoonotic but are now mainly confined to humans. Transmission occurs via a vector such as a mosquito. Some land-use changes favor increase in mosquitoes, including forest clearing and road construction, which can increase human exposure to this type of disease in regions where it is endemic. Climate change can lead to range expansion of the vectors (e.g., mosquitoes), carrying the disease to new regions and new human populations, as is happening with dengue fever extending northward into the state of Texas (Kilpatrick & Randolph 2012). Changes in precipitation strongly affect the population size of mosquitoes, with a trend toward wetter conditions potentially leading to increases and a trend toward drier conditions leading to lower populations (Mills et al. 2010). Although climate change can affect the range of vectors, Kilpatrick and Randolph (2012) suggest that changes in land use and social factors will likely have a larger influence on the dynamics of vector-borne disease than climate change.
3. **Direct transmission from animal host, no secondary transmission.** These include rabies, an endemic zoonotic disease in much of the world, and hantavirus (hantavirus pulmonary syndrome), with wild rodents serving as the reservoir. People can become infected by hantavirus through exposure to urine or feces of infected rodents, and occasionally by a bite from an infected animal. Disease from hantavirus infection was first identified during the Korean War and then emerged in the Southwest region of the United States in 1993. The many different species of hanta-like viruses have a global distribution. Similar to the diseases described above, climate change can lead to range expansion of host animal species and some land-use changes can create favorable habitat for host species.
4. **Pathogens with reservoirs in both wild and domestic animal populations.** Wild birds, particularly waterfowl and shorebirds, can carry avian influenza type A viruses and can infect domestic birds. Wild birds generally do not become sick from the virus, as they are predominantly stomach viruses. They can cause sickness or mortality among populations of domestic poultry when they become respiratory pathogens. Avian influenza type A viruses can pass from poultry to people and can sustain person-to-person transmission (World Health Organization 2014).

5. **Paramyxoviruses.** Several recently emerged zoonotic diseases are paramyxoviruses that have bats as a reservoir and have been transmitted to humans through a livestock intermediary. These include the Hendra virus, emerging in Australia during the past two decades, which passed from bats to horses to people who had been in close contact with the infected horses. The Nipah virus, another type of paramyxovirus, passed from bats to pigs to people in Malaysia in the late 1990s. In Bangladesh, people contracted the Nipah virus directly from bats when they drank date palm juice contaminated with saliva of infected bats. There has been limited person-to-person transmission Nipah virus through direct exposure to secretions and excretions (Wang and Crameri 2014).

6. **Filoviruses.** Filoviruses include Ebola and Marburg. Bats also serve as the uninfected reservoir (Box 2.2). Wild primates can become infected by bats, and primates are a likely source of infection in humans (e.g., contact through hunting and butchering). Direct transmission from bats to people can occur, but it is rare. Spread between bats, primates, and humans, and within human populations, occurs via contact with bodily fluids (e.g., blood and mucus) or through contact with items contaminated with infected bodily fluids (World Health Organization 2014).

7. **Coronaviruses.** This is a group of related viruses that cause diseases in mammals and birds. In humans, coronaviruses cause respiratory tract infections that can be transmitted between people by respiratory droplets. Bats are a common reservoir of coronaviruses, and bats are the likely host of the three recent coronavirus EIDs (SARS, MERS, and COVID-19). Direct transmission from bats to people is thought to be extremely rare and an intermediate host is generally involved, such as a civet (SARS) or camel (MERS). Some coronaviruses can cause mild infections, such as some cases of the common cold, while others can cause more severe, even lethal, infections, such as those that cause SARS, MERS, and COVID-19. A coronavirus consists of a strand of RNA with a thin plasma membrane that is easily broken by soap/detergents, alcohol (60%-80%), or bleach, which is why hand washing and other disinfectant practices are effective at limiting spread. The coronaviruses are relatively large for a virus and have self-correcting mechanisms that significantly reduce their mutation rates (Sanjuán & Domingo-Calap 2016). Although they mutate slowly, they have a very high rate of replication which means that they evolve as fast as most RNA viruses (Holmes et al. 2016).

Figure 2.3 Transmission of diseases from animals to humans. On the left, a civet which is believed to have been the intermediate host that passed the SARS virus to humans in China in 2003. On the right, a camel which is believed to have been the intermediate host that transmitted the MERS virus.

© Thomas Nicolon / WWF DRC

The benefits of bats

Insect eaters—Small bats can eat up to 2,000 insects every night.

Pollinators—Over 300 species of fruit depend on bats for pollination.

Seed distributers—Bats help spread seeds for nuts, figs, allspice and cacao.

Medicine—About 80 medicines come from plants that rely on bats for their survival.

Why bats make such great reservoirs

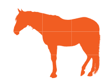
Bats are natural reservoir hosts and sources of infection for several microorganisms, including pathogens that cause severe human diseases. More than 200 viruses have been associated with bats, and almost all are RNA viruses due to their ability to adapt to changing environmental conditions through a higher genetic variability. This number is a significant underestimate as there are over a thousand species of bats, and less than 10% have been surveyed for viruses. There have been six major outbreaks of zoonotic EIDs in the past 25 years caused by proven or suspected bat-borne viruses, including the COVID-19 pandemic (Table 2.2; Wang et al. 2020).

Bats have a range of characteristics that make them particularly common as reservoirs or hosts of viruses that become zoonotic EIDs in people. Their physiology and metabolism give them a special tolerance to viruses, allowing them to carry high viral loads and shed viruses without becoming sick (Brook & Dobson 2015). Further, the mammalian order that contains bats, Chiroptera, has a high species richness of over 1,200 (20% of all mammals), resulting in a high viral richness. Bats also roost in colonies of thousands to tens of millions of individuals, facilitating the spread of viruses. Because they are highly mobile, they can carry viruses to many types of habitats and potentially expose many other mammal species. They are also widespread in urban areas, not only coming into close contact with both domestic animals and humans, but also contaminating houses with guano and urine. This combination makes them ideal reservoirs and explains why they are frequently implicated in novel zoonotic disease emergence.

2.3 Recent outbreaks of zoonotic disease

The World Bank estimates that the economic burden of just six zoonotic diseases amounted to US$80 billion over 12 years (World Bank 2012), not including the current COVID-19 pandemic with an impact on global economies that will likely be measured in the trillions of dollars (Orlik et al. 2020). Table 2.2 provides a list of seven zoonotic disease outbreaks with detailed descriptions provided in Appendix B.

Table 2.2 Summary characteristics of major outbreaks for zoonotic EIDs in the past 25 years from Wang et al. 2020. SARS=severe acute respiratory syndrome. MERS=Middle East respiratory syndrome. hCoV-EMC=human coronavirus Erasmus Medical Center. 2019-nCoV=2019 novel coronavirus. HARS-CoV=Han acute respiratory syndrome coronavirus. For 2019-nCoV, data are for Feb 9, 2020. *Although the 2014 Ebola outbreak was believed to start with a direct bat-to-human transmission, non-human primates have been indicated in previous Ebola outbreaks.

	Year of first major outbreak	Countries or regions affected	Bat origin status	Main intermediate animal host responsible for human infection
Hendra	1994	Australia	Confirmed	 Horses
Nipah	1998-99	Malaysia and 4 other countries	Confirmed	 Pigs
SARS	2002-03	China and 25 other countries	Confirmed	 Civets
MERS	2012	Saudi Arabia and 26 other countries	Suspected	 Camels
Ebola	2014	Guinea and 6 other countries	Highly suspected	Non-applicable*
2019-nCoV	2019-20	China and 24 other countries	Suspected	Presently unknown

2.4 Conservation impacts of zoonotic pandemics

Zoonotic EIDs can threaten wildlife populations already imperiled by other risks such as poaching and logging, drive abundant species to rarity or extinction, and alter the structure of ecosystems (Langwig et al. 2015). Direct mortalities due to zoonotic EIDs, while rare, have been documented in many wildlife taxa. Widespread mortality of gorillas and other primates occurred after numerous Ebola outbreaks in Gabon and the Democratic Republic of Congo between 1997 and 2004, with death rates of up to 97% in some groups (Caillaud et al. 2006). Females and young animals were disproportionately affected, with implications for population recovery. Trichomonosis, a novel fatal disease of birds, reduced breeding populations of greenfinches and chaffinches in some parts of Britain by 35% and 21% respectively, killing more than half a million birds (Robinson et al. 2010). There is very good evidence that avian malaria and avian pox caused the extinction of much of Hawaii's avifauna in the late 19th century (McCallum 2012). The highly contagious and often fatal canine parvovirus, which evolved from feline parvovirus and infects domesticated dogs, wolves, and coyotes, developed into a global pandemic in 1978 (McCarthy et al. 2007). Canine distemper virus poses an important conservation threat to many carnivore species. Spillover from domestic or feral dogs to wild species has led to mass mortalities in African wild dogs, bat-eared foxes, felids, hyaenas, seals, ferrets, civets, red pandas, and raccoons, and may have contributed to the extinction of the Tasmanian tiger (McCarthy et al. 2007). A recent study (Melin et al. in review) suggests that apes and African and Asian monkeys, as well as some lemurs, are all likely to be highly susceptible to SARS- CoV-2. The authors recommend urgent actions to limit their exposure to humans.

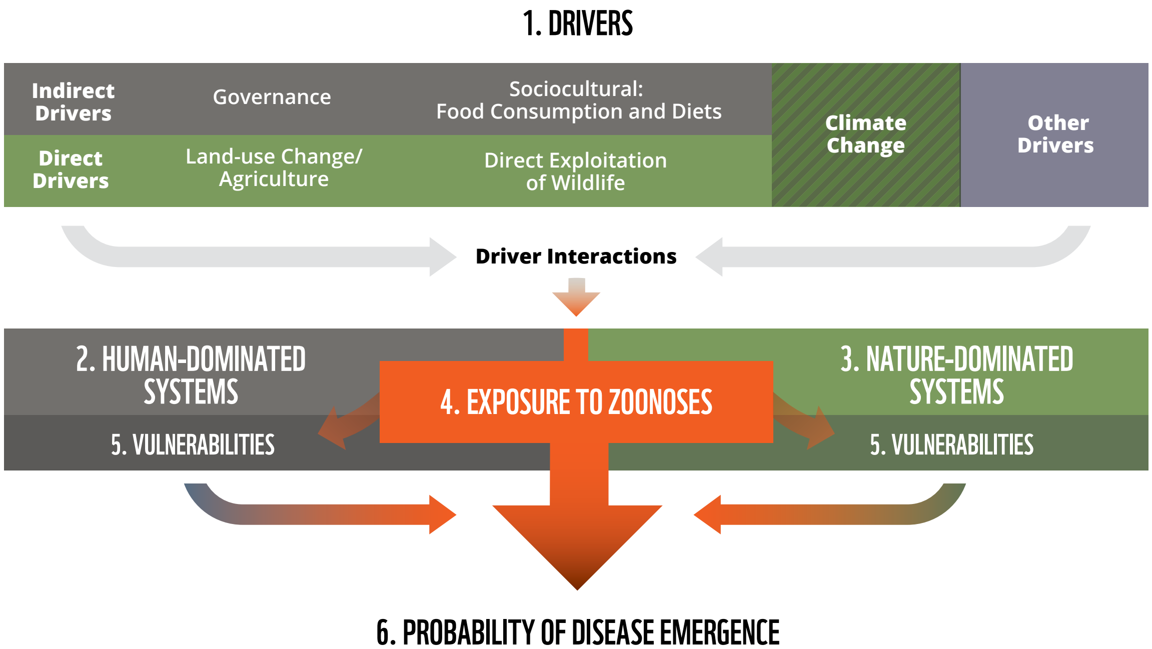
Zoonotic disease can also profoundly affect ecosystem structure and function (Buck & Ripple 2017). Impacts on wild predator populations can result in cascading effects downward through food webs, affecting prey and plant populations, biodiversity, and the delivery of ecosystems services. Diseases spread by humans also affect marine vertebrates and marine food webs (Bogomolni et al. 2008).

Section 3. Conceptual approach

Many of us are looking for simple, impactful, and meaningful solutions to address the emergence of zoonotic diseases such as COVID-19. However, solutions that do not take into account the interactions between the environment, society, and the economy will fall short of their objective in the long term, or worse, exacerbate the decline of human health and/or nature (Di Marco et al. 2020; Wallace et al. 2020). Changes in land use, including changes in food production, are among the leading drivers of the emergence of infectious disease in humans (Allen et al. 2017). Increasing contact at the human-animal-environment interface facilitates emergence of zoonotic diseases. Loss and degradation of ecosystems and the decline of biodiversity are altering pathogen abundance, composition, distribution, and evolution while human behavior and economic activity such as global travel, the use of antimicrobial agents, dietary shifts, and climate change are affecting pathogen movement, their animal host ranges, and their persistence and virulence (Wilcox & Gubler 2005; Faust et al. 2017). This results in host-pathogen systems that are complex due to changing dynamics and nonlinear behavior (Plowright et al. 2017; Sokolow et al. 2019). It is no surprise, therefore, that the incidence and frequency of emergence of zoonotic infectious diseases has increased in the last 50 years in unpredictable ways (Smith et al. 2014).

To make sense of this complexity for conservation, we provide a simple, causal diagram that describes the direct and indirect drivers of change in human- and nature- dominated systems that increase the risk of novel disease emergence by increasing the exposure and/or the vulnerability of humans to pathogens (Figure 3.1). Indirect drivers are those that operate diffusely by altering and influencing direct drivers as well as other indirect drivers (IPBES 2019). Direct drivers (natural and anthropogenic) are those that unequivocally influence biodiversity and ecosystem processes. Indirect drivers play a major role in influencing direct drivers of biodiversity and ecosystem change, as well as strongly influencing other indirect drivers. For example, the indirect driver of governance can influence the direct driver of land-use change with subsequent environmental implications. An understanding of the role of indirect drivers, such as culture and governance, is critical to sustainable ecosystem management (IPBES 2019).

Figure 3.1 Conceptual diagram of zoonotic disease. Drivers (1) include governance, the primary indirect driver that affects land-use change and agriculture; human behavior and consumption; and climate change. These causal factors and their interactions influence vulnerability of human-dominated systems (2) as well as nature-dominated systems (3). The more vulnerable human-dominated systems or nature-dominated systems become (5), and the greater people's exposure to zoonoses (4) becomes, the higher the probability of disease emergence (6). Adapted from Wilcox & Gubler 2005; Gortazar et al. 2014; Hosseini et al. 2017.



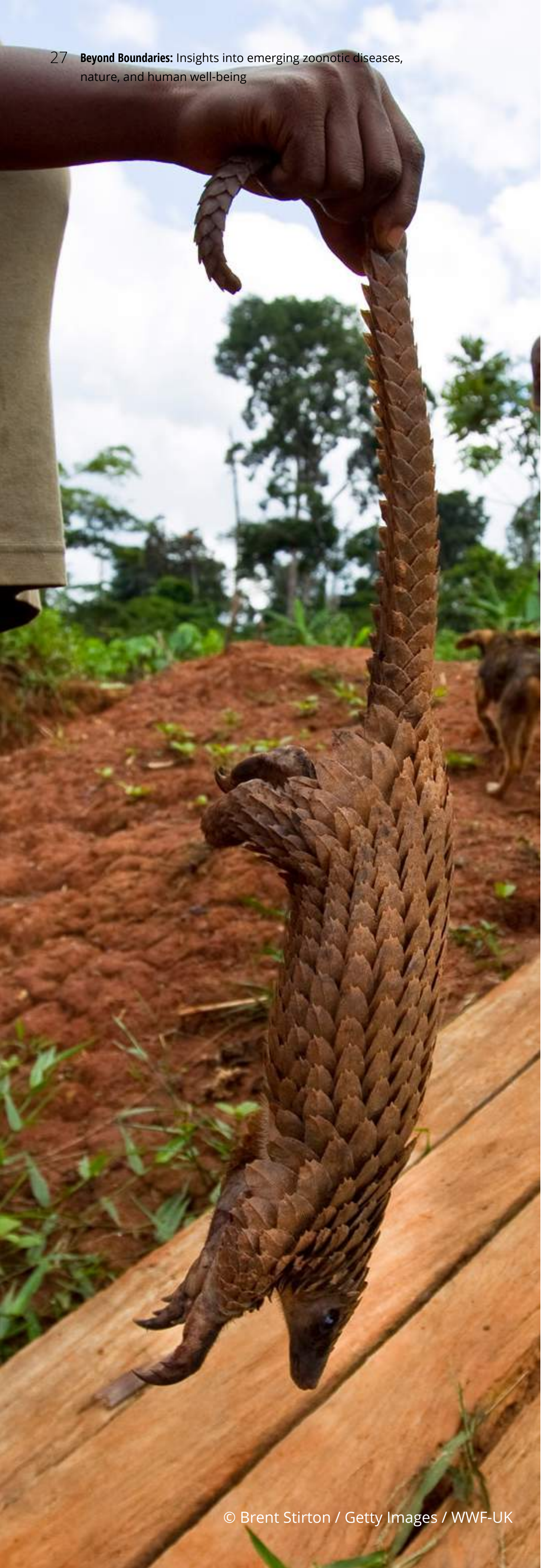
We employ a simplified model of the risk to help us organize information and communicate how the drivers interact to affect the probability of zoonotic disease emergence and to help WWF make strategic decisions regarding our interventions (National Research Council 1983; IPCC 2014). The emergence of a zoonotic risk depends on the interaction of exposure to a potentially zoonotic pathogen in wild or domestic animals and the drivers that affect the vulnerability of social and natural systems (Figure 3.1, Comte et al. 2019). We define exposure as the likelihood of contact with a pathogen and vulnerability as the likelihood that a given exposure to a pathogen will cause harm.

Conservation actions can affect the risk of zoonotic diseases by influencing the exposure and/or vulnerability. For example, increasing human contact with wild and/or domesticated animals increases the likelihood of pathogen exposure, while underlying health problems increase a person's vulnerability to infection and disease. Throughout this science brief, we delineate the drivers of change in both pathogens and human exposure, and the vulnerability to zoonotic disease that results. Each of those drivers invites different interventions to decrease the risk of disease emergence. Choosing the right intervention(s) given the causal links for any given disease is critical for success and to minimize unintended consequences. For example, closing all permanent live animal markets (i.e., wet markets) in Asia will decrease exposure to novel coronavirus, but it may decrease access to nutritional foods, thus increasing the vulnerability of people in the community by affecting their health status.

Both direct and indirect drivers influence exposure and vulnerability to zoonotic EIDs:

- Drivers that ***increase*** exposure can be social and economic (e.g., forest clearing and habitat loss, wildlife trade, wild food consumption, human encroachment, nature tourism, suburbanization, expansion of small scale farming, domestic livestock as intermediate host, roads, population growth, fragmentation) or climate-influenced (e.g., habitat change, animal species range shifts, vector shifts).
- Drivers that ***reduce*** exposure can be social and economic (e.g., urbanization, education, culture, behavior, restrictions on movement, monitoring of zoonoses in sentinel species and management of protected areas and buffer zones.)
- Human vulnerability to a disease outbreak can be influenced by nutrition, poverty, gender equity, natural disasters, armed conflict, and health-related social factors.
- Ecosystem vulnerability to a disease outbreak can be influenced by ecological intactness, degradation, fragmentation, and sea level rise.

We do not address the mechanisms controlled by epidemiological processes that facilitate spillover at the stage of enabling an animal pathogen to establish infection in a human host (Plowright et al. 2017). This stage is not readily influenced by conservation intervention, and thus we focus on direct and indirect drivers, exposure, and vulnerability that have the potential for effective conservation intervention. In analyzing the zoonotic disease and conservation problem in this way, we hope to inform WWF's design and implementation of effective and sustainable strategies that enhance the health of nature and people (Díaz et al. 2015).



© Brent Stirton / Getty Images / WWF-UK

Section 4. Drivers of zoonotic disease exposure

The direct and indirect drivers that affect the emergence of infectious disease are numerous and complex, and their relative impact on the emergence of new disease differs geographically and depends on a number of underlying conditions. Global models that attempt to predict hotspots of emergence of infectious disease, therefore, have little explanatory power (Keesing et al. 2010). Human activities that facilitate close contact between wildlife and humans (e.g., hunting, consumption, habitat encroachment) have increased opportunities for animal-human interactions and facilitated zoonotic disease spillover (Johnson et al. 2020). At the local scale, we can understand drivers that affect the emergence of infectious disease by exploring their influence on exposure and vulnerability of the local populations.

A number of drivers directly affect the exposure of people to potential zoonotic viruses. The direct drivers that increase exposure include land-use change, defaunation and other forms of disturbance (e.g., deforestation, habitat loss, infrastructure construction, human encroachment, suburbanization), wildlife trade and wild meat consumption, intensification of agriculture and livestock production (e.g., expansion of small- and large- scale farming, intensification of animal production), and climate change (e.g., animal species range shifts, vector shifts; (Mills et al. 2010; IPCC 2018a; Harvard C-CHANGE 2020).

Direct and indirect drivers affect vulnerability and can amplify or diminish the likelihood of bad outcomes like disease outbreaks, some of which can also be managed directly. Much of the literature conflates the components of social and ecosystem vulnerability that have direct and indirect effects on the emergence of infectious disease.

In this section, we explore the direct and indirect drivers of the emergence of zoonoses, their interactions, and their effect on exposure and vulnerability.

4.1 Land-use change and disturbance

Main points

- Expansion or intensification of human activity in natural ecosystems can expose humans to animal viruses, increasing the risk of a zoonotic EID event.
- A recent research synthesis found that biodiversity has little net effect on most human diseases and that the conditions for dilution effect with biodiversity increases are unlikely for most important human diseases.
- At intermediate levels of land conversion, the probability of spillover is highest. The largest, but less frequent, epidemics occur at the highest levels of land conversion.
- Globally, land-use change has contributed to almost half of the emergence events for zoonotic disease in humans from 1940–2005.

Evidence indicates that growing intrusion of humans into wildlife habitats—through the expansion or intensification of human activities in natural ecosystems—increases human-animal interactions that enhance the probability of transmission of pathogens (Chan et al. 2013). Here, we look at the impact of land use change on endemic and novel zoonotic EIDs, the interactions between biodiversity richness and zoonotic EIDs, and the extent to which land use change influence these EIDs. The expansion of human activities is often led with road development on the forest fringes, often linked to logging and mining, which facilitates human settlements into natural habitats. Road development then leads to forest conversion to agriculture, resulting in the decline of natural habitats.

Following decades of widespread deforestation and fragmentation, the global extent of intact forest has declined dramatically (Morgan et al. 2019). About 70% of forests globally are within 1 kilometer of a forest edge and exposed to further fragmentation, and one-third of tropical forests have been logged with widespread impacts on ecosystem processes and biodiversity (Edwards et al. 2014; Ewers et al. 2015). Species richness in these logged and fragmented forests has declined by 13%–75% (Haddad et al. 2015), and the loss is projected to continue in all biodiverse regions (Newbold et al. 2015). We are developing roads at an unprecedented rate, both in total length and spatial extent (Laurance et al. 2015; Laurance and Arrea 2017). Worldwide, we have increased paved roads by 12 million km since 2000, with an additional 25 million km of paved roads expected by 2050 (Dulac 2013). In addition, there has been significant expansion of unpaved roads, in some places into protected areas, which stimulates the expansion of human settlements (Kleinschroth and Healey 2017). Road development and extractive industries, mainly mining, are often linked. Many of the world's remaining areas of extensive humid and semi-arid forest are sites of important mineral, oil, coal and natural gas reserves (Bebbington et al. 2018). Globally, changes in land use have caused almost half of the emergence events for zoonotic disease in humans from 1940–2005 (Keesing et al. 2010).

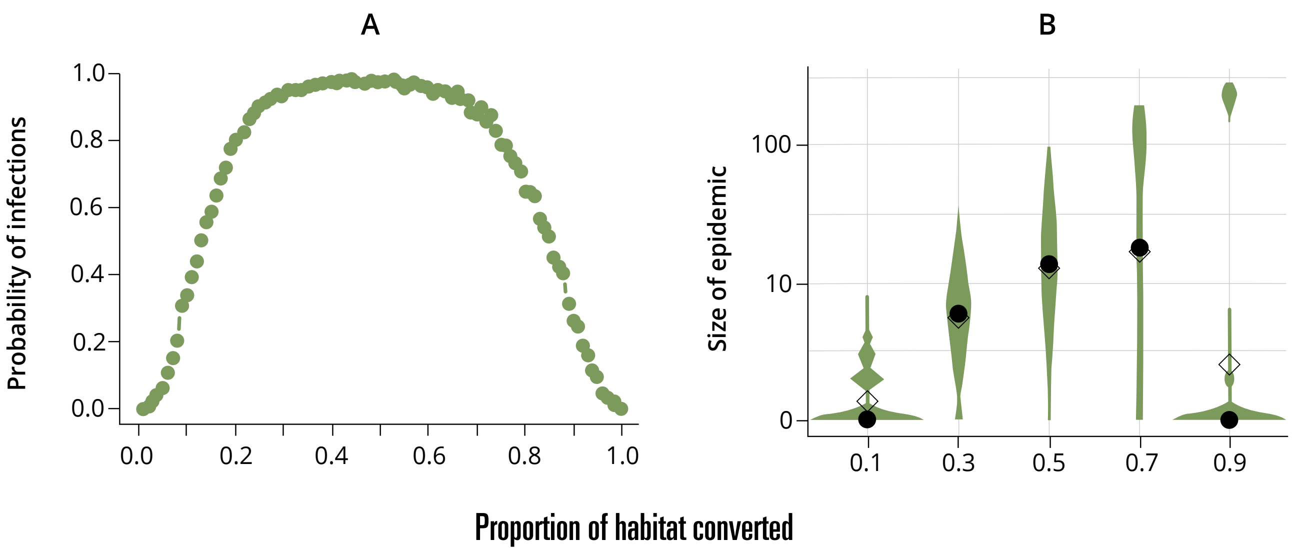
The loss and degradation of forests increases the risks associated with both novel and endemic EIDs. In a study of 131 emerging vector-borne zoonotic diseases, particularly those transmitted by ticks and mosquitoes, researchers found that land-use change was the most important factor (Swei et al. 2019). Studies on zoonotic endemic diseases, conducted in the Brazilian Amazon, found that malaria incidences increase following deforestation (MacDonald & Mordecai 2019). In contrast, a study of 17 countries in sub-Saharan Africa found that deforestation was not associated with higher malaria prevalence, potentially because deforestation in sub-Saharan Africa occurs in regions where malaria is already endemic and previous exposure is high (Bauhoff & Busch 2020).

The increase in risk of novel zoonotic EIDs associated with deforestation occurs because deforestation increases a person's exposure to a diverse array of animals that host pathogens novel to humans. For example, deforestation and forest fragmentation are identified as primary drivers of Ebola transmission (European Food Safety Authority 2015; Rulli et al. 2017). More in-depth analysis has linked Ebola outbreaks to human activities that increase interactions with fruit bat species overlapping in Central and West Africa, mainly in closed forests, both intact and disturbed (Olivero et al. 2017). Others argue that the risk of novel zoonotic EIDs is greater in forested tropical regions where wildlife biodiversity (i.e., mammal species richness) is high (Allen et al. 2017).

But the relationship between biodiversity (i.e., measured as species richness and composition) and risk of novel zoonotic EIDs is complicated, with evidence for both reduced risk with increasing biodiversity (i.e., the dilution effect) and increased risk with increasing biodiversity (i.e., the amplification effect; Faust et al. 2017). The dilution effect occurs when a higher diversity of species susceptible to infection leads to lowering the infection prevalence in the host species. This decreases the pathogen spillover to humans. In the amplification effect, increased species diversity increases the risk of zoonoses (Wood et al. 2014). A recent research synthesis found that the conditions for dilution effect are unlikely for the most important human diseases and that biodiversity has little net effect on most human diseases (Wood et al. 2014). Others find that the effect will depend on the pathogen transmission mode. That is, the dilution effects are primarily found in frequency-dependent transmission of pathogens, such as Lyme disease, while amplification effects are found in density-dependent pathogens in which infections increase with the density of the infectious host, such as SARS (Faust et al. 2017). Disease risk is more likely a local phenomenon that relies on the specific composition of reservoir hosts and vectors, their ecology, and specific human contact with pathogens, rather than patterns of species biodiversity (Salkeld et al. 2013).

Pathogen transmission from wildlife and humans changes across different types of land cover types—core forests to forest edge to mosaic land uses. Human alteration of natural habitats changes the architecture of forest landscapes, resulting in species movements and composition in response to the availability of resources which has implications for pathogen spillover. The highest spillover rates are projected to be at intermediate levels of habitat conversion while the spillovers that lead to the largest epidemics are projected to occur less frequently at the extremes of land conversion (Figure 4.1; Faust et al. 2018). At low levels of conversion, there is a large reservoir of species with potential to be infected. With converted lands, there are very few. This changes as conversion increases. When there is a relatively high level of conversion, there is a much smaller spillover effect.

Figure 4.1 In a modeling study, Faust et al. found that (a) at intermediate levels of land conversion, the probability of spillover is high, and (b) the largest, but less frequent, epidemics occur at the highest levels of conversion (figure adapted from Faust et al. 2018).



Changes in extent and intensity of agriculture close to forests tend to increase the proximity to and contact between wildlife pathogen reservoirs and intermediate domestic animal hosts, increasing the risk of spillover of animal pathogens to humans. A review conducted in 2015 identified several major wildlife-livestock pathogen transmissions (Wiethoelter et al. 2015). Influenza A was transmitted from wild birds to pigs and people (Ma et al. 2008). Another example includes the Hendra virus which spread from large fruit bats (flying foxes) to horses and then to humans (Table 2.2; Plowright et al. 2017). Also, the Nipah virus in which the intensification of pig farms adjacent to mango plantations attracted fruit bats, a reservoir for the virus (Table 2.2; Pulliam et al. 2012). The expansion and intensification of agriculture into tropical forest landscapes increases the risk of spillover.

Commercial agriculture is the most important driver of deforestation and habitat conversion, followed by subsistence agriculture, with regional variations. Currently, over 40% of the global land area is under some sort of cultivation (Springmann et al. 2018). A portion of the demand for land has been met by converting forest to agriculture (Gibbs et al. 2010). A global forest loss assessment in the period from 2001–2015 found that 27% of forest loss results from expansion of land-use change for commodity production, 26% is attributed to forestry, 24% to shifting agriculture, and 23% to wildfires (Curtis et al. 2018). Timber extraction and logging drives most of the degradation, followed by fuelwood collection and charcoal production, uncontrolled fire, and livestock grazing (Hosonuma et al. 2012). This has implications for human density on rural landscapes, the configuration of land-use systems, and the type of interactions of local people with nature. Thereby, some local contexts are more exposed to zoonotic diseases transmitted by wildlife and others by domesticated animals (Bloomfield et al. 2020).

4.1.1 Hotspots

There have been numerous attempts to identify spatially explicit hotspots for EIDs (Bogomolni et al. 2008; Jones et al. 2008; Allen et al. 2017). Their complexity (Table 2.1) and a lack of good, representative, and explanatory data make predicting future outbreaks difficult (Allen et al. 2017). A global analysis of demographic, environmental, and biological correlates of wildlife-related EID events show they are best predicted by the distribution of tropical forested regions, high mammalian species richness, and shifts in agricultural land use. However, the analysis fails to be predictive because it is only able to explain the variance in half of all outbreaks, likely because they are not able to effectively incorporate behaviors and other uses of these spaces.

4.2 Wildlife trade and wild meat consumption

© Karine Aigner / WWF-US

Main points

- Wildlife use and meat consumption is a direct driver of zoonotic EIDs, with certain species carrying a higher risk of transmission. Bats, pangolins, palm civets, raccoon dogs, rodents, primates, shrews, ungulates, and carnivores are the primary wildlife hosts for zoonotic diseases while domestic species such as cats, cows, buffalo, goat, sheep, and pigeons are the primary intermediate hosts.
- Several recent zoonotic EID outbreaks originated either in permanent live animal markets (e.g., COVID-19, SARS), concentrated animal feeding operations (e.g., H5N1 – avian influenza, H1N1 – swine flu), or from consumption of wild meat (e.g., HIV, Ebola).
- Wild meat consumption drives the wildlife trade that supplies market networks beyond national boundaries.
- Wild meat is a crucial source of protein, fat, iron, and other micronutrients in many rural communities in developing countries.
- Wildlife is also used for biomedicines, ornaments, clothing, investment and symbols of power, and for cage display as pets. All of these markets have supply chains that place humans in direct contact with wildlife, increasing the possibility of zoonoses.

Wildlife trade is big business. In the only systematic analysis to date, researchers found that over a 20-year period (1975–2014), the volume of reported wildlife trade (as listed by Convention on International Trade in Endangered Species of Wild Fauna and Flora or CITES) rose from 25 million whole-organism equivalents per year in 1975 to 100 million in 2014 (Harfoot et al. 2018) and involves a large array of species including birds, mammals, amphibians, and reptiles (Scheffers et al. 2019). The increase was mostly due to trade in captive species. The ratio of wild- to captive- sourced trade declined substantially over that period. Reliable data about the magnitude of illegal wildlife trade, however, is much less accessible and varies greatly from source to source ('t Sas-Rolfes et al. 2019). It has been estimated that one in five vertebrates that live on land are traded on wildlife markets (Scheffers et al. 2019).

The wildlife trade has played a role in the emergence of zoonotic EIDs (Daszak 2020). Recent studies have found intense human-animal contact is a key risk factor for zoonotic disease emergence, particularly in permanent live animal markets (Li et al. 2020). In addition, captive-bred animals from wildlife farms are a growing proportion of trade in some wildlife species (Lin 2004). Captive wildlife farms have experienced unprecedented growth in recent decades (Lin 2004, Nijman 2010). Like permanent live animal markets, wildlife farms concentrate people and 'wild' animals, which increases exposure to potential zoonotic pathogens. One study from 2004 tested animals from civet farms around a market in Guangzhou, China and found that civets on farms were free from SARS-CoV infection, but that 80% of the animals from the market contained significant levels of antibody to SARS-CoV (Tu et al. 2004). Although more rigorous testing is needed, this suggests the infection of civets in the market was associated with post-farm transport, handling, and sale under concentrated conditions with people and live wild animal species in the permanent live animal markets (Tu et al. 2004), and farmed animals are likely a lower risk than wild-caught animals (Daszak 2020). To lower that risk, regulations that call for disease surveillance, veterinary care, sanitary transport, market conditions, and control of the source of traded animals would need to be implemented (Bell 2004, Daszak 2020, Li et al. 2020).

Wild meat complements and supports local livelihoods in many regions and is an important source of meat in many urban contexts, such as in Central Africa (Fa et al. 2019). In the Global South it plays an essential role in some people's diets, especially where livestock husbandry and fishing are not feasible options. Reliance on wild meat is important in poorer rural households where it is a crucial source of protein, fat, iron, and other micronutrients (Coad et al. 2019). Around the world, the benefits of wild meat from ungulates, rodents, rabbits and hares, kangaroos, reptiles, and bats and its role in food security are substantial, as are the detriments (Hoffman & Cawthorn 2012). In addition to meat, wildlife is also used for biomedicines, ornaments, clothing, investment and symbols of power (Neijman & Nekaris 2014), and in the pet trade, where there are significant risks of disease spillover from wildlife to people (Chomel et al. 2007).

Apart from contributing substantially to food security, wild meat consumption is linked to wild meat trade, much of which takes place illegally. Trade of wild meat not only provides income streams in regions where few alternatives exist (Coad et al. 2019) but it also supplies local and proximate urban markets where wild meat is sold and consumed. A study in the Yangambi landscape in the Democratic Republic of Congo found that 103–145 tons of wild meat are consumed per year in rural and urban areas, the most consumed source of meat in the region (Van Vliet et al. 2019). About a quarter of markets and restaurants were found to sell wild meat in the Kinshasa–Brazzaville metropolitan area in Central Africa (Fa et al. 2019). Wild meat consumption is also linked to wildlife trade that feeds wider market networks beyond national boundaries. This also puts pressure on wildlife population decline, such as the one linked to the pangolin trade in Myanmar (McEvoy et al. 2019).

Wildlife use is a direct driver of zoonotic EID events, or spillover. Transmission of a virus can be directly from a virus reservoir (e.g., bats) to humans or through intermediate hosts such as camels, civets, antelope, deer, rodents, bats, or insects (Kruse et al. 2004). But not all wild species are equal with respect to transmission risk. In the case of the 2003 SARS epidemic, palm civets and racoon dogs were intermediate hosts. After analyzing a database of 2,805 associations between more than 750 mammal species and viruses, researchers found that three groups—bats, primates and rodents—carried more viruses than other groups of mammals (Olival et al. 2017). Overall, there may be considerable zoonotic risks to people involved in the hunting, butchering or consumption of wild meat, particularly in Southeast Asia, and these should be considered in public health strategies (Cantlay et al. 2017). In addition, wild species living in close proximity to dense human populations carried proportionally more zoonotic viruses. Contact between humans and these high-risk species, in particular, should be more strictly regulated, accompanied by more intensive disease surveillance (Betsem et al. 2011).

Box 4.1 Risky taxa

Taxonomic richness within an animal group also matters. The number of species within a taxonomic group (Order) that host zoonoses is strongly correlated with the total number of species within a group (Han et al. 2016). Six groups stand out—rodents, bats, shrews and shrew-like relatives, primates, carnivores, and ungulates. Rodents carry 85 zoonotic diseases, carnivores 83, primates 61, ungulates 52, bats 25, and shrews 21.


© Pixaby.com

The probability of zoonotic disease emergence increases dramatically when humans and wildlife come in close contact with one another (Bonilla-Aldana et al. 2020). This can happen during the construction of infrastructure and the transport, processing, trade, and consumption of wild animals (Morse et al. 2012). Introducing hundreds or thousands of people—primary workers and those seeking secondary employment—into remote regions for infrastructure projects such as hydropower dams, results in local increases of wildlife hunting and increased human exposure to zoonotic pathogens (Jones & Bull 2020). Even so, without surveillance, it is difficult to pinpoint the place of a spillover event. While it is clear the initial source of the SARS-CoV-2 virus is a bat, much uncertainty remains about where and how COVID-19 emerged, including the wildlife or domestic species that may have served as intermediate host and the transmission routes (Hui et al 2020). Andersen et al. (2020) conducted comparative genomic analyses and concluded that the proximal origin of COVID-19 is not a laboratory construct or a purposefully manipulated virus. It is also not known if the evolution to a human disease happened within an animal or within a human. If SARS-CoV-2 pre-adapted in another animal species, then there is the risk of future re-emergence events (Andersen et al. 2020). While the market is at the center of the spread of COVID-19, it may not be where the spillover event occurred.

4.3 Intensification of agriculture and livestock production

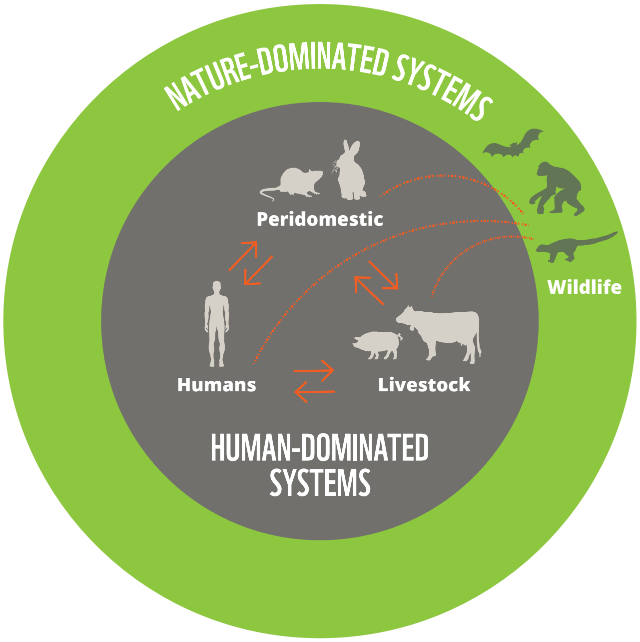
Main points

- Producing food for an expected population of 10 billion people by 2050—and the associated increase of land converted for food production—will create even greater human-livestock, human-wild animal, and livestock-wild animal contact rates, increasing the likelihood of spillover events.
- Extensive and intensive domestic and wild animal production brings people into more frequent and intimate contact with livestock and wild animals, increasing the likelihood of animal-to-human pathogen transfer and zoonoses.
- There is strong evidence linking intensive livestock production with zoonotic disease emergence, but it is unclear whether intensification in and of itself leads to more disease emergence and amplification.
- The increased use of antibiotics in livestock production is considered a threat to global health, food security, and development today.

© Brent Stirton / Reportage by Getty Images / WWF

A changing and increasingly interconnected world means increasing opportunities for pathogens to adapt and rapidly spread (Coker et al. 2011). The expansion and intensification of agriculture promotes encroachment into wildlife habitats, bringing humans and livestock into closer proximity to wildlife and potential zoonotic pathogens (Jones et al. 2013). In the last 50 years, as the growth in the human population increased, the demand for animal protein and wildlife products increased, intensifying human-animal and human-wildlife-livestock interaction through livestock production, wildlife farming, and live wildlife trade across the globe (Figure 4.2, Chomel et al. 2007, Jones et al. 2013). This intensification has facilitated pathogen spillover from wildlife to livestock and has increased the likelihood that livestock become intermediate hosts in which pathogens are transmissible to humans (Jones et al. 2013). Whereas in intact ecosystems coevolution of hosts and pathogens favors low pathogenicity microorganisms, it is the opposite in intensive production systems where low genetic diversity and intense livestock management creates higher rates of contact and a greater number of opportunities for pathogens to transmit and amplify (Jones et al. 2013). In addition, increasingly extensive transportation networks, the sale and transport of live animals (both domestic and wild), and the juxtaposition of agriculture and recreation with wildlife contribute to emergence and increasing virulence of zoonotic pathogens. Many wildlife species have thrived in this transitional landscape and have become reservoirs for disease in livestock and humans (Jones et al. 2013).

Figure 4.2 Pathogen flow at the wildlife–livestock–human interface. Arrows indicate direct, indirect, or vector-borne pathogen flow. If a pathogen is also transmissible in a new host species, then a new transmission cycle or pathway may be established. The rate and direction of pathogen flow will depend on the nature and intensity of interaction between humans-wildlife, livestock-wildlife, and humans-livestock (Jones et al. 2013).



© Luis Barreto / WWF-UK

In developed countries, intensive production systems and their associated value chains predominate. These systems, which allow for efficient production of large quantities of animal products, are becoming increasingly important in developing countries (Otte et al. 2007) where, historically, extensive, pastoral livestock production practices have been used. These modern modes of agriculture for producing poultry, cattle, and pigs may be contributing to the emergence of zoonoses in some domesticated animals. Examples of zoonotic pathogens that circulate in livestock populations include the avian influenza viruses H7N9 and H5N1, both of which are highly lethal with low transmissions rates to humans; numerous bacterial, viral, and parasitic pathogens in cattle including the human coronavirus HCoV-OC43 (Pelzer et al. 2009, Cui et al. 2019); and several variants of swine flu including H1N1, H1N2, and H3N2 (Maldonado 2006). Pigs are of particular concern as they are carriers of both human and bird influenza viruses and can, therefore, function as intermediate hosts or 'mixing vessels' in which new viruses evolve and emerge (Bronn et al. 1998).

A central tenet of epidemiology is that the incidence of directly transmitted infectious disease should increase proportionally with host density and, therefore, increasing human and livestock densities should cause increases in directly transmitted infectious disease (Parker et al. 2015). Intensive animal production systems may follow this tenet and contribute to a rise in zoonotic diseases. In these systems, animals are selected based on their genetic ability to efficiently produce, hundreds of animals are reared in confined environments in close proximity, and management practices—including vaccination and strict biosecurity protocols to prevent disease—create optimal opportunity for a new pathogen from the outside (e.g., from wild birds in the case of influenza A virus). Such scenarios can have devastating consequences, result in huge economic losses, and endanger supplies of animal protein. If the pathogen is zoonotic, it can endanger human health worldwide. Thus, it is possible that intensive animal production facilities can be a source of zoonotic disease spillover (Pew Charitable Trusts 2008). Although there is strong evidence linking modern farming practices with disease emergence (Jones et al. 2013), it is still unclear whether the net effect of intensified livestock production in and of itself leads to more disease emergence and amplification (B. A. Jones et al. 2013).

The discovery that feeding sub-therapeutic levels of antibiotics could improve animal performance (e.g., growth rates and feed efficiency) and control endemic diseases occurred in the 1950s and corresponded with the development of intensive animal production practices (Gustafson and Bowen 1997). Widespread prophylactic use of antibiotics soon became common in food animal production. Now, after decades of overusing of antimicrobial drugs in both agriculture and in human medicine, many pathogens that cause diseases such as pneumonia, tuberculosis, malaria, HIV, Staphylococcus aureus, and some forms of influenza are resistant to treatment from antibiotics or antiviral drugs. This antimicrobial resistance is estimated to result in approximately 700,000 human deaths per year (O'Neill et al. 2016). Because use of antibiotics in agriculture is one of the leading causes of antimicrobial resistance, this practice has come under scrutiny and regulatory control in many developed countries.

4.4 Changing diets

Main points

- The increased global demand for animal protein is leading to changes in how we produce food and our proximity and relationship to domesticated animals and wildlife, thus increasing our exposure to zoonotic disease.
- Nutritional status is a critical determinant of vulnerability to infectious disease as chronically undernourished individuals often have reduced immune responses, and obesity and associated underlying conditions may increase a person's risk for severe disease and death from COVID-19.
- Animal source foods have the largest environmental impact including deforestation and land-use change from the expansion of agriculture.
- Any reduction in consumption of animal source foods should not be done at the expense of increasing the risk of undernutrition among the most vulnerable.

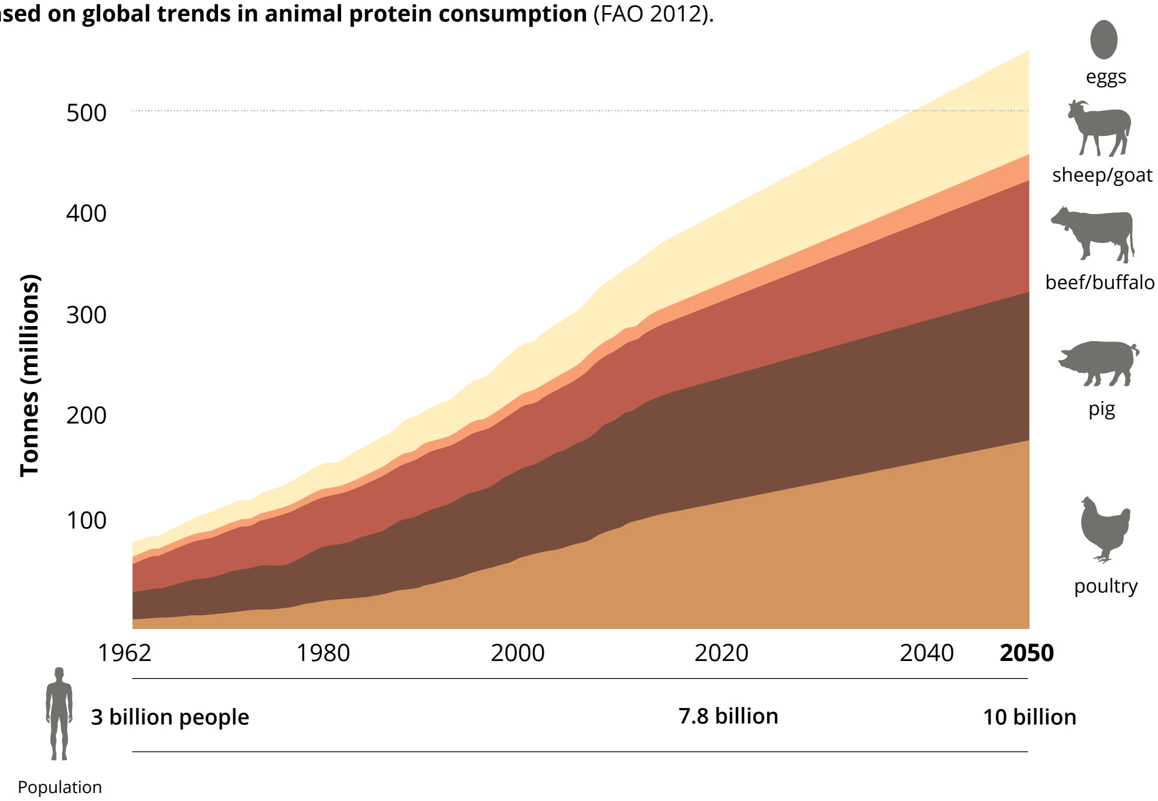

© WWF / Simon Rawles

The growing risk from zoonotic EIDs and the need to sustainably feed the global population represent two of the most formidable ecological and public health challenges of the 21st century, and they interact in complex ways (Godfray et al. 2010; Foley et al. 2011; Rohr et al. 2019). For example, approximately 820 million people are chronically undernourished, and millions suffer from micronutrient deficiencies. Nutritional status can be a critical determinant of vulnerability to infectious disease as chronically undernourished individuals often have reduced immune responses, leading to higher rates of morbidity and mortality from infectious disease. Conversely, obesity rates are soaring with nearly 800 million people considered obese and 40 million children under the age of five considered overweight. Obesity, and associated underlying conditions such as cardiovascular disease, can also increase vulnerability to infectious disease, and these conditions have been found to increase a person's risk for severe disease and death from COVID-19 (Jordan et al. 2020).

The specific diet and consumption patterns driving rising obesity and associated non-communicable diseases is mainly driven by an underconsumption of more healthy foods such as nuts, fruits, vegetables, and legumes; an over-consumption of less healthy foods, including diets increasingly dominated by refined grains, added sugars, and highly processed foods; and more often choosing protein foods that come from animals than plants (Willett et al. 2019). At the same time, animal source foods have the largest environmental impact including deforestation and land use from expansion of agriculture (Tilman and Clark 2014; Clark et al. 2019).

Currently, consumption of animal source foods is rapidly increasing, with rising incomes and urbanization driving a global dietary transition in which traditional diets are being replaced by diets higher in animal source foods (Tilman and Clark 2014). Since 1961, global meat production has more than quadrupled (Figure 4.3) and with the global population expected to increase to nearly 10 billion people by 2050 and 11 billion by 2100, we are creating the ideal conditions that could give rise to additional global pandemics. Given this and the urgency to reduce environmental impacts of the food system, consumption of animal source foods, especially red meat, should be reduced where it is high. However, small to moderate amounts of unprocessed red meat and other non-red meat animal source foods are an important source of nutrients for some populations and their reduction should not be done at the expense of increasing the risk of undernutrition among the most vulnerable (GAIN 2020).

Figure 4.3 Global meat production from 1962 until today and estimated production to 2050 based on global trends in animal protein consumption (FAO 2012).



Increasing demand for animal protein is a leading risk factor associated with the emergence of zoonotic disease (FAO 2004). This increased demand for animal protein is changing how we produce food and our proximity and relationship to domesticated animals and wildlife, thus increasing our exposure to potential zoonotic EIDs. Several recent zoonotic disease outbreaks have come from either permanent live animal markets (e.g., COVID-19, SARS; Woo, Lau, and Yuen 2006), concentrated animal feeding operations (e.g., H5N1 – avian influenza, H1N1 – swine flu; Graham et al. 2008), or from consumption of wild meat (e.g., HIV, Ebola). Given that around 70% of EIDs, and almost all recent pandemics, originate from animals and have potential to cause widespread morbidity and mortality, disruption to trade and travel, and devastating economic impacts, there is a growing call to reevaluate how animal source food is produced. This includes accounting for pandemic risk in sustainable development (Di Marco et al. 2020), closing unregulated and illegal live animal markets, regulating the transport, processing, sale, and consumption of risky species, and taking decisive action to ensure that enough animal protein to meet global needs is produced in ways that prevent the emergence of zoonotic disease and no longer contribute to the increasing risks associated with antimicrobial resistance.

4.5 Governance

Main points

- Command-and-control or market-based land-use governance rarely, if ever, considers zoonoses.
- Permanent live animal markets and wild animal trade are long-established, government-supported economic endeavors.
- Governance of markets may involve banning certain species, improved regulation, and market closures of various durations. While all three have been shown to be effective locally while enforced, they can also drive the sale of wild animals to the black market.
- Trust in government and institutions can be a critical determinant of the spread of zoonotic EIDs.

Here we look at how the governance of land-use change, and animal trade enable or hinder zoonotic EIDs. We then explore some of the specific governance and market feedbacks that occur post-emergence that enable spread, with potential cascading impacts for conservation. We conclude the section by looking back at how governance and management systems have adapted to past disease outbreaks.

4.5.1 The governance of emergence

4.5.1.1 The governance of land-use change

As emphasized in 4.1, land-use change is a direct driver that increases the risk from zoonotic EIDs. Land-use change is influenced by several regulatory and policy frameworks and institutional arrangements, as well as customary norms that prevail in areas controlled by local communities.

Governance for land use can either comprise command-and-control and/or market-based and demand-led approaches (Lambin et al. 2014). Command-and-control governance includes establishment of protected areas, issuance of concessions, deployment of infrastructure, and regulations encouraging deforestation for the purposes of establishing land tenure. Focusing specifically on land tenure, a meta-analysis investigating 118 cases linking forest change with land tenure found that land tenure security was positively associated with less deforestation, regardless of the form of tenure (Robinson et al. 2014). Market-based or demand-led governance approaches include instruments such as certification systems—community roundtables that are designed to supplement formal governance of land use. A recent review by Lambin et al. (2014) examined the effectiveness of such instruments, and how they interact with formal, public systems of land-use governance. The review found that while hybrid approaches that weave together market-based, demand-led, and public governance can provide benefits, public systems of land-use governance have an essential and irreplaceable role to play in governing land use. The review also found that hybrid interventions must be designed with close attention to possible interactions during different stages of regulatory processes (e.g., agenda setting and negotiation, implementation, monitoring and evaluation; Lambin et al. 2014) to ensure hybrid approaches enhance, and not undermine one another.

Despite the public health implications of land-use change in tropical forests, governments rarely evaluate the health implications of their land-use decisions, and nature conservation is rarely valued for its public health benefits (Farnese 2014). Policy decisions regarding land use are often disconnected from environmental protection and human health, and there is a lack of coordination between policy makers that would mandate or facilitate the consideration of public health impacts in land-use planning (Karjalainen et al. 2010).

4.5.1.2 The governance of animal trade

Past disease outbreaks have led to taxa-specific live animal trade bans, such as China's strict ban on the consumption and farming of wild animals in February 2020, the 2004 ban on selling civet in China's Guangdong province (Cheng et al. 2007), and Hong Kong's ban on aquatic birds (Webster 2004). Market closures, such as China's closure of live bird markets following the avian flu in 2013 (Li et al. 2018), are another governance action. These market closures can take many forms, including permanent closure, long- and short- term closure, and recursive closures in which markets are closed for a number of days in a given period (e.g., weekly, biweekly, monthly). Each of these methods has been implemented in Chinese live bird markets since 2013. Wang et al. (2020) analyzed each method and found that permanent closure led to the greatest reduction in human avian flu infection. Bans of taxa in live animal markets can be effective (Leung et al. 2012), but doubts about the efficacy of narrow bans frequently cite their likelihood of increasing illegal trade (Cooney & Jepson 2006; Nguyen et al. 2017).

Although it might seem appropriate from a conservation perspective to distinguish between domestic animal markets and live animal markets, the line between these markets is blurred by the existence of wildlife farms where non-domesticated animals like peacocks, civets, and porcupines are raised for food, pets, medicine, and research and by the co-mingling of wild and domestic animals in the permanent live animal markets in Asia and Africa. Wildlife farms have been supported by the Chinese government since the 1960s (Greer & Doughty 1976). A government-sponsored report by the Chinese Academy of Engineering (2017) values the farmed wildlife industry at US$74 billion, and it employs more than 14 million people. This industry includes animals for food (US$18 billion), fur (US$56 billion), medicine (US$714 million), pets (US$93 million), and research (US$57 million). Although there have been calls for the closing of all permanent live animal markets (e.g., Forgery 2020), the banning of all wildlife trade (e.g., the 200 conservation organizations who have signed an open letter; Lion Coalition 2020) or the banning of permanent live animal markets that sell wildlife for human consumption (e.g., the acting director of the CBD quoted in Greenfield 2020), others have pointed to these other markets as evidence that addressing wildlife trade in permanent live animal markets, is only a small part of the challenge (Wang et al. 2020).

4.5.1.3 The social consequences of governing 'emergence'

The policies and politics that govern animal markets and land-use change inevitably have mixed implications for different groups of people. With a number of zoonoses perceived to have emerged from China, it's important to consider the broader social, economic, and political systems within which permanent live animal markets are embedded.

Scholarship on the dynamic and changing nature of China's food system shows the complex top-down and bottom-up forces that shape and politicize the Chinese food system (Si & Scott 2019) and have cascading implications for social equity and food security. For example, a study from Nanjing, China shows that permanent live animal markets are still the dominant source for purchasing fresh produce and meat (Si et al. 2019). Other studies show the importance of permanent live animal markets for social cohesion (Mele et al. 2015) and the broad appeal to consumers given the accessibility of these markets, the freshness of goods, and capacity for bargaining, compared with modern retail shops (Maruyama et al. 2016). And several case examples demonstrate the structural inequities that underlie China's evolving food system (Fearnley 2015; Huang 2019). In one case, an anthropologist found that two factors drove many farmers into the breeding of wild geese during the late 1990s. One factor was the opportunity to meet consumer demand without illegal poaching of animals, and the other was a path toward higher-value production at a time when rural smallholder farmers faced increasing economic pressure from industrial food producers (Fearnley 2015). As a result, any reactive policies against markets and trade could have cascading impacts on more vulnerable small-scale farmers with implications for local food security.

4.5.2 Governance post-emergence

After the initial spillover of a virus to humans in a market, farm, or forest, the actions taken during the subsequent days and weeks affect whether a zoonotic disease is controlled or becomes an epidemic with pandemic potential. These actions can have cascading impacts across all dimensions of society, both in the short and long term. Here we examine evidence from the past on how different dimensions of governance and the global economy enabled or hindered the spread of disease post-emergence, and the relevance of these indirect drivers for conservation.

4.5.2.1 The cascading impacts of transparency and trust in institutions

Transparency is often touted as critical for ensuring that broad-scale governance is effective in the aftermath of disease emergence, yet is widely recognized as difficult to measure (O'Malley et al. 2009). Looking back, some have argued that since the time of SARS in 2003, governments have greatly improved the transparency of information during the initial stages around outbreaks. For example, during SARS, there was a five-month delay in communication from the time of the initial case identification and the Chinese government's admission of a serious outbreak (Huang 2004). It took less than a month for the Chinese government to announce the COVID-19 outbreak (Huang et al. 2020). Subsequently, governments responded immediately to the news, while others took considerably longer.

Lack of transparency is one of many factors that can influence the general public's trust in institutions during periods of crises and uncertainty. Evidence of institutional failures and the associated feedback generated with behavioral responses to these failures during past epidemics demonstrate the fragility of our global governance systems and their limited capacity to both manage pandemics and safeguard public health. The spread of Ebola was accelerated by poor decision-making within government institutions (Gulland 2015) and research post-Ebola shows that Liberians who distrusted government took fewer precautions against Ebola and were also less compliant with Ebola control (Blair et al., 2017). In fact, authoritarian-imposed measures (e.g., the centralized 21-day isolation of asymptomatic people who were in contact with positive Ebola cases) hindered the control of transmission by undermining socially acceptable, locally driven quarantine measures (Pellecchia 2017). The data from today's outbreak in the United States shows a range of mixed reactions and responses to state and federal government attempts to implement quarantine measures (see emerging data from Google 2020).

© Ola Jennersten / WWF-Sweden

The actions that governments take in the days and weeks post-emergence can have lasting implications on the level of trust people have in the government institutions tasked with governing societies and safeguarding well-being. Decades of social science literature highlight the critical role that trust in institutions play for successful governing of natural resources (Ostrom 1990; Turner et al. 2016). The possible cascading impacts on the relationships between communities and governments where co-management is critical for conservation outcomes is important to note.

4.5.2.2 Complex feedbacks in trade and finance

The very nature of our global market connectedness erodes our defense against disease transmission and spread. Our global economy in which people and goods circulate with ease simultaneously generates new avenues for pathogens to do the same (Elbe 2010). For example, during the SARS outbreak, countries with close economic and cultural ties to China, such as Hong Kong and Taiwan, traced the origin of local SARS outbreaks to intra-region travel and business (Chen et al. 2005). The decision to delay sharing information about the risks and spread of the disease during SARS has also been traced back to concerns regarding the economic fallout from the disease (Knobler 2004).

Finance also plays a significant role in our capacity to contain diseases once they have spread. Lack of appropriate financial capacity to address initial emergence accelerates the initial spread and lives lost. In the case of the 2014 Ebola outbreak, WHO's failure to act quickly after the initial patient was diagnosed by declaring a 'Public Health Emergency of International Concern' was motivated by fear of the economic and political ramifications. This, in turn, contributed to the outbreak spreading rapidly without the necessary international support and resources needed to control the spread of the disease. Lessons from this outbreak demonstrate the importance of a global health fund to properly resource future disease outbreaks to slow the spread (Gostin & Friedman 2015).

The intertwined nature of disease spread, markets, and finance demonstrate the rapid feedbacks that spiral out of control in periods of rapid and uncertain change. Our overly connected economies that magnify disease risk can result in financial burdens that not only feedback to harm economies but could also pose great risk through cascading budget cuts to the conservation community's capacity to carry out its necessary work, both within government agencies and civil society organizations. How this plays out in specific countries will inevitably vary.

4.6 Climate change

Main points

- Strong scientific evidence suggests that climate change will increase the incidence of many existing endemic zoonotic diseases by expanding their geographic ranges.
- Climate change is already increasing the spread of some endemic vector-borne zoonotic diseases, including Lyme disease, malaria, and dengue fever.
- Climate change does not readily influence the emergence of novel zoonotic EIDs like COVID-19.
- In some places where the climate becomes too hot or dry for hosts or vectors, existing infectious diseases may decline.
- It is possible that zoonotic EIDs involving novel pathogens will increase with climate change, but the existing scientific evidence is more limited.

There is strong scientific evidence that climate change will make the incidence of many existing endemic zoonotic diseases worse by increasing their geographic ranges (Mills et al. 2010; Gortazar et al. 2014; Turner et al. 2016). Climate change is already increasing the spread of some endemic vector-borne zoonotic diseases, including Lyme disease, malaria, and dengue fever (Kilpatrick & Randolph 2012; Harvard C-CHANGE 2020). At the same time, in some places where the climate becomes too hot or dry, existing infectious diseases may decline. It is possible that novel zoonotic EIDs will increase with climate change, but the existing scientific evidence is more limited.


© James Frankham / WWF

4.6.1 Climate change and COVID-19

In the short term, there is no direct evidence that climate change is currently impacting the spread or transmission of COVID-19 (Harvard C-CHANGE 2020). However, the COVID-19 pandemic is having several near-term indirect impacts on the drivers of climate change and societal response to it. First, as of April 1, the 2020 COP in Glasgow has been delayed to 2021 ("COP26 Postponed | UNFCCC" 2020). COVID-19-related impacts on governments may delay their ability or decrease their ambition in delivering updated nationally determined commitments (Farand 2020). Second, current stay-at-home and quarantine mandates have significantly decreased greenhouse gas emissions in the short term (Ambrose 2020; Evans 2020; Harvey 2020). While this short-term drop in emissions has produced cleaner air and media attention, the shutting down of the global economy hardly represents an appropriate long-term climate solution. While overall emissions are down in some locations and sectors, quarantine measures may increase emissions where individuals use more home-based energy and order more deliveries (Harvey 2020). At the same time, some lessons learned from COVID-19-related cancellations may yield insights for some behavioral changes that contribute to climate change mitigation, such as limiting unnecessary travel (Harvey 2020).

In the long term, there is no direct evidence that climate change will influence the spread of COVID-19, but there are several considerations specifically related to opportunities and challenges for climate change related to COVID-19. First, there are some opportunities for learning from the COVID-19 pandemic which could be applied to climate change policy. Many articles have highlighted that the global cooperation marshalled to limit the spread of COVID-19 provides insights that can be applied toward efforts to reduce greenhouse gas emissions. While these insights may be useful for guiding long-term policy and strategy, they should not be emphasized while countries are still dealing with the immediate challenge of the pandemic.

© Sean Rayford / Stringer / Getty Images

4.6.2 Climate change and infectious diseases

This section focuses on climate change impacts on zoonotic EIDs, and does not summarize the extensive evidence on how warming will increase death from heat strokes, undernutrition, malnutrition, or other health-related impacts (IPCC 2018b).

4.6.2.1 Climate change and endemic infectious diseases

Overall, higher temperatures will increase infectious disease transmission in some locations and decrease infectious disease transmission in other places. The variability depends on the disease, the region of interest, and the degree of warming (Mills et al. 2010; Gortazar et al. 2014; IPCC 2018b).

Climate change is already increasing the spread of some endemic vector-borne zoonotic diseases, including Lyme disease, malaria, and dengue fever (Kilpatrick & Randolph 2012; Harvard C-CHANGE 2020). Even under a 1.5°C warming scenario, deaths from malaria may increase by 60,000 by 2030 (World Health Organization 2014; IPCC 2018b). Risks are likely to increase further with 2°C warming, and would further expand the geographic ranges of malaria and other infectious diseases (Ebi et al. 2018; IPCC 2018b). Increased prevalence is also expected for dengue fever and chikungunya based on expanded geographic ranges, though in some places the current climate may become too hot or dry for the vector mosquito to survive (Ebi et al. 2018). In the United States, there is some evidence of climate change-related expansion of Rift Valley fever and West Nile virus (McCormick 2016). Further, extreme weather events associated with climate change, such as heavy rains and drought, can have indirect impacts on disease emergence. Outbreaks of Rift Valley fever, endemic in many parts of Africa, often occur following periods of heavy rainfall. It is postulated that these outbreaks are sequelae to improved conditions for mosquito breeding.

4.6.2.2 Climate change and novel zoonotic EIDs

As human and wildlife populations migrate to adapt to climate change, and as climate can impact where diseases occur, an increase in zoonotic EIDs is expected (Altizer et al. 2013; Barry 2019; Harvard C-CHANGE 2020). Data on the link between climate change and novel zoonotic EIDs are fewer than the relatively stronger data that describe the links between between between climate change and novel zoonotic EIDs (Semenza & Menne 2009), and debate has been ongoing in the scientific literature on the extent to which climate change will increase the risk of novel zoonotic EIDs (Rohr et al. 2011; Kilpatrick & Randolph 2012; Altizer et al. 2013). There are many complex interactions to follow, such as evidence that bats can increase virus shedding under food shortage conditions linked to climate change (Bannerjee et al. 2020).

As climate change causes melting in northern latitudes, there is the potential for the re-emergence of some viruses that have been buried in permafrost (McKenna 2017). In addition, people in northern latitudes near melting permafrost are also likely to face increased exposure to existing infectious diseases due to climate change (Parkinson et al. 2014). However, the likelihood that such viruses would transmit widely enough to significantly impact human health is thought to be low (Yong 2014).

4.7 Interactions and feedbacks between drivers

Main points

- The relative importance of the direct and indirect drivers varies tremendously in different geographic contexts.
- Biodiversity, wild meat consumption, roads, malnutrition, fragmentation, conflict, and climate change can act together (synergistically or antagonistically) to either have positive impacts on both exposure and vulnerability, or positive impacts on one and negative impacts on the other.
- It is critical to look for win-wins for nature and people by curbing potential transmission pathways while also maintaining beneficial interactions between humans, nature, food, and climate.


© Greg Armfield / WWF-UK

4.7.1 Complexity

The complex processes that give rise to EIDs, especially those associated with wildlife-related zoonoses, makes it difficult to predict and manage. In this section, we briefly explore some of the issues associated with this complexity, dive deeper into the conceptual model outlined in Section 3, and discuss specifically how drivers may interact and the types of feedbacks that should be considered before interventions are designed and implemented.

The science of how drivers interact is woefully incomplete. In complex systems, with multiple drivers and poorly known causal mechanisms, interpreting the evidence to act decisively can be especially daunting. It is easy to mistake correlation for causality, and it may appear that one driver has primary responsibility for a zoonotic EID, when in fact, it is a related, but unmeasured driver that is causally responsible. Also, it can be extremely difficult to find statistically significant evidence of a link between drivers and the emergence of zoonoses, especially when a single driver (e.g., biodiversity) affects multiple pathways. It could simply be that the complex relationship requires so much data to analyze that we cannot determine statistically if there is a positive relationship. It is also possible that simple analyses show one result (e.g., biodiversity on net increases the emergence of zoonotic disease outbreaks), while a more multidimensional, multi-pathway analysis would reveal both positive and negative relationships, depending upon the pathway and compounding factors and underlying conditions. Lastly, all of the above are made more difficult if the drivers we are examining are secondary and tertiary in their relationship to the outcome of interest.


© Paul Weinberg / WWF

As mentioned throughout this science brief, some drivers seem to have antagonistic effects on the likelihood of disease emergence (e.g., the consumption of wild meat has been shown to both increase the chance of zoonotic EIDs through increased exposure while also increasing food security which could potentially reduce vulnerability; Friant et al. 2020). Other drivers may have synergistic impacts, both increasing exposure and vulnerability (e.g., new roads in forested areas can increase exposure and also increase ecosystem vulnerability). Recognizing these dual pathways of impact is important in order to maintain benefits while managing risks (Table 4.1). The dual pathways also show how some human communities that are not normally considered the frontlines of zoonotic EID, may become so if we don't pay attention. For instance, fishing dependent communities may depend on wild meat for a diversified food portfolio (Teh et al. 2016) and will turn to wild meat in times when access to fish is limited (Mildenstein et al. 2016). As a result, a failure to protect access to sustainable and productive coastal or freshwater fisheries could lead to EID outbreaks (or conversely, community conservation initiatives could decrease such risks).

Table 4.1 Drivers that may affect both exposure and vulnerability ('+' indicates increased exposure or vulnerability, '-' diminishes exposure or vulnerability.)

Driver	Exposure Impact	Vulnerability Impact
biodiversity	+ provides more types of virus that can become zoonotic	− by increasing ecological integrity that buffers against epidemics
wild meat consumption	+ by increasing contact with wild animals	− by increasing food security
roads	+ by increasing contact with wild animals	+ by increasing forest fragmentation
malnutrition	+ leading to more agricultural clearing and reliance on wild meat	+ by increasing susceptibility to disease
fragmentation	+ increasing contact	+ reducing forest health
conflict	− by discouraging hunting due to increased danger	+ by increasing social vulnerability − by reducing ecological impacts from hunting
climate change	+ by changing ranges wildlife and people	+ by increasing other types of disease

+ indicates increased exposure or vulnerability − diminishes exposure or vulnerability

4.7.2 Feedbacks

The same pathways that allow for the provision of nature's benefits to people can also result in negative outcomes. A failure to properly manage human-nature interactions, unconstrained human activities that lead to nature degradation, and climate change can all lead to negative impacts on the provisioning of ecosystem services and a simultaneous increase in the likelihood of zoonotic EIDs. Forest degradation and shifts in land use can lead to climate change, which can in turn lead to more land-use change and range shifts in people and animals, thus leading to a higher likelihood of EIDs.

While it is difficult to identify all possible feedbacks, positive and negative feedbacks as well as co-benefits and co-costs of any management or policy action need to be carefully thought through and modeled, even if only conceptually. In our rush to curb potential transmission pathways we should take care not to diminish the flow of beneficial interactions between humans, nature, food, and climate.

© Luis Barreto / WWF-UK

Section 5. What the future holds: scenarios for human health and conservation

Main points

- The history of societal responses to zoonotic disease outbreaks vary. There is some evidence of substantial, positive learning post-outbreak, while other evidence indicates our tendency to repeat past mistakes.
- Outside of market-focused bans, there has been little change of conservation practices in the wake of zoonotic EID outbreaks to help prevent them.
- Future scenarios help illustrate radically different potential futures, and based on the evidence in this science brief, explore how the relationships between zoonotic diseases, human health, and conservation play out over time.
- There is an opportunity for transformative change, recognizing that periods of great uncertainty often offer windows of opportunity to radically transform the system behaviors, structures, and underlying norms and values that govern our global society.

© Luis Barreto / WWF-UK

5.1 Learning from the past

Looking at how governments and societies have responded to past zoonotic disease outbreaks offers a window into what the future could look like. There are some promising examples where governance systems have learned and adapted. For example, the elevation of public health as an area of critical concern for international relations was a significant shift post-SARS (Fidler 2004). More recently, the Union of Concerned Scientists (2013) argued that the rapid integration of cutting-edge science and communications helped stop Ebola from becoming a global pandemic. And in some countries, such as China, capacity to deal with emerging epidemics is argued to have improved (Wei et al. 2016). At the same time, mistakes continue to be repeated. Governmental responses to avian influenza show that swift action only came once the disease spread was already out of control (Scoones 2010).

Conservation responses after zoonotic EID outbreaks are similarly mixed. Based on past epidemics, we can expect additional bans on live wildlife animal and wildlife meat sales in food markets, accompanied by the need for greater enforcement on black markets. Despite the urgent need for more systemic approaches to address pandemics (including tactics to integrate interdisciplinary knowledge on disease spread and to facilitate solution co-production and coordination between sectors; Bardosh et al. 2017), outside of market-focused bans, there has been very little alteration of conservation practices in the wake of zoonotic EID outbreaks to help prevent them.

5.2 What could the future hold?

We cannot predict future pandemics. One way of gaining insight into the future, however, is forecasting. There are well-developed methods for doing this which involve gathering data on current conditions, identifying the variables that shape the future, and rigorously modeling them as mathematical variables. However, this approach is not adequate for a long-range future in a complex system (Raskin 2005). Scenario analysis provides an alternative way of examining the various pathways leading to informed decisions.

Scenario planning frames and re-frames possible futures to help encourage creative thinking about how the future may unfold. Many global scenarios used to understand societal change converged around four distinct types—futures shaped predominately by market forces, policy reform, isolationism, and sustainability. Each type differs in how it describes change in social, technological, economic, environmental, and political drivers (Hunt et al. 2012).

Here we use these four scenarios to explore what a post-COVID-19 world could look like in which zoonotic EIDs, conservation, and human health increasingly interact. Based on our understanding of the past, we present four possible futures, (Raskin 2005; Kubiszewski et al. 2017) designed to explore how the specific interactions between people, nature, and zoonotic diseases could play out.

5.2.1 Market forces

The market forces (MF) scenario is characterized by a market-driven world that is similar to the current state. In a post-COVID-19 world, we imagine demographic, economic, environmental, and technological trends snapping back to 'business-as-usual' and proceeding without reacting to unfolding trends. Equity issues continue to grow, with clear income disparity both between and within countries. While the poorer regions of the world grow rapidly, the disparity between the rich and poor continues to widen. Populations continue to grow, leading to high demand for food and natural resources, with wild meat holding its place as a critical source of food security for many of the world's poorest. There is little regard for climate action and land conversion continues unabated, providing fertile breeding ground for zoonotic EID events. Social and environmental concerns are secondary. There is belief that competitive markets lead to self-correction (e.g., high demand for food results in higher prices which then controls consumption). With inadequate focus on social and environmental concerns and a rapid push for development, both exposure and vulnerability of the society to zoonotic diseases is increased and the economic development fails to tackle it.


© Shutterstock.com

5.2.2 Policy reform

The policy reform (PR) scenario makes small incremental changes to MF, moving control from corporations to governments. PR envisions a policy-enabled sustainable future, then works backwards building steps to achieve it. In a post-COVID-19 world, we might imagine leaders recognizing the interconnections between human health, the economy, and the natural world. There is political will, governments cooperate, and intergovernmental bodies like the United Nations are empowered to bend the curve of development towards sustainability targets. PR balances environmental sustainability and human development, and we can imagine in such a world, governments learn from past mistakes and unify to develop global response systems to zoonotic pandemics. Yet with uncertain evidence on the relationships between human health, conservation, economic development, and other priority national issues like security, the efficacy of the policy decisions that flow from such a unified response will remain unclear. How governments navigate trade-offs between economic development, and global and human health remain to be seen. In such a world, we may see an increase in trust in institutions as they achieve joint society goals, but that could come at the cost of meaningful collective action. And finally, the pace of social and technological changes needed to achieve this balance and the political will needed to move from the market forces to an effective policy reform present big challenges for PR.

5.2.3 Isolationism

The isolationism scenario reflects power devolved to small groups isolated from the rest of humanity and the environment. In a post-COVID-19 world, following failures by governments worldwide, we may continue to see globally relevant problems that are increasingly unmanaged, resulting in chaos. The self-correcting assumption of the market forces fails to address the environmental and socio-economic tensions leading to even more crises. Powerful actors use their influence to exploit nature to provide for themselves while others are left vulnerable. In such a future, there is no governing body to make sense of the interactions between human health and the environment, which increases the likelihood of disease emergence and spread. With increasing isolation, the levels of travel and trade reduce, which leads to disease emergence becoming more localized, impacting some countries more than others. Problems like resource scarcity, hunger, and recession are so deep that the structures of the market forces can no longer suffice. Social vulnerability is at its highest, yet opportunities for collective action open.

5.2.4 Sustainability

The sustainability scenario describes a values-led shift toward management by civil society and engaged citizens. In such a future, society comes out of this crisis with a deep recognition of what truly matters, feeling more and more connected to the natural world. A new development paradigm emerges, emphasizes the quality of life and material sufficiency, human solidarity, and global equity. Resource use is controlled by a quest for deeper happiness, health, and fulfillment. Governance influences all levels from global to local and corporations adopt social responsibilities to benefit society. Efforts like those that focus on the health of local communities around conservation areas speak to this scenario, where the power to effect change occurs at multiple levels (Naidoo et al. 2019). In this sustainable future, we can imagine efforts by civil society and governments to limit the risk from zoonotic disease outbreaks will be well connected to issues such as equity and food security, and that change will be negotiated fairly across geographies and spatial scales.

© WWF / Yunaidi Joepoet

Table 5.1 Trajectories of future change under four scenarios. Table 5.1 looks at 13 attributes and how they might change under the four possible global futures. Note these are hypothesized changes based on the limited evidence compiled in this science report, shown here to spark creative thinking, not predict the future. Future efforts should draw on evidence to better project possible trajectories of future change.

Broad drivers/ outcomes	Specific components	Market forces	Policy reform	Isolationism	Sustainability
Conservation	• Unified response to climate change	↓	↑	↓	↑
	• Levels of forest fragmentation and degradation, and deforestation	↑	↓	↑	↓
	• Security of biodiversity	↓	→	↓	↑
Economic development	• Intensification of agriculture	↑	→	→	→
	• Open wildlife markets	↑	↓	↑	↓
	• Economically-oriented Infrastructure development	↑	↓	↑	↓
Markets and finance	• Strength of global trade and travel	↑	→	↓	→
	• Financial capacity for EID response	↑	↑	↓	↑
	• Trust in institutions	→	↑	↓	↑
Human behavior, social well-being, and equity	• Social equity	↓	↑	↓	↑
	• Food security	↑	→	↓	↑
	• Consumer demand for animal protein	↑	→	↑	↓
	• Collective action	↑	↓	↑	→

5.3 Navigating to a sustainable future: opportunities for transformative change

The above scenarios show that many possible futures lie ahead. The opportunity for transformative change during windows of opportunity, be they large-scale disasters, crises, or longer periods of societal change, is a concept well-developed across different research and practice disciplines (e.g., Westley et al. 2013). Navigating these windows of opportunity in ways that initiate and sustain positive change for both people and nature is critical.

Transformational change manifests in three distinct ways that are often mutually reinforcing—change that involves underlying structural shifts (e.g., shifts in our economic system), change in the dynamics of systems with clearly defined boundaries, or change that is enabled through bottom-up agency (Scoones et al. 2020). Already we can see traces of these changes occurring from the COVID-19 pandemic. For example, there are many examples of collective action and innovation that are emerging and helping people cope during COVID-19 (e.g., StartUp Blink 2020).

Zoonotic EIDs like COVID-19 have much in common with issues we care about in conservation. For example, zoonotic EIDs and climate change are both phenomena with local origins with dominant economic development models as root causes, leading to global impacts that cascade back down to local effects on economies, livelihoods, and human well-being. While there are important differences, there are nevertheless lessons for governance, communication, global action, and complex causal relations from the world's response to pandemics, such as COVID-19, that are valuable for the way we deal with climate change.

The three types of transformative change help us make better sense of the changes already happening, the future outcomes that may arise as a result (Section 5.2), and make informed decisions about leverage points in which conservation interventions can help us navigate towards a safe and just future.

© Shutterstock.com

Section 6. Effective interventions

Main points

- We can identify leverage points to reduce our exposure and vulnerability to zoonotic EIDs in both the near and long term.
- There are seven potential leverage points for conservation organizations, including:
    1. reducing the potential for viral transmission and amplification through regulation of interaction between humans and animals associated with permanent live animal markets, particularly high-risk wildlife taxa,
    2. reducing consumption of taxa with high risk for transmitting zoonotic disease,
    3. strengthening early warning systems for zoonotic EIDs,
    4. re-engineering production systems and supply chains to minimize exposure,
    5. strengthening public trust in institutions to minimize vulnerability to zoonotic EIDs,
    6. fostering transparency and evidence-informed policy as part of a cross-sectoral coalition that enables systemic change, and
    7. re-examining major conservation interventions with a zoonotic EID lens.
- There are substantive risks of perverse outcomes for people, nature, and climate from the rapid implementation of poorly designed interventions intended to address the link between zoonotic EIDs and biodiversity conservation. Evidence-informed strategy design could help mitigate many of these risks.

6.1 Context

In this chapter, we identify potential leverage points for addressing the risks of zoonotic EIDs in ways that have positive impacts on people, nature, and climate, based on the drivers of zoonotic disease emergence and their transmission pathways in the context of complex human-natural systems. Drawing on the ideas in the sustainability scenario (Section 5), we identify interventions at each leverage point that can operate across multiple scales and allow for the emergence of local solutions. Some of these interventions are viable in the near-term, others reflect long-term, system-wide change. Where possible, we identify one or more specific interventions that could effectively influence these leverage points, but this is not intended to be exhaustive.

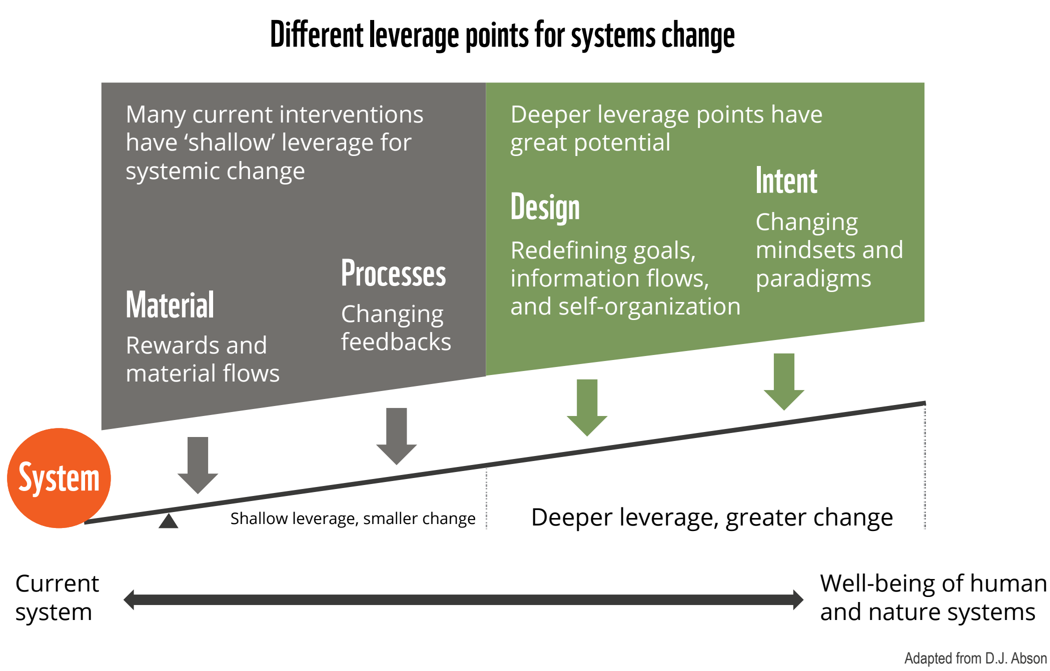
Any intervention will generate 'winners' and 'losers' (Gill et al. 2019). Many will have the potential to create synergies and trade-offs with other interventions. Where possible, we identify these winners and losers, with particular attention to where an intervention reinforces pre-existing structural inequalities (i.e., where already vulnerable or marginalized groups lose as a result of the intervention; Gupta et al. 2020). Finally, we discuss the unintended impacts and potential perverse outcomes for people and nature that may arise from poorly designed interventions.

6.2 Leverage points: where to intervene in the system

Leverage points are places in complex systems where small shifts have the potential to bring about fundamental changes to the system as a whole (Meadows 2008; Abson et al. 2017). Meadows (1999) identified a hierarchy of potential leverage points. They range from 'shallow', where interventions are easy to implement but unlikely to affect the overall functioning of the system to 'deep', which are harder to alter but more likely to create large-scale change (Figure 6.1). Here, we provide an evidence-informed assessment of the interventions, or levers that are likely and unlikely to work at each leverage point, and which might have unintended consequences.

Drawing on our conceptual framework (Figure 3.1), we focus on conservation leverage points that have potential to either (a) disrupt pre-emergence transmission pathways between potential zoonotic pathogens and humans, or (b) lengthen the post-emergence time available to implement effective epidemic control measures (i.e., the critical response time; Muzemil et al. 2015). We classify these leverage points by whether they act to reduce exposure to zoonoses (i.e., the likelihood of contact) or limit vulnerability to those zoonoses (i.e., the likelihood of harm, given exposure; Hosseini et al. 2017).

Figure 6.1 A hierarchy of leverage points, and the system characteristics they influence (Fischer and Riechers 2019).



Different transmission pathways, different solutions

Since 1940, more than 200 EID events have been recorded, with 72% of these events emerging from wildlife. The transmission pathways of these zoonoses differ markedly (Figure 2.1; Salkeld et al. 2013), even for those with shared evolutionary origins (e.g., coronaviruses; Anthony et al. 2017). Transmission pathways are the product of complex, context-specific interactions between the pathogen, host species, and the presence of disease vectors (Salkeld et al. 2013; Faust et al. 2017), mediated by the broader environment (Allen et al. 2017; Faust et al. 2017). Regional differences in coronavirus diversity, for example, have been detected in bats, the evolutionary reservoirs of coronaviruses. In Latin America and Africa, bats in permanent live animal markets and restaurants were more likely to test positive for coronaviruses than those in other environments (Anthony et al. 2017). In contrast, bats in South Asia were more likely to test positive for coronavirus in and around human dwellings, suggesting important regional differences in transmission pathways are likely to exist (Anthony et al. 2017).

Highly variable transmission pathways overlaid on very different social-ecological systems suggests that there may be few universally applicable leverage points, where targeted interventions can deliver positive impacts for people and nature.

Consequently, we focus on identifying seven leverage points, each with multiple targeted interventions aimed at disrupting emergence of zoonoses (e.g., SARS-COV2) with similar transmission pathways (Table 2.1). The seven key leverage points (and the number of interventions per leverage point) explored in detail in Appendix C are:

1. limit potential for virus amplification and cross-species transmission in permanent live animal markets (3),
2. reduce consumption of taxa with high risk for transmitting zoonotic disease (4),
3. strengthen early warning systems for zoonotic EIDs (3),
4. re-engineer production systems and supply chains,
5. strengthen public trust in institutions (1),
6. foster transparency and evidence-informed policy (1), and
7. re-examine major conservation interventions with a zoonotic EID lens (1).

It is worth noting that many of these leverage points and interventions are relatively 'shallow' (i.e., they are easier to change, but less likely to have long-lasting system-wide changes). There is less direct evidence to support some of the 'deep' leverage points which are harder to change, but they have greater potential to create lasting systems change (as by their nature, they are often hidden). Consequently, we suggest further examination of the deep leverage points (Table 6.1), and further systems analysis to identify other potential deep leverage points.

Table 6.1 Leverage points and potential 'levers' (i.e., interventions) for addressing zoonotic disease risk in the context of nature conservation. ***Disruption of transmission pathway:*** identifies whether a leverage point acts to prevent or reduce the mechanisms that lead to the emergence of zoonotic disease (i.e., pre-emergence) or those that affect its spread (i.e., post-emergence). ***Risk reduction***: identifies how a leverage point acts to overall risk (i.e., the potential source of harm) from a zoonotic EID, by either reducing exposure (i.e., the likelihood of contact between humans and a zoonotic EID or vulnerability (i.e., the likelihood of harm, given exposure; Hosseini et al. 2017). Leverage type: refers to the typology of places to intervene in a system (Section 6).

Leverage point	Disruption of transmission pathway		Risk reduction		Possible 'levers' (Interventions)
	Pre-emergence	Post-emergence	Reduced exposure	Reduced vulnerability	
Limit potential for viral transmission and amplification in permanent live animal markets		✕	✕		Closure of permanent live animal markets
	✕	✕	✕		Removal of high-risk taxa (with legal enforcement)
	✕	✕		✕	Strengthen food safety practices
Reduce consumption of taxa with high risk for transmitting zoonotic disease		✕	✕		Regulate consumption of high-risk taxa, where viable alternatives exist
		✕	✕	✕	Targeted behavior change interventions to address (a) cultural preferences for wild meat in urban environments and (b) high-risk 'food tourism' behaviors
	✕	✕	✕		Regulate legal commercial production and trade of wild meat
		✕	✕		Regulate international trade of wild meat products
Strengthen early warning systems for emerging zoonotic disease	✕	✕	✕	✕	Develop integrated zoonotic disease surveillance systems (that can also inform conservation action)
	✕		✕	✕	Align global incentives for early warning systems
	✕		✕	✕	Examine future zoonotic EID risk given climate and development trajectories
Re-engineer production systems and supply chains	✕	✕	✕		Decrease global demand for animal source foods and optimize agricultural land globally to relieve the pressure on natural ecosystems
Strengthen public trust in institutions	✕			✕	Create arenas for trust building between local leaders and local communities
Foster transparency and evidence-informed policy	✕			✕	Convene conservation actors to discuss role of conservation sector in communicating and addressing disease risk and outbreaks
Re-examine major conservation interventions with a zoonotic EID lens.	✕	✕	✕	✕	Examine theories of change for major conservation interventions based on a mechanistic, transdisciplinary understanding of transmission pathways.

Crucially, there are substantive risks of perverse outcomes for people, nature, and climate from rapid implementation of poorly designed interventions intended to address the link between zoonotic EIDs and biodiversity conservation. These include market closures and regulations creating a hard-to-monitor illegal wild meat trade, the rapid expansion of land conversion for livestock production in regions where wild meat is currently an important source of dietary protein, adverse impacts on the food security of marginalized and vulnerable communities, and the potential alienation of local stakeholders where the links between biodiversity conservation and zoonotic disease are overstated. Evidence-informed strategy design could help mitigate many of these risks.

6.3 Risks and unintended consequences of rushed interventions

In the race to identify leverage points and interventions to prevent the emergence and spread of future zoonotic diseases and swiftly develop appropriate policy responses to the current COVID-19 pandemic, there is a risk of implementing interventions that have unintended impacts on people, nature, and climate. These include unintended negative impacts on food security, public health, the acceleration of land conversion for agriculture, and attempts to control or eradicate species seen as disease vectors by policymakers or the broader public.

Many of these risks stem from (a) the oversimplification of the relationship between nature and zoonotic EIDs (Salkeld et al. 2013; Wood et al. 2014), (b) unfounded assumptions of substitutability of dietary protein sources (Coad et al. 2019), and (c) failure to recognize important variations in zoonotic disease exposure and vulnerability across geographies (Jones et al. 2008; Salkeld et al. 2013; Allen et al. 2017), as well as within and among social groups (Nasi et al. 2011; Salkeld et al. 2013).

In this section, we highlight the potential unintended impacts for people, nature, and climate that could emerge from the interventions being proposed in the scientific literature, by popular media, and civil society organizations.

Risk 1: Legal closure of wildlife animal markets creates new illegal trade
The widespread closure of permanent live animal markets, in the absence of effective enforcement and interventions to address the demand for wild meat is likely to expand the illicit trade in wild meat. Previous regional bans on the sale and consumption of wild meat following Ebola outbreaks were widely ignored, and their legal and evidential basis questioned by local communities (Bonwitt et al. 2018). Given that illegally traded products are harder to monitor, the growth of an illicit wild meat trade may hamper efforts to detect future zoonotic EIDs (Webster 2004). Li et al. (2018) provide evidence that the closure of live bird markets during the early stages of an H7N9 influenza outbreak in China in 2013 expanded the infection to uninfected areas. They point to the risks of sudden changes in movement patterns of live birds after live market closure.

Risk 2: Policy interventions to reduce wild meat consumption lead to rapid agricultural expansion
While consumers of wild meat resist switching to other sources of dietary protein (Coad et al. 2019), particularly during temporary resource shocks (Cawthorn & Hoffman 2015), sustained interventions to promote the consumption of protein from domestic livestock may trigger the rapid expansion of agricultural land. For example, if wild meat consumption was replaced by locally produced beef in the Congo Basin, it is likely that 25 million hectares of land would need to be converted to livestock production (Nasi et al. 2011). Agricultural conversion is a leading driver of nature loss (IPBES 2019), which expands the human-nature interface posing a significant zoonotic EID risk (Allen et al. 2017).

Risk 3: Rapid expansion of livestock production increases exposure to other novel or endemic zoonotic EIDs
Domestic livestock are significant reservoirs of zoonotic pathogens and have been implicated in the transmission of both novel and endemic zoonotic EIDs (Cawthorn & Hoffman 2015; Shah et al. 2019). Interventions designed to reduce the consumption of wild meat, that result in the expansion of livestock production, risk increasing exposure to other novel or endemic zoonotic diseases. A recent synthesis of studies in Southeast Asia concluded that agricultural land uses consistently exacerbate zoonotic disease risk, with agricultural workers 1.74 times more likely to be infected with a zoonotic pathogen than those who work outside the sector (Shah et al. 2019). This effect was particularly pronounced on oil palm and rubber plantations and for non-poultry livestock production (Shah et al. 2019). Consequently, efforts to reduce zoonotic EID risk from the consumption, trading, or processing of wild meat, may simultaneously increase exposure to endemic diseases.

Risk 4: Indiscriminate bans on wild meat trade and consumption reduce dietary protein to marginalized communities, leading to micronutrient deficiencies and growth disorders
Wild meat makes a significant contribution to household food security in regions (Cawthorn & Hoffman 2015; Coad et al. 2019). While reliable data on the contribution of wild meat to dietary protein requirements is scarce, recent estimates from the Congo and Amazon basins suggest wild meat consumption delivers an average of 60%–80% of daily protein consumption (Coad et al. 2019). The importance of wild meat to household food security is greatest in marginalized communities, including the poorest households and those with existing health conditions such as HIV/AIDS or during resource shocks (Cawthorn and Hoffman 2015; Nielsen et al. 2018).

The loss of access to wild meat is likely to have significant, adverse impacts on food security, and well-being (Fa et al. 2003; Golden et al. 2011). Critically, it is likely to reduce access to dietary protein, an important source of micronutrients. Micronutrient deficiencies are linked to growth disorders, stunting, greater risk of chronic disease, and increased risk of mortality due to other factors (Caulfield et al. 2006). Consequently, interventions to limit wild meat consumption pose serious risks to human health, particularly of marginalized and vulnerable social groups, unless they explicitly create alternative sources of safe, nutritious, and socially acceptable protein.

© André Bärtschi / WWF

Risk 5: Role of conservation interventions in preventing future zoonotic EIDs is simplified or exaggerated, alienating support among local communities

While synergies exist between the objectives of reducing risk of zoonotic EID events and conserving nature, pursuing those synergies should be done carefully to avoid potential miscommunications and even counterproductive reactions. One risk concerns optics that undermine needed partnerships. By emphasizing or exaggerating these potential synergies, conservationists may appear to be looking for a 'silver lining' in a human health crisis (e.g., Williams 2014) or to be using zoonotic EID risk reduction as a 'Trojan horse' to achieve their objectives and thus to "care more about indigenous fauna and flora than they do about indigenous humans," (Pooley et al. 2015). Given the growing importance of working directly with communities to secure durable conservation of nature, the effectiveness of those partnerships could be undermined if governments and communities perceive conservationists as being opportunistic. A second risk involves an erosion of credibility for governments and NGOs in the eyes of communities if policies, such as prohibitions on the hunting or selling of wild meat, are applied in ways that are overly broad. For example, because most communities have never directly experienced disease transmission from wild meat—and indeed have relied on it as an important source of protein—blanket bans on wild meat during an outbreak have been found to erode trust and willingness to comply with policies. This erosion of trust may then hinder subsequent application of refined policies that target specific high-risk taxa or activities (Bonwitt et al. 2018).

© Greg Armfield / WWF-UK

Conclusion

Reimagine a new and better world.

The devastating human and economic losses resulting from the COVID-19 pandemic are now central in the lives of people throughout the world. Beyond the immediate challenge of rebuilding lives and the global economy looms both a sense of uncertainty about the future and also an opportunity to reimagine a new and better world. This is not the first time a new and deadly virus has emerged, and it won't be the last. Although we cannot always foresee and prevent disease, if we continue to destroy the natural world, we will continue to make these events more likely and severe. This science brief reviewed the evidence for that assertion and identified key interventions for WWF and other organizations to implement in pursuit of a future where emerging infectious diseases are less likely to become a recurring threat to our health and economic prosperity.

This science brief highlights that the majority of EIDs are zoonoses, or viruses that spillover from wildlife and domestic animals to people. It provides further evidence that no matter how much we think humans and nature are separate, our civilization has always and will always depend on human health, flourishing natural systems, and the wise stewardship of natural resources. While the relationship between humans and nature lies at the heart of the debate about the origins of the current crisis, the inextricable link between the two offers the potential for transformative solutions. Just as the conservation of nature is central to addressing the biodiversity, climate, and inequality crises, it also has a crucial role in achieving a future with a much lower risk of pandemics. As a leading global conservation organization, WWF can play a key role in achieving this goal.

Achieving this goal, however, requires that we identify key interventions or 'no-regret' actions. Yet, finding these leverage points in a system demands that we also avoid the temptation to move rapidly into adopting simple, quick solutions which, too often, fail to meet inflated expectations, cause unintended negative impacts, or even backfire. Rather, the identification of constructive interventions hinges on a careful review of the evidence, builds on a sound, mechanistic understanding of the drivers associated with the emergence and spread of disease, and evaluates the opportunities, risks, and trade-offs that surround possible interventions.

Existing evidence highlights the risks of acting without attention to the evidence. For example, the production and harvesting of wild meat often supports local livelihoods and economics and provides a crucial source of macro and micronutrients for poor rural households. Management interventions that seek to limit wild meat hunting, sale, or consumption to reduce risk of zoonotic EIDs should be designed to limit their impact on income, nutrition, and food security. Poorly designed interventions also risk undermining trust in conservation and/or government if they lead to excessive negative impacts on human well-being and could even exacerbate the risk of disease or loss of biodiversity.

The evidence indicates that three direct drivers of change result in the greatest risk of zoonotic EID exposure and vulnerability: 1) land-use change which results in the loss and degradation of nature; 2) intensification of livestock production to meet increasing demand for animal protein worldwide and; 3) the sale and consumption of high-risk wild animals in and out of live markets. To reduce the growing threat posed by zoonotic EIDs from these three drivers, we propose a non-exhaustive list of no-regret interventions, or leverage points, the conservation community should embrace both in the short and long term.

Some no-regret interventions focus on traditional conservation measures modified to address the new and growing threat to human health and the global economy from zoonotic EIDs, while also achieving significant conservation outcomes that address the climate, biodiversity, and inequality crises. Examples include (1) protecting forests and promoting land-use policies and planning that limit people's exposure to zoonotic EID pathogens or (2) implementing policies that remove high-risk taxa from permanent live animal markets and strengthen food safety practice and regulations. Other interventions reimagine the traditional role of conservation in a world of multiple converging crises. Examples of expanded no-regret interventions include (1) redesigning food production systems and supply chains to ensure nutritious, sustainable food to everyone on the planet while decreasing both the likelihood and severity of a zoonotic EID outbreak or (2) strengthening early warning systems for zoonotic EIDs. These are just a few of the many, yet-to-be-discovered opportunities for the conservation community in creating a new and better world.

As we emerge from the COVID-19 crisis and reboot the global economy through stimulus packages, we have an unprecedented opportunity to reimagine global conservation so that we decrease the severity and likelihood of future zoonotic EID events and their impact on human health and the global economy. As the Global Science team at WWF, we believe that the evidence presented in this science brief is both sufficient and strong enough to support immediate action. We cannot waste this opportunity on returning to the broken system that will continue to erode planetary health. However, this brighter future hinges on increased cooperation between governments, the private sector, and civil society organizations. The COVID-19 crisis has shown us that a different world is possible. It has also shown us just how much we depend on each other, as one humanity living on one planet. Together, let's seize this opportunity to redesign conservation to not only protect biodiversity, but also reduce the likelihood of another zoonotic EID having similar or greater consequences to human health and the global economy.

Appendices

Appendix A: Questions from the WWF network

1. What is the genesis of the virus that causes COVID-19?
  a. COVID-19 is the name given to the current infectious disease caused by SARS-coronavirus 2 (SARS-CoV-2), for which there is some evidence that it emerged in China in late 2019.

2. Which species may have caused the deadly outbreak of COVID-19?
  a. SARS-CoV-2 is believed to have zoonotic origins, likely a bat due to the genetic similarity to bat coronaviruses and potentially delivered through an intermediary species. The SARS-CoV-2 virus appears to be able to infect a range of hosts. Sunda pangolins have been suggested as an intermediate host because they harbor coronaviruses similar to the SARS-CoV-2 virus. However, genetic analysis has found viruses in pangolins are not similar enough to be the direct precursor.

3. What is the role of illegal or unregulated wildlife markets?
  a. Wildlife use and meat consumption can be a direct driver of zoonotic EIDs, with some species carrying a higher risk of transmission, such as bats, pangolins, palm civets, racoon dogs, rodents, primates, shrews, ungulates, and carnivores for SARS-like coronaviruses.
  b. Several recent zoonotic EID outbreaks have been linked to permanent live animal markets (e.g., COVID-19, SARS).
  c. Specific practices or types of markets are also associated with higher risk, including crowded conditions and mixing of species, and the inclusion of high-risk taxa.

4. What is the link between the loss and degradation of nature and biodiversity and the increasing likelihood of pandemics?
  a. Evidence indicates that growing intrusion of humans in wildlife habitats through the expansion or intensification of human activities in natural ecosystems increases human-animal interactions that enhance the probability of transmission of pathogens.
  b. Following decades of widespread deforestation and fragmentation, the global extent of intact forest has declined considerably. The loss and degradation of forests increases the risks associated with both novel and endemic zoonotic diseases.
  c. Globally, land-use changes have likely contributed to almost half of the emergence events for zoonotic EIDs in humans from 1940–2005.
  d. Various studies in the literature on the relationship between biodiversity and risk of zoonotic EIDs have reported evidence for both biodiversity reducing risk (i.e., dilution) and increasing risk (i.e., amplification).
  e. Disease risk is influenced by the reservoir hosts and vectors, the intensity of human contact with zoonotic pathogens, rather than patterns of species biodiversity.

5. How are diets contributing to risks?
  a. Several recent zoonotic EID outbreaks have come from either permanent live animal markets (e.g., COVID-19, SARS), concentrated animal feeding operations (e.g., H5N1 – avian influenza, H1N1 – swine flu), or from consumption of wild meat (e.g., HIV, Ebola).
  b. Increasing demand for animal protein is listed as one of the leading risk factors for novel zoonotic EIDs.
  c. The increased demand for animal protein is leading to changes in how we produce food and our proximity and relationship to domesticated animals and wildlife—and thus exposure to potential zoonotic EIDs.
  d. Nutrition is a critical determinant of vulnerability to infectious disease.

6. How would interventions to curb it affect human diets, especially of the poor?
  a. Wild meat supports local livelihoods and provides a crucial source of protein, fat, iron, and other micronutrients for poor rural households, and thus management interventions that seek to limit wild meat hunting, sale, or consumption to reduce risk of zoonotic EIDs should be carefully designed to not undermine nutrition and food security.

7. What are the links with climate change?
  a. Strong scientific evidence suggests that climate change will increase the incidence of endemic zoonotic diseases by expanding their geographic ranges.
  b. Climate change is already increasing the spread of some endemic vector-borne zoonotic diseases, including Lyme disease, malaria, and dengue fever.
  c. In some places where the climate becomes too hot or dry (e.g., for hosts or vectors), endemic zoonotic diseases may decline.
  d. It is possible that zoonotic EIDs involving novel pathogens will increase with climate change, but the existing scientific evidence is more limited.

8. Which lessons can we take from this pandemic to inform strategies, campaigns, and other interventions?

a. We can identify leverage points to reduce our exposure and vulnerability to zoonotic EIDs in both the near and long term.

b. There are seven potential leverage points for nature conservation organizations, including (1) limiting the potential for viral transmission and amplification in permanent live animal markets, (2) reducing consumption of taxa with high risk for transmitting zoonotic disease, (3) strengthening early warning systems for zoonotic EIDs, (4) re-engineering production systems and supply chains to minimize exposure, (5) strengthening public trust in institutions to minimize vulnerability to zoonotic EIDs, (6) fostering transparency and evidence-informed policy (as part of a cross-sectoral coalition that enables systemic change), and (7) re-examining major conservation interventions with a zoonotic EID lens.

c. There are substantive risks of perverse outcomes for people, nature, and climate from the rapid implementation of poorly designed interventions intended to address the link between zoonotic EIDs and biodiversity conservation and evidence-informed strategy design could help mitigate many of these risks.

Appendix B: Brief overview of recent outbreaks or pandemics

Avian influenza is a viral infection of both wild birds, particularly waterfowl, and domestic poultry caused by the Type A strain of the influenza virus. This virus generally doesn't affect humans, but certain strains have transmitted to people through contact with sick or dead poultry, and then sustained person-to-person transmission through a respiratory route. Live bird markets may act as a reservoir of the virus (World Health Organization 2014). The 1918 Spanish flu may have had an avian origin (Taubenberger & Morens 2019).

Nipah virus (NiV) first emerged in the late 1990s in Malaysia as pig farmers became ill with encephalitis (Daszak et al. 2006). Outbreaks have continued most years since then in the region, spreading to Bangladesh, India, and Singapore, in addition to Malaysia. Fruit bats are the primary reservoir of NiV, and they can contaminate food or water with their saliva and these contaminated sources can spread the virus to a range of other mammals including pigs, dogs, cats, horses, and people. The primary outbreaks have been associated with pig farm workers becoming infected through contact with urine or saliva of infected pigs, or with objects infected with those fluids. NiV infection causes flu-like symptoms that can progress to potentially fatal encephalitis. The case fatality rate for NiV infection ranges from 40%–75%. Person-to-person transmission has occurred primarily to health care workers who are in close contact with infected secretions of sick people (World Health Organization 2014). In Malaysia, researchers found that fruit trees located within pig farms were a route of exposure to the virus, as pigs ate fruit that had fallen to the ground after bats had fed on it and infected it with their saliva. Removing fruit trees from pig farms has been found to prevent or reduce outbreaks of NiV (Wang & Crameri 2014).

Ebola virus disease, caused by the Ebola virus, is a viral hemorrhagic fever that has high case fatality rates (up to 90% with an average of about 50%). Ebola virus first emerged in 1976 with simultaneous outbreaks in Sudan and the Democratic Republic of Congo. Fruit bats serve as the reservoir of Ebola virus and bats can transmit the virus to apes and monkeys. The virus transmits to people generally through close contact with infected blood or other bodily fluids of infected animals, such as may occur during butchering of a primate. Human-to-human transmission also occurs through close contact with bodily fluids of a person infected or deceased from Ebola virus. Burial ceremonies have been implicated in the spread of the virus (World Health Organization 2014). The largest outbreak of Ebola virus disease occurred between 2013 and 2016, primarily in the West African nations of Guinea, Sierra Leone, and Liberia. Nearly 30,000 people were infected during this outbreak, with 11,310 deaths and a case fatality rate of 40% (World Health Organization 2016).

Severe acute respiratory syndrome (SARS) is caused by the novel human coronavirus SARS-coronavirus (SARS-CoV), a zoonotic virus that emerged in 2002 in the Guangdong province of China. The reservoir of SARS-CoV is believed to be a bat though the transmission to humans likely occurred through a civet as an intermediary host. Spread between people can occur through contact with respiratory droplets of an infected individual (World Health Organization 2014). Following emergence, an outbreak of SARS occurred in 2003, ultimately infecting just over 8,000 people and causing 774 deaths for a case fatality rate of approximately 10% (World Health Organization 2020b).

Middle East respiratory syndrome (MERS) is caused by the novel human coronavirus MERS-coronavirus (MERS-CoV), a zoonotic virus that emerged in 2012 in Saudia Arabia. Bats serve as the reservoir for MERS-CoV with camels likely acting as an intermediate host. Camels are believed to be the primary cause of transmission to people. Mechanisms of transmission between people are not well understood and most person-to-person transmission has occurred within hospitals involving health care workers in close contact with infected individuals (World Health Organization 2014). By 2019, seven years after the first emergence, there had been 2,494 recorded cases across 11 countries, primarily in the Middle East (Saudia Arabia has had 84% of all cases), with a case fatality rate of 34% (World Health Organization 2019).

COVID-19 is the name given to the current infectious disease caused by SARS-coronavirus 2 (SARS-CoV-2), which emerged in China in late 2019. It is believed to have zoonotic origins, likely a bat due to the genetic similarity to bat coronaviruses and potentially delivered through an intermediary species. The SARS-CoV-2 virus appears to be able to infect a range of hosts. Sunda pangolins have been suggested as an intermediate host because they harbor coronaviruses similar to the SARS-CoV-2 virus. However, genetic analysis has found viruses in pangolins are not similar enough to be the direct precursor. Transmission between people occurs through exposure to respiratory droplets from infected individuals. As of April 21, 2020, there are over 2 million cases of COVID-19 and over 170,000 deaths worldwide (Johns Hopkins University 2020).

Appendix C: Leverage points and interventions for addressing zoonotic disease risk in the context of nature conservation

Leverage Point 1: Limit potential for virus amplification and cross-species transmission in permanent live animal markets

The early cluster of COVID-19 cases centered on the Huanan seafood market has refocused global scientific and media attention on the role of permanent live animal markets in facilitating cross-species transmission and viral amplification (Webster 2004; Peiris et al. 2016). Recent genetic studies of COVID-19 patients and vector species (including Horseshoe Bat, Rhinolophus affinis; Malayan Pangolin, Manis javanica) suggest other plausible transmission pathways (including repeated single human infections in the past with a mutation allowing for human-to-human transmission), but do not discount the potential role of permanent live animal markets (Anderson et al. 2020).

The conditions in permanent live animal markets facilitate cross-species transmission (both wild and domestic) and viral amplification. Live animals are frequently housed in crowded market conditions for days (or weeks, in the case of more expensive animals). The daily introduction of new animals into the market, together with the immuno-suppressive effects of stress (Padgett & Glaser 2003) create the optimum conditions for viral amplification (Webster 2004). For example, analysis of previous coronavirus emergence suggests that civets on farms supplying wild markets had low rates of infection, but those in permanent live animal markets had up to 80% infection rates (Tu et al. 2004).

Given the role of permanent live animal markets in previous zoonotic disease outbreaks (e.g., SARS; Tu et al. 2004; Webster 2004) interventions to reduce the viral burden and the potential for cross-species transmission represent a clear leverage point, with multiple possible interventions that may be effective singly or in combination.

Potential Intervention: Closure of permanent live animal markets
The emergence of COVID-19 has led to many calls in the media for the closure of permanent live animal markets in China and elsewhere. The Chinese government has already issued a temporary ban on the buying, selling, and transport of wild animals and wild meat for consumption, with calls for other countries in Southeast Asia and elsewhere to follow. Closure of permanent live animal markets in favor of centralized slaughter and the sale of chilled or frozen products is likely to significantly reduce the potential for cross-species transmission and viral amplification (Peiris et al. 2016).

While some commentators (e.g., Robinson and Walzer 2020) have argued for complete closure of permanent live animal markets and commercial trade in wildlife for human consumption, others (e.g., Lam et al. 2020) have called for the removal of some high-risk species from these markets, while others (e.g., Daszak et al. 2020) have argued for improved regulation and surveillance of the markets themselves and wild and captive-bred species being supplied, rather than market closure. There are, however, significant obstacles to effectively implementing the closure of permanent live animal markets, including strong cultural preferences (Peiris et al. 2016), and the ability of state agencies to enforce closure (Hui et al. 2020). The closure of legal markets when cultural preferences persist may lead to the creation or expansion of illicit markets either physically or online. There are important geographical differences within and between countries on the viability of closing permanent live animal markets in favor of centralized slaughter. Frequent interruptions to power supply or lack of electrification limit the feasibility of markets with chilled/frozen products.

There is some evidence that temporary market closures are feasible and effective in reducing transmission and spread after an emerging zoonotic disease is detected (i.e., as a public health intervention to lengthen critical response time). For example, during an outbreak of H7N9 influenza, the temporary closure of live poultry markets was highly effective at reducing viral spread (Peiris et al. 2016). There may, however, be unintended consequences such as transport of infected birds to unaffected areas (Li et al. 2018).

Potential Intervention: Removal of high-risk taxa from permanent live animal markets
The targeted removal of high-risk ‘zoonotic reservoir’ species from permanent live animal markets has been proposed as a mechanism to disrupt cross-species transmission pathways. Evidence from similar interventions during outbreaks of avian influenza suggests that the targeted removal of disease vector species from markets is effective at reducing (although likely not eliminating) cross-species transmission; Webster 2004). For example, all aquatic birds (including wild-caught geese and ducks) were banned from Hong Kong’s permanent live animal markets, or were sold as chilled meat products, in response to avian influenza, likely reducing the frequency of future outbreaks (Webster 2004).

The ability to identify high-risk taxa, and the subsequent enforcement of regulations prohibiting their presence in permanent live animal markets likely determine the effectiveness of this intervention. Evidence suggests these taxa may include birds and bats as well as pangolins, ungulates, primates, and rodents (Han et al. 2016).

The range of taxa classified as a high risk poses substantial challenges to taxa-specific regulations. There are 816 human diseases of zoonotic origin, of which 130 are known to be emerging or re-emerging (Woolhouse & Gowtage-Sequeria 2005). This latter group are not strongly associated with particular types of non-human hosts (i.e., spanning many mammal and non-mammal taxa) and have broad host ranges (i.e., each zoonosis is able to infect multiple host species; Woolhouse and Gowtage-Sequeria 2005), suggesting that taxa-specific regulations may need to be wide-ranging to be effective. Machine-learning informed by life-history characteristics to identify high-risk taxa holds promise for practical, but credible 'rules-of-thumb' (Han et al. 2016).

Potential Intervention: Strengthen food safety practices and regulation
The role of permanent live animal markets in amplifying viral loads and facilitating cross-species transmission stems from the crowded, and often unsanitary conditions in the markets. Interventions known to effectively target high-risk food safety and animal husbandry practices (reducing exposure and vulnerability) in permanent live animal markets include (a) 'rest days' when markets are closed to reduce viral amplification (Kung et al. 2003; Yu et al. 2014) (b) regulations to prevent live animals being kept in markets overnight (Peiris et al. 2016), (c) enhanced disease monitoring and surveillance (Wu et al. 2014), (d) discouraging the sale of wild-caught animals, and (e) the education of customers and stallholders (Peiris et al. 2016).

Leverage Point 2: Reduce consumption of taxa with a high risk for transmitting zoonotic disease

Recognition that the hunting, farming, butchering, and consumption of wild meat has been linked to multiple zoonotic EID events (e.g., SARS, Ebola; Smith et al. 2014; Cantlay et al. 2017), has led to long-standing calls for regulations on the trade and consumption of wild meat. The emergence of SARS-COV-2 and the subsequent global COVID-19 health crisis has refocused attention on the issue in the media and by civil society organizations.

Patterns and drivers of wild meat consumption are highly context specific, linked to the availability of wild meat in a landscape, price and availability of alternative protein sources, the wealth of the consumer, consumer preferences, and broader social and economic context (Coad et al. 2019). In some regions, wild meat consumption is important for food security, representing 60%–80% of dietary protein intake (Coad et al. 2019) and is particularly important for isolated, marginalized, or vulnerable communities (Golden et al. 2011; Nielsen et al. 2018; Coad et al. 2019). Similarly, the sale of wild meat provides an important source of cash income in regions with few alternative livelihood options or during times of crisis (Coad et al. 2019). Elsewhere, urban consumption is driven by long-standing cultural preferences for wild meat over domestic livestock (Coad et al. 2019).

To be effective in reducing zoonotic EIDs, interventions designed to influence the consumption of wild meat need to:

- recognize the considerable variation and context-specificity in the patterns and drivers of wild meat consumption; and
- explicitly safeguard the food security, livelihoods, and disease risk of marginalized or vulnerable communities, by ensuring co-designed, socially acceptable, financially viable alternatives to wild meat exist, prior to the implementation of interventions to reduce wild meat consumption.

Here, we outline potential interventions for *reducing the risk of zoonotic EIDs from wild meat consumption and trade*, with the caveat these interventions are only likely to be effective with adequate attention to the context and appropriate mitigation of risks to food security and income.

Potential intervention: Regulate consumption of high-risk taxa, where viable alternatives exist
While hunting, butchering, processing, and consumption of wild meat has been linked to multiple zoonotic EIDs (Smith et al. 2014; Cantlay et al. 2017), not all taxa consumed as wild meat are hosts for high-risk zoonoses (Coad et al. 2019). Consequently, there is an opportunity to target regulations or other interventions toward those taxa that pose the greatest human health risk. These taxa will likely vary across geographies, due to different pathogen-host-environment interactions, and different hunting, butchering, and processing practices. Models of zoonotic EID risk (e.g., Allen et al. 2017), coupled with life-history characteristics (e.g., Han et al. 2016), and in-depth analyses on wild meat processing practices could be combined to allow for the participatory and context-specific identification of high-risk taxa, under a broader regulatory framework.

Appropriate governance mechanisms will likely differ between countries and may also differ between rural and urban communities where the patterns and drivers of wild meat consumption differ markedly (Coad et al. 2019). In rural communities, co-management of wild meat harvest and consumption is likely to be more effective than centralized enforcement by under-resourced government agencies (Coad et al. 2019) adopting the principles of common pool resource management (Ostrom 1990) In newly urbanizing communities, appropriate development of alternative sources of protein may be more effective than regulatory frameworks alone (Coad et al. 2019). In established urban centers, regulation of markets and behavior change interventions to reduce cultural preferences for wild meat (Nasi et al. 2011) both discussed elsewhere in this section, may be more relevant.

Potential intervention: Targeted behavior change interventions to address cultural preferences for wild meat in urban environments and high-risk 'food tourism' behaviors

Strong cultural preferences for wild meat drive consumption patterns in large metropolitan areas (Coad et al. 2019). Highly targeted interventions that build on credible theories of behavior change, may be effective at reducing consumer demand for high-risk taxa (e.g., Chaves et al. 2018). These cultural preferences may stem from the role of wild meat in customary practices and norms, an expression of cultural ties to rural communities, and the perception of wild meat as a luxury item (Chausson et al. 2019). Addressing urban consumer demand for wild meat requires the deconstruction of the taxa-specific social norms, perceptions, and values surrounding consumption (Chausson et al. 2019). These will vary geographically, as well as within and among social groups (e.g., Shairp et al. 2016). Effective demand reduction requires evidence-informed targeting of different consumer groups, to identify messaging, messengers, and communication channels that are most likely to shift behavioral intent (Michie et al. 2011; Chausson et al. 2019).

Potential intervention: Commercial production of wild meat

For those species more amenable to sustainable consumption (Cawthorn & Hoffman 2015) and with a lower risk of zoonotic EID, the commercial production of wild meat (i.e., game meat farming) may be a viable intervention to reduce exposure to emerging zoonoses (Tensen 2016). An assessment is needed to understand the overlap between those taxa hunted for wild meat which pose lower zoonotic disease risk (e.g., Olival et al. 2017) and those for which commercial production is feasible (Cawthorn & Hoffman 2015).

A recent synthesis of the commercial production of wild meat (Tensen 2016) suggests that it is only viable where:

1. farmed products seen as equal in value to wild-caught meat (i.e., consumer substitution occurs),
2. a substantial proportion of demand is met,
3. demand does not increase in response to the farmed market,
4. farmed products are cheaper,
5. commercial ventures do not restock from wild populations, and
6. the laundering of wild-caught meat into the farmed supply chain does not occur.

These conditions are unlikely to be met in many cases under current regulatory frameworks (Tensen 2016). For commercial wild meat production to be a viable intervention, routine disease surveillance and on-farm veterinary care would need to be strengthened (Daszak et al. 2020). The potential of regulatory frameworks, market incentives, and social marketing to create the conditions under which these criteria are met is underexplored (Bulte & Damania 2005) and merits further examination.

The unintended consequences of commercial wild meat production, including the impact on in situ conservation, the risks of wild-caught individuals entering the supply chain, and the ability of local communities who co-exist with wild populations of farmed taxa to benefit from those species are largely unknown.

Potential intervention: Regulate international trade of wild meat products and wildlife

The global trade in wild meat products and live wildlife is extensive and growing. Available data (limited to CITES species) from 2012 to 2016 suggest live wild species were exported from 189 countries, with China, Nicaragua, Peru, and South Africa as key exporters (Can et al. 2019). However, the trade is driven by high-income countries, the United States in particular (Can et al. 2019). For import countries, the international trade in wildlife may represent a significant source of zoonotic EID risk (Smith et al. 2014), given that other contextual factors linked to EID risk are relatively low (Allen et al. 2017).

Trade bans on high-risk taxa have been proposed as a key intervention for reducing zoonotic EID exposure. Previous trade bans (often enacted unilaterally by major import countries), designed to limit invasive (not zoonotic disease risk) species have had some impact on trade volume. However, new trade routes often emerge in response to national or regional bans (Reino et al. 2017). A global ban on the international trade in high-risk taxa may be more effective than country-specific bans (Fèvre et al. 2006). The political feasibility of such a ban is unclear, but given the breadth of taxa likely classified as high-risk (Han et al. 2016; Olival et al. 2017) it may be difficult to enforce (Can et al. 2019).

The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) is intended to create a framework for international cooperation on the wildlife trade (Fèvre et al. 2006) and represents a potential vehicle for controlling zoonotic EID risk. The sanctions mechanisms under CITES have been successful at reducing the trade in some species, but not others (Symes et al. 2018). There is potential to modify CITES to also act as an international mechanism for limiting the trade of high-risk taxa, but other trade agreements should also be considered, or a new agreement negotiated under the joint auspices of WHO and the World Organization for Animal Health.

To effectively limit the trade in high-risk taxa for zoonotic EID (and limit the likelihood of expanding the illegal trade), any trade ban would need to be highly targeted toward high-risk taxa (rather than seek to enact broad taxonomic controls), and accompanied by highly targeted behavior change initiatives in both import and export nations. A plausible alternative may regulate the trade more closely, require improved biosecurity and surveillance (Can et al. 2019; Daszak et al. 2020) and provide education on safe handling of wild meat/live animals to traders and consumers (Pavlin et al. 2009). However, the costs involved in a more highly regulated trade may be prohibitive.

Leverage Point 3: Strengthen early warning systems for emerging zoonotic disease

Surveillance systems for detecting a zoonotic EID are chronically under-resourced (Cleaveland et al. 2017), with the majority of monitoring efforts focused on regions that are low risk for emerging zoonoses (Jones et al. 2008). Less than one in five countries meets their commitments to global health security surveillance and monitoring under International Health Regulations (Burkle 2015; Cleaveland et al. 2017). Consequently, the policymakers and public health professionals have little ability to detect the emergence of a zoonotic infectious disease, prior to human-to-human transmission. In the case of COVID-19, SARS-CoV-2 was not detected until human-to-human transmission had occurred potentially in multiple localities (Wang et al. 2020a). During outbreaks of zoonotic EID, substantial investments are made in diagnostic and monitoring capacity, but these are not sustained once the immediate threat has passed (Cleaveland et al. 2017). This lack of early warning systems means that many epidemiological interventions are no longer feasible or effective, as the critical response window is so narrow (Muzemil et al. 2015).

Daszak et al. (2020) call for research and investment in three areas to prevent future zoonotic EIDs including surveillance of wildlife to identify high-risk pathogens, monitoring of people at the human-animal interface to identify spillover events early, and improved biosecurity in the wildlife trade.

Potential intervention: Develop integrated zoonotic disease surveillance systems that can also inform conservation action
To maximize the critical response time available for public health interventions to constrain the spread of future zoonotic EIDs, we need feasible, scalable surveillance systems (Daszak 2012; Daszak et al. 2020) that are targeted at disease hotspots (Jones et al. 2008), monitor indicators across a range of disciplines (Salkeld et al. 2013; Cleaveland et al. 2017), and allow for rapid responses when disease emergence is suspected. Well-designed surveillance systems, which control for confounding factors, can also enable us to test hypotheses about the relationship between nature, zoonotic EID risk, and the effectiveness of interventions.

Importantly, from a conservation perspective, the high-resolution data on disease-risk relevant confounding factors, and high-risk taxa also have considerable value for the design and adaptive management of conservation interventions. Consequently, there is significant opportunity to create a multi-purpose monitoring network targeted in regions where rates of biodiversity loss are highest, and the risk of zoonotic EIDs is greatest (Cleaveland et al. 2017; Daszak et al. 2020).

Potential intervention: Align global incentives for early warning systems
Global health security discussions are centered on the role of zoonotic EIDs, given their potential to have significant public health and economic impacts. In those countries where zoonotic EID risks are greatest (e.g., in Southeast Asia, sub-Saharan Africa: Jones et al. 2008), policymakers are typically focused on other chronic, public health concerns including inadequate water and sanitation, and endemic zoonotic disease burden (Burkle 2015; Cleaveland et al. 2017). Endemic EIDs are responsible for greater morbidity and mortality than novel zoonotic EIDs (Cleaveland et al. 2017), with estimates suggesting that the 13 most prevalent endemic EIDs are responsible for at least 2.2 million human deaths and 2.4 billion illnesses every year (Grace et al. 2012). Misdiagnosis and under-reporting makes it likely the true figure is higher (Cleaveland et al. 2017).

Integrating surveillance systems for endemic and novel zoonotic EIDs aligns incentives, addressing the high disease burden of endemic EIDs, and high risk of novel zoonotic EIDs in the Global South, with the funding capacity and emerging-disease focus of the Global North (Cleaveland et al. 2017). Information needs for monitoring endemic and novel zoonotic EIDs are similar. Integrating endemic and novel zoonotic EID surveillance systems may have further benefits during future disease outbreaks, building important diagnostic and public health capacity in high-risk regions that can be repurposed in a crisis (Altizer et al. 2013; Barry 2019; Harvard C-CHANGE 2020).

Potential intervention: Examine future zoonotic EID risk given climate and development trajectories
The rapid acceleration of environmental change may increase the likelihood of future zoonotic EIDs. But some scientists have also challenged the extent to which climate change may influence the risk of zoonotic EIDs (Rohr et al. 2011; Kilpatrick & Randolph 2012; Altizer et al. 2013) and further research is needed on how human responses to environmental change may exacerbate or ameliorate risk (IPBES 2019).

We recommend the integration of zoonotic EID risk into global scenario models, to identify how diseased risk will shift with accelerating climate, environmental, and social change (Di Marco et al. 2020). These models need to explicitly incorporate mechanistic models of disease transmission pathways (Allen et al. 2017). These models can inform the identification of future leverage points and interventions to address the risks of zoonotic EIDs.

Leverage Point 4: Re-engineer production systems and supply chains

Any solution to the food system designed to reduce the risk of EIDs needs to focus on both the consumption and production sides of the supply chain. On the consumption side, global demand for animal source foods, namely red meat and dairy, needs to dramatically decrease in certain parts of the world (i.e., G20 countries), and the trend toward high consumption of animal source foods in other parts of the world needs to be prevented. A global shift toward diets that are less predominated by animal source foods and more by plant-based foods would relieve agricultural pressure on land use and land conversion and allow humanity to grow food on the same land or ideally less land than what is used today. In addition, a decrease in global demand for animal source foods would also allow the majority of animals to be grown on rangelands and pasture lands, thereby decreasing the need for concentrated animal feeding operations.

On the production side, agricultural land needs to be optimized globally to relieve the pressure on natural ecosystems. This includes closing yield gaps, spatially distributing cropland to grow the right crops in the right places, adopting more sustainable practices for soil, water, and nutrients, and rebalancing nitrogen and phosphorus fertilizer use between over- and under-applying regions. While deforestation and conversion of natural habitats must be eliminated from food supply chains, large investments must be made to restore degraded lands and rehabilitate degraded soils. In addition, adopting agroecological principles, such as integrating conservation objectives into current agricultural landscapes, would help to protect biodiversity.

Leverage Point 5: Strengthen public trust in institutions

Solutions designed to address the threats from zoonotic diseases in the past have been shown to favor the development of technical capacities (e.g., diagnostic testing) over ‘soft’ capacities like communications, leadership, and trust building (Cleaveland et al. 2017). Given the important role of both transparency and trust immediately post-emergence (e.g., Liberia during Ebola; Blair et al. 2017) strengthening these soft capacities will be critical for ensuring the resilience of social systems to future epidemics. For example, trust can be developed through regular interactions between stakeholders, and can have particular relevance for disease risk management and control if they include representatives of heterogeneous communities, such as those responsible for delivering public health solutions, and/or livestock management (Cleaveland et al. 2017).

Potential intervention: Create arenas for trust building between local leaders and local communities
Those who support community-based conservation already put significant time and energy into building institutional capacity for natural resource management at local levels. This often involves fostering good working relationships between resource management groups and local governments. Creating more open arenas that strive to build trust between broader sets of stakeholders (including diverse members of communities and officials with mandates beyond just natural resource management) could both foster a more systematic approach to natural resource management that recognizes the complex feedbacks between different issue areas and foster social resilience that enhance the soft capacities needed to withstand and contain future disease outbreaks. This will require more flexible mandates and deliverables that allow field staff themselves to build trust with stakeholders prior to facilitating these kinds of convenings

Leverage Point 6: Foster transparency and evidence-informed policy

The response of global policymakers to the COVID-19 pandemic has highlighted marked differences in the levels of transparency and evidence-informed action across governments. While conservation organizations have a limited direct role to play in fostering transparency and evidence-informed once a zoonotic EID becomes a public health crisis, conservation actors do have a clear role in the transparent communication and evidence-gathering of the relationship between the loss of nature and zoonoses, and the strategies to employ to avoid those conditions to avoid future zoonotic EIDs (Section 4.3).

Potential intervention: Convene conservation actors to discuss role of conservation sector in communicating and addressing disease risk and outbreaks
Clear national and international guidelines are needed for the roles of scientists, officials, and politicians in communicating and addressing disease outbreaks (Wang et al. 2020a). In the conservation realm, the first step in this approach would be convening conservation actors to discuss the role of the conservation sector in fostering transparency through communication and providing evidence for informed policymaking on the conservation-related drivers linked to disease risk.

Leverage Point 7: Re-examine major conservation interventions with a zoonotic EID lens

The loss of biodiversity and the growing risks of exposure to zoonotic EIDs are affected by similar drivers (Section 4). Given these shared causal pathways, conservation interventions, designed to stem the loss of nature and its contributions to people, may have intended or unintended impacts on human health that may be positive or negative (Kilpatrick et al. 2017). These impacts are likely to be highly variable and unpredictable, given that exposure to zoonotic disease is a complex product of ecological dynamics, transmission pathways, and spatial scale (Salkeld et al. 2013). In some cases, conservation interventions may reduce zoonotic host species diversity, by reducing interactions with livestock or other species that live in close proximity to humans, which can represent a significant proportion of the zoonotic host species population (Kilpatrick et al. 2017). In others, conservation interventions may act to amplify risks of emerging zoonotic diseases by creating new transmission pathways, increasing exposure or increasing the vulnerability of communities to a disease (Di Marco et al. 2020). For example, DiMarco et al. (2020) speculate that conservation corridors, designed to foster connectivity between habitat fragments in large-scale landscapes, may facilitate the transmission of zoonotic diseases. There are few empirical studies exploring this issue, but this interaction and the role of animal migration in either mitigating or amplifying zoonotic merits further examination.

Potential intervention: Examine theories of change for major conservation interventions based on a mechanistic, transdisciplinary understanding of transmission pathways

Conservation interventions have impacts on human health and well-being via multiple pathways (McKinnon et al. 2016), creating synergies and trade-offs that can reinforce or undermine existing social inequities (Gupta et al. 2020). The implications of specific conservation strategies on zoonotic EID risk is poorly understood (Kilpatrick et al. 2017), and there is a need to re-examine theories of change for major interventions, based on a mechanistic understanding of transmission pathways (Salkeld et al. 2013; Wood et al. 2014) to identify interventions which either hold promise for reducing zoonotic EID risk, or those which elevate risks. We recommend incorporating these reviews into a broader re-examination of the impacts of conservation interventions on human well-being, to ensure that interventions which substantially lower exposure or vulnerability to zoonotic EIDs do not have significant detrimental impacts on other components of human well-being or marginalized social groups.

Glossary

Coronaviruses – a group of related viruses that cause diseases in mammals and birds. In humans, coronaviruses cause respiratory tract infections that can be mild, such as some cases of the common cold, and others that can be lethal, such as the zoonotic diseases SARS, MERS, and COVID-19

COVID-19 – the coronavirus disease that emerged in 2019

Emerging infectious disease (EID) - diseases that have recently appeared within a human population or those diseases that are endemic but whose incidence or geographic range is rapidly increasing or threatens to increase in the near future

Epidemic – the spread of a disease in a community or region over a specific amount of time

Exposure – the likelihood of contact with a pathogen

Infectious disease – diseases caused by organisms such as bacteria, viruses, fungi, or parasites

One Health – an approach to designing and implementing programs, policies, legislation, and research in which multiple sectors communicate and work together to achieve better public health outcomes

Outbreak – an epidemic of a more limited geographic area

Pandemic – worldwide spread of a new disease

Pathogen – an organism that causes disease including viruses, bacteria, fungi, and parasites

Permanent live animal market – a market at which live and dead animals of different wild and domestic species are sold for human consumption. Permanent live animal markets (i.e., wet markets), provide a source of vertebrate and invertebrate animals for customers in tropical and subtropical regions of the world

Reservoir – an animal that carries a pathogen but is not susceptible to its disease

SARS- coronavirus 2 (SARS-CoV-2) – the virus that causes the current pandemic of coronavirus disease 2019 (COVID-19) that likely emerged in China in late 2019 and believed to have zoonotic origins

Spillover – the disease dynamics that enable a pathogen to be transmitted into a susceptible target host population from its reservoir population

Transmission – the spread or transfer of a disease pathogen from one individual to another

Vulnerability – the likelihood that a given exposure to a pathogen will cause harm

Zoonosis – an animal disease that can be transmitted from animals to humans

Zoonoses – plural of zoonosis

Zoonotic disease – a disease transmitted to humans from other animals via a pathogen

Zoonotic emerging infectious disease – an emerging infectious disease of animal origin

References

Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., von Wehrden, H., Abernethy, P., Ives, C.D., Jager, N.W. & Lang, D.J. (2017). Leverage points for sustainability transformation. *Ambio*, 46, 30–39.

Aguiar, L., Brito, D. & Machado, R.B. (2010). Do current vampire bat (Desmodus rotundus) population control practices pose a threat to Dekeyser's nectar bat's (Lonchophylla dekeyseri) long-term persistence in the Cerrado? *Acta Chiropterologica*, 12, 275–282.

Allen, T., Murray, K.A., Zambrana-Torrelio, C., Morse, S.S., Rondinini, C., Di Marco, M., Breit, N., Olival, K.J. & Daszak, P. (2017). Global hotspots and correlates of emerging zoonotic diseases. *Nature Communications*, 8, 1124–1124.

Altizer, S., Ostfeld, R.S., Johnson, P.T.J., Kutz, S. & Harvell, C.D. (2013). Climate Change and Infectious Diseases: From Evidence to a Predictive Framework. *Science*, 341, 514–519.

Ambrose, J. (2020). Carbon emissions from fossil fuels could fall by 2.5bn tonnes in 2020. *The Guardian*.

Andersen, K.G., Rambaut, A., Lipkin, W.I. et al. (2020). The proximal origin of SARS-CoV-2. *Nature Medicine*, 26, 450–452.

Anderson, R.M., Heesterbeek, H., Klinkenberg, D. & Hollingsworth, T.D. (2020). How will country-based mitigation measures influence the course of the COVID-19 epidemic? *The Lancet*, 395, 931–934.

Anthony, S.J., Johnson, C.K., Greig, D.J., Kramer, S., Che, X., Wells, H., Hicks, A.L., Joly, D.O., Wolfe, N.D., Daszak, P., Karesh, W., Lipkin, W.I., Morse, S.S., Mazet, J.A.K. & Goldstein, T. (2017). Global patterns in coronavirus diversity. *Virus Evol*, 3.

Banerjee, A., Baker, M. L., Kulcsar, K., Misra, V., Plowright, R. & Mossman, K. (2020). Novel insights into immune systems of bats. *Frontiers in Immunology*, 11, 26.

Bardosh, K.L., Scoones, J.C., Grace, D., Kalema-Zikusoka, G., Jones, K.E., de Balogh, K., Waltner-Toews, D., Bett, B., Welburn, S.C., Mumford, E. & Dzingirai, V. (2017). Engaging research with policy and action: what are the challenges of responding to zoonotic disease in Africa? *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372, 20160172.

Barry, M. (2019). *Conflict and the global threat of pandemics*.

Barton, M.D. (2000). Antibiotic use in animal feed and its impact on human health. *Nutrition Research Reviews*, 13, 279–299.

Bauhoff, S. & Busch, J. (2020). Does deforestation increase malaria prevalence? Evidence from satellite data and health surveys. *WORLD DEVELOPMENT*.

Bebbington, A.J., Bebbington, D.H. & Sauls, L.A. (2018). Assessment and Scoping of Extractive Industry and Infrastructure in Relation to Deforestation: Global and Synthesis Report. Clark University, Worcester, MA.

Bell, D., Roberton, S. & Hunter, P. R. (2004). Animal origins of SARS coronavirus: possible links with the international trade in small carnivores. *Philosophical Transactions of the Royal Society of London*. Series B: Biological Sciences, 359, 1107–1114.

Betsem, E., Rua, R., Tortevoye, P., Froment, A. & Gessain, A. (2011). Frequent and recent human acquisition of simian foamy viruses through apes' bites in central Africa. *PLOS Pathogens*, 7, e1002306–e1002306.

Blair, R.A., Morse, B.S. & Tsai, L.L. (2017). Public health and public trust: Survey evidence from the Ebola Virus Disease epidemic in Liberia. *Social Science & Medicine*, 172, 89–97.

Bloomfield, L. S. P., McIntosh, T. L. & Lambin, E. F. (2020). Habitat fragmentation, livelihood behaviors, and contact between people and nonhuman primate in Africa. *Landscape Ecology*, 35, 985-1000.

Bogomolni, A.L., Gast, R.J., Ellis, J.C., Dennett, M., Pugliares, K.R., Lentell, B.J. & Moore, M.J. (2008). Victims or vectors: a survey of marine vertebrate zoonoses from coastal waters of the Northwest Atlantic. *Diseases of aquatic organisms*, 81, 13–38.

Bolzoni, L. & De Leo, G.A. (2013). Unexpected Consequences of Culling on the Eradication of Wildlife Diseases: The Role of Virulence Evolution. *The American Naturalist*, 181, 301–313.

Bonilla-Aldana, D.K., Dhama, K. & Rodriguez-Morales, A.J. (2020). Revisiting the one health approach in the context of COVID-19: a look into the ecology of this emerging disease. *Adv Anim Vet Sci*, 8, 234–237.

Bonwitt, J., Dawson, M., Kandeh, M., Ansumana, R., Sahr, F., Brown, H. & Kelly, A.H. (2018). Unintended consequences of the 'bushmeat ban' in West Africa during the 2013–2016 Ebola virus disease epidemic. *Social Science & Medicine*, 200, 166–173.

Brook, C.E. & Dobson, A.P. (2015). Bats as 'special' reservoirs for emerging zoonotic pathogens. *Trends in Microbiology*, 23, 172–180.

Brown, I.H. (2000). The epidemiology and evolution of in£uenza viruses in pigs.Vet. *Microbiol*, 29–46.

Buck, J.C. & Ripple, W.J. (2017). Infectious Agents Trigger Trophic Cascades. *Trends in Ecology & Evolution*, 32, 681–694.

Bulte, E.H. & Damania, R. (2005). An Economic Assessment of Wildlife Farming and Conservation. *Conservation Biology*, 19, 1222–1233.

Burkle, F.M. (2015). Global Health Security Demands a Strong International Health Regulations Treaty and Leadership From a Highly Resourced World Health Organization. *Disaster Medicine and Public Health Preparedness*, 9, 568–580.

Caillaud, D., Levréro, F., Cristescu, R., Gatti, S., Dewas, M., Douadi, M., Gautier-Hion, A., Raymond, M. & Ménard, N. (2006). Gorilla susceptibility to Ebola virus: the cost of sociality. *Current Biology*, 16, R489–R491.

Can, Ö.E., D'Cruze, N. & Macdonald, D.W. (2019). Dealing in deadly pathogens: Taking stock of the legal trade in live wildlife and potential risks to human health. *Global Ecology and Conservation*, 17, e00515–e00515.

Cantlay, J. C., Ingram, D. J. & Meredith, A. L. (2017). A Review of Zoonotic Infection Risks Associated with the Wild Meat Trade in Malaysia. *EcoHealth*, 14, 361–388.

Caulfield, L.E., Richard, S.A., Rivera, J.A., Musgrove, P. & Black, R.E. (2006). Stunting, Wasting, and Micronutrient Deficiency Disorders. In: *Disease Control Priorities in Developing Countries* (eds. Jamison, D.T., Breman, J.G., Measham, A.R., Alleyne, G., Claeson, M., Evans, D.B., Jha, P., Mills, A. & Musgrove, P.). World Bank, Washington (DC).

Cawthorn, D.-M. & Hoffman, L.C. (2015). The bushmeat and food security nexus: A global account of the contributions, conundrums and ethical collisions. *Food Research International*, Food and Nutrition Security: Can science and good governance deliver dinner?, 76, 906–925.

Chan, J.F.-W., To, K.K.-W., Tse, H., Jin, D.-Y. & Yuen, K.-Y. (2013). Interspecies transmission and emergence of novel viruses: lessons from bats and birds. *Trends in Microbiology*, 21, 544–555.

Chausson, A.M., Rowcliffe, J.M., Escouflaire, L., Wieland, M. & Wright, J.H. (2019). Understanding the Sociocultural Drivers of Urban Bushmeat Consumption for Behavior Change Interventions in Pointe Noire, Republic of Congo. *Hum Ecol*, 47, 179–191.

Chaves, W.A., Monroe, M.C. & Sieving, K.E. (2019). Wild Meat Trade and Consumption in the Central Amazon, Brazil. *Human Ecology*, 47, 733–746.

Chaves, W.A., Valle, D.R., Monroe, M.C., Wilkie, D.S., Sieving, K.E. & Sadowsky, B. (2018). Changing Wild Meat Consumption: An Experiment in the Central Amazon, Brazil. *Conservation Letters,* 11, e12391.

Chen, K.T., Twu, S., Chang, H. & Wu, Y. (2005). SARS in Taiwan: An overview and lessons learned. *International Journal of Infectious Diseases*, 9, 77–85.

Cheng, V.C.C., Lau, S.K.P., Woo, P.C.Y. & Yuen, K.Y. (2007). Severe Acute Respiratory Syndrome Coronavirus as an Agent of Emerging and Reemerging Infection. *Clinical Microbiology Reviews*, 20, 660–694.

Chinese Academy of Engineering. (2017). *Sustainable development of China's wild animal breeding industry*.

Chomel, B.B., Belotto, A. & Meslin, F.X. (2007). Wildlife, exotic pets, and emerging zoonoses. *Emerging Infectious Diseases,* 13, 6-11.

Cinelli, M., Quattrociocchi, W., Galeazzi, A., Valensise, C.M., Brugnoli, E., Schmidt, A.L., Zola, P., Zollo, F. & Scala, A. (2020). The covid-19 social media infodemic. *arXiv preprint arXiv:2003.05004*.

Clark, M.A., Springmann, M., Hill, J. & Tilman, D. (2019). Multiple health and environmental impacts of foods. *PNAS*, 116 (46), 23357-23362.

Cleaveland, S., Sharp, J., Abela-Ridder, B., Allan, K.J., Buza, J., Crump, J.A., Davis, A., Del Rio Vilas, V.J., de Glanville, W.A., Kazwala, R.R., Kibona, T., Lankester, F.J., Lugelo, A., Mmbaga, B.T., Rubach, M.P., Swai, E.S., Waldman, L., Haydon, D.T., Hampson, K. & Halliday, J.E.B. (2017). One Health contributions towards more effective and equitable approaches to health in low- and middle-income countries. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372, 20160168.

Coad, L., Fa, J., Abernethy, K., van Vliet, N., Santamaria, C., Wilkie, D., El Bizri, H., Ingram, D., Cawthorn, D. & Nasi, R. (2019). *Towards a sustainable, participatory and inclusive wild meat sector*. CIFOR, Bogor, Indonesia.

Cohen, J. (2020). New coronavirus threat galvanizes scientists. *Science*, 367, 492–493.

Coker, R., Rushton, J., Mounier-Jack, S., Karimuribo, E., Lutumba, P., Kambarage, D., Pfeiffer, D., Stärk, K. & Rweyemamu, M. (2011). Towards a conceptual framework to support one-health research for policy on emerging zoonoses. *The Lancet,* 11, 326-331.

Comte, A., Pendleton, L.H., Bailly, D. & Quillérou, E. (2019). Conceptual advances on global scale assessments of vulnerability: Informing investments for coastal populations at risk of climate change. *Marine Policy*, 99, 391–399.

Cooney, R. & Jepson, P. (2006). The international wild bird trade: what's wrong with blanket bans? *Oryx*, 40, 18–23.

COP26 Postponed | UNFCCC [WWW Document]. (2020). . URL https://unfccc.int/news/cop26-postponed

Corlett, R.T., Primack, R.B., Devictor, V., Maas, B., Goswami, V.R., Bates, A.E., Koh, L.P., Regan, T.J., Loyola, R., Pakeman, R.J., Cumming, G.S., Pidgeon, A., Johns, D. & Roth, R. (2020). Impacts of the coronavirus pandemic on biodiversity conservation. *Biological Conservation*, 108571–108571.

Cunningham, A.A., Daszak, P. & Wood, J.L.N. (2017). One Health, emerging infectious diseases and wildlife: two decades of progress? *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372, 20160167.

Curtis, P.G., Slay, C.M., Harris, N.L., Tyukavina, A. & Hansen, M.C. (2018). Classifying drivers of global forest loss. *Science*, 361, 1108–1111.

Daszak, P. (2012). Anatomy of a pandemic. *The Lancet*, 380, 1883–1884.

Daszak, P., Olival, K.J. & Li, H. (2020). A strategy to prevent future epidemics similar to the 2019-nCoV outbreak. *Biosafety and Health*.

Daszak, P., Plowright, R., Epstein, J.H., Pulliam, J., Abdul Rahman, S., Field, H.E., Smith, C.S., Olival, K.J., Luby, S. & Halpin, K. (2006). The emergence of Nipah and Hendra virus: pathogen dynamics across a wildlife-livestock-human continuum. *Disease Ecology: Community structure and pathogen dynamics*, 186–201.

Degeling, C., Lederman, Z. & Rock, M. (2016). Culling and the Common Good: Re-evaluating Harms and Benefits under the One Health Paradigm. *Public Health Ethics*, 9, 244–254.

Di Marco, M., Baker, M.L., Daszak, P., Barro, P.D., Eskew, E.A., Godde, C.M., Harwood, T.D., Herrero, M., Hoskins, A.J., Johnson, E., Karesh, W.B., Machalaba, C., Garcia, J.N., Paini, D., Pirzl, R., Smith, M.S., Zambrana-Torrelio, C. & Ferrier, S. (2020). Opinion: Sustainable development must account for pandemic risk. *PNAS*, 117, 3888–3892.

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J.R., Arico, S., Báldi, A., Bartuska, A., Baste, I.A., Bilgin, A., Brondizio, E., Chan, K.M., Figueroa, V.E., Duraiappah, A., Fischer, M., Hill, R., Koetz, T., Leadley, P., Lyver, P., Mace, G.M., Martin-Lopez, B., Okumura, M., Pacheco, D., Pascual, U., Pérez, E.S., Reyers, B., Roth, E., Saito, O., Scholes, R.J., Sharma, N., Tallis, H., Thaman, R., Watson, R., Yahara, T., Hamid, Z.A., Akosim, C., Al-Hafedh, Y., Allahverdiyev, R., Amankwah, E., Asah, S.T., Asfaw, Z., Bartus, G., Brooks, L.A., Caillaux, J., Dalle, G., Darnaedi, D., Driver, A., Erpul, G., Escobar-Eyzaguirre, P., Failler, P., Fouda, A.M.M., Fu, B., Gundimeda, H., Hashimoto, S., Homer, F., Lavorel, S., Lichtenstein, G., Mala, W.A., Mandivenyi, W., Matczak, P., Mbizvo, C., Mehrdadi, M., Metzger, J.P., Mikissa, J.B., Moller, H., Mooney, H.A., Mumby, P., Nagendra, H., Nesshover, C., Oteng-Yeboah, A.A., Pataki, G., Roué, M., Rubis, J., Schultz, M., Smith, P., Sumaila, R., Takeuchi, K., Thomas, S., Verma, M., Yeo-Chang, Y. & Zlatanova, D. (2015). The IPBES Conceptual Framework — connecting nature and people. *Current Opinion in Environmental Sustainability*, Open Issue, 14, 1–16.

Dobson, A.P. & Carper, E.R. (1996). Infectious Diseases and Human Population History. *BioScience*, 46, 115–126.

Dulac, J. (2013). Global Land Transport Infrastructure Requirements: Estimating road and railway infrastructure capacity and costs to 2050. IEA.

Ebi, K.L., Hasegawa, T., Hayes, K., Monaghan, A., Paz, S. & Berry, P. (2018). Health risks of warming of 1.5\ hspace0.167em°C, 2\hspace0.167em°C, and higher, above pre-industrial temperatures. *Environ. Res. Lett.*, 13, 063007.

Edwards, D.P., Tobias, J.A., Sheil, D., Meijaard, E. & Laurance, W.F. (2014). Maintaining ecosystem function and services in logged tropical forests. *Trends in Ecology & Evolution*, 29, 511–520.

Elbe, S. (2010). Haggling over viruses: the downside risks of securitizing infectious disease. *Health Policy Plan*, 25, 476–485.

European Food Safety Authority. (2015). Drivers for occasional spillover event of Ebola virus. *EFSA JOURNAL*.

Evans, S. (2020). Analysis: Coronavirus set to cause largest ever annual fall in CO2 emissions [WWW Document]. *Carbon Brief*. URL https://www.carbonbrief.org/analysis-coronavirus-set-to-cause-largest-ever-annual-fall-in-co2-emissions

Ewers, R.M., Boyle, M.J.W., Gleave, R.A., Plowman, N.S., Benedick, S., Bernard, H., Bishop, T.R., Bakhtiar, E.Y., Chey, V.K., Chung, A.Y.C., Davies, R.G., Edwards, D.P., Eggleton, P., Fayle, T.M., Hardwick, S.R., Homathevi, R., Kitching, R.L., Khoo, M.S., Luke, S.H., March, J.J., Nilus, R., Pfeifer, M., Rao, S.V., Sharp, A.C., Snaddon, J.L., Stork, N.E., Struebig, M.J., Wearn, O.R., Yusah, K.M. & Turner, E.C. (2015). Logging cuts the functional importance of invertebrates in tropical rainforest. *Nature Communications*, 6, 6836.

Fa, J.E., Currie, D. & Meeuwig, J. (2003). Bushmeat and food security in the Congo Basin: linkages between wildlife and people’s future | Environmental Conservation | Cambridge Core. *Environmental Conservation*, 30, 71–78.

Fa, J. E., Wright, J. H., Funk, S. M., Márquez, A. L., Olivero, J., Farfán, M., Guio, F., Mayet, L., Malekani, D., Holo Louzolo, C., Mwinyihali, R., Wilkie, D. S. & Wieland, M. (2019). Mapping the availability of bushmeat for consumption in Central African cities. *Environmental Research Letters*, 14, 094002.

Fablet, C. (2009). An overview of the impact of the environment on enzootic respiratory diseases in pigs. In: *Sustainable animal production: The challenges and potential developments for professional farming*. pp. 239–260.

Farand, C. (2020). Coronavirus slows developing nations’ plans to step up climate action in 2020. *Climate Home News*.

Farnese, P.L. (2014). The Prevention Imperative: International Health and Environmental Governance Responses to Emerging Zoonotic Diseases. *Transnational Environmental Law*, 3, 285–309.

Fauci, A.S. (2001). Infectious Diseases: Considerations for the 21st Century. *Clin Infect Dis*, 32, 675–685.

Faust, C.L., Dobson, A.P., Gottdenker, N., Bloomfield, L.S.P., McCallum, H.I., Gillespie, T.R., Diuk-Wasser, M. & Plowright, R.K. (2017). Null expectations for disease dynamics in shrinking habitat: dilution or amplification? *Phil. Trans. R. Soc. B*, 372, 20160173.

Faust, C.L., McCallum, H.I., Bloomfield, L.S.P., Gottdenker, N.L., Gillespie, T.R., Torney, C.J., Dobson, A.P. & Plowright, R.K. (2018). Pathogen spillover during land conversion. *Ecology Letters*, 21, 471–483.

Fearnley, L. (2015). Wild Goose Chase: The Displacement of Influenza Research in the Fields of Poyang Lake, China. *Cultural Anthropology*, 30. Fèvre, E.M., Bronsvoort, B.M. de C., Hamilton, K.A. & Cleaveland, S. (2006). Animal movements and the spread of infectious diseases. *Trends in Microbiology*, 14, 125–131.

Fèvre, E.M., Bronsvoort, B.M. de C., Hamilton, K.A. & Cleaveland, S. (2006). Animal movements and the spread of infectious diseases. *Trends in Microbiology*, 14, 125–131.

Fidler, D.P. (2004). Germs, governance, and global public health in the wake of SARS. *J Clin Invest*, 113, 799–804.

Fischer, J. & Riechers, M. (2019). A leverage points perspective on sustainability. *People and Nature*, 1, 115–120.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D. & Zaks, D.P.M. (2011). Solutions for a cultivated planet. *Nature*, 478, 337–342.

Forgery, Q. (2020). 'Shut down those things right away': Calls to close 'wet markets' ramp up pressure on China - POLITICO. *Politico*.

Friant, S., Ayambem, W.A., Alobi, A.O., Ifebueme, N.M., Otukpa, O.M., Ogar, D.A., Alawa, C.B.I., Goldberg, T.L., Jacka, J.K. & Rothman, J.M. (2020). Eating Bushmeat Improves Food Security in a Biodiversity and Infectious Disease "Hotspot." *EcoHealth*, 17, 125–138.

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N. & Foley, J.A. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *PNAS*, 107, 16732–16737.

Gill, D.A., Cheng, S.H., Glew, L., Aigner, E., Bennett, N.J. & Mascia, M.B. (2019). Social Synergies, Tradeoffs, and Equity in Marine Conservation Impacts. *Annual Review of Environment and Resources*, 44, 347–372.

Global Alliance for Improved Nutrition (GAIN). (2020). Animal-source Foods for Human and Planetary Health: GAIN's Position. Global Alliance for Improved Nutrition (GAIN). Geneva, Switzerland. Briefing Paper Series #2.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M. & Toulmin, C. (2010). Food Security: The Challenge of Feeding 9 Billion People. *Science*, 327, 812–818.

Golden, C.D., Fernald, L.C.H., Brashares, J.S., Rasolofoniaina, B.J.R. & Kremen, C. (2011). Benefits of wildlife consumption to child nutrition in a biodiversity hotspot. *PNAS*, 108, 19653–19656.

Google. (2020). COVID-19 Community Mobility Report [WWW Document]. *COVID-19 Community Mobility Report*. URL https://www.google.com/covid19/mobility

Gortazar, C., Reperant, L.A., Kuiken, T., de la Fuente, J., Boadella, M., Martínez-Lopez, B., Ruiz-Fons, F., Estrada-Peña, A., Drosten, C., Medley, G., Ostfeld, R., Peterson, T., VerCauteren, K.C., Menge, C., Artois, M., Schultsz, C., Delahay, R., Serra-Cobo, J., Poulin, R., Keck, F., Aguirre, A.A., Aguirre, A.A., Henttonen, H., Dobson, A.P., Kutz, S., Lubroth, J. & Mysterud, A. (2014). Crossing the interspecies barrier: opening the door to zoonotic pathogens. *PLoS Pathog.*, 10, e1004129.

Gostin, L.O. & Friedman, E.A. (2015). A retrospective and prospective analysis of the west African Ebola virus disease epidemic: robust national health systems at the foundation and an empowered WHO at the apex. *The Lancet*, 385, 1902–1909.

Grace, D., Mutua, F., Ochungo, P., Kruska, R.L., Jones, K., Brierley, L., Lapar, M.L., Said, M.Y., Herrero, M.T., Phuc, P.M., Thao, N.B., Akuku, I. & Ogutu, F. (2012). *Mapping of poverty and likely zoonoses hotspots* (Report). ILRI.

Graham, J.P., Leibler, J.H., Price, L.B., Otte, J.M., Pfeiffer, D.U., Tiensin, T. & Silbergeld, E.K. (2008). The Animal-Human Interface and Infectious Disease in Industrial Food Animal Production: Rethinking Biosecurity and Biocontainment. *Public Health Rep*, 123, 282–299.

Greenfield, P. (2020). Ban wildlife markets to avert pandemics, says UN biodiversity chief. *The Guardian*.

Greer, C.E. & Doughty, R.W. (1976). Wildlife Utilization in China. *Envir. Conserv.*, 3, 200–208.

Gulland, A. (2015). Institutional failure led to Ebola outbreak "spiraling out of control," says MSF. *BMJ*, 350.

Gupta, J., Scholtens, J., Perch, L., Dankelman, I., Seager, J., Sánder, F., Stanley-Jones, M. & Kempf, I. (2020). Re-imagining the driver–pressure–state–impact–response framework from an equity and inclusive development perspective. *Sustain Sci*, 15, 503–520.

Gustafson, R.H. & Bowen, R.E. (1997). Antibiotic use in animal agriculture. *Journal of Applied Microbiology*, 83, 531–541.

Haddad, N.M., Brudvig, L.A., Clobert, J., Davies, K.F., Gonzalez, A., Holt, R.D., Lovejoy, T.E., Sexton, J.O., Austin, M.P., Collins, C.D., Cook, W.M., Damschen, E.I., Ewers, R.M., Foster, B.L., Jenkins, C.N., King, A.J., Laurance, W.F., Levey, D.J., Margules, C.R., Melbourne, B.A., Nicholls, A.O., Orrock, J.L., Song, D.-X. & Townshend, J.R. (2015). Habitat fragmentation and its lasting impact on Earth's ecosystems. *Sci Adv*, 1, e1500052.

Han, B.A., Kramer, A.M. & Drake, J.M. (2016). Global Patterns of Zoonotic Disease in Mammals. *Trends in Parasitology*, 32, 565–577.

Harfoot, M., Glaser, S.A.M., Tittensor, D.P., Britten, G.L., McLardy, C., Malsch, K. & Burgess, N.D. (2018). Unveiling the patterns and trends in 40 years of global trade in CITES-listed wildlife. *Biological Conservation*, 223, 47–57.

Harvard C-CHANGE. (2020). Coronavirus, Climate Change, and the Environment. *C-CHANGE | Harvard T.H. Chan School of Public Health*.

Harvey, C. (2020). How the Coronavirus Pandemic Is Affecting CO2 Emissions - Scientific American. *Scientific American*.

Hoffman, L.C. & Cawthorn, D.-M. (2012). What is the role and contribution of meat from wildlife in providing high quality protein for consumption? *Animal Frontiers*, 2, 40–53.

Hollenbeck, J.E. (2016). Interaction of the role of Concentrated Animal Feeding Operations (CAFOs) in Emerging Infectious Diseases (EIDS). *Infection, Genetics and Evolution*, 38, 44–46.

Holmes, E.C., Dudas, G., Rambaut, A. & Andersen, K.G. (2016). The Evolution of Ebola virus: Insights from the 2013–2016 Epidemic. *Nature*, 538, 193–200.

Hosonuma, N., Herold, M., Sy, V.D., Fries, R.S.D., Brockhaus, M., Verchot, L., Angelsen, A. & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. *Environ. Res. Lett.*, 7, 044009.

Hosseini, P.R., Mills, J.N., Prieur-Richard, A.-H., Ezenwa, V.O., Bailly, X., Rizzoli, A., Suzán, G., Vittecoq, M., García-Peña, G.E., Daszak, P., Guégan, J.-F. & Roche, B. (2017). Does the impact of biodiversity differ between emerging and endemic pathogens? The need to separate the concepts of hazard and risk. *Philos Trans R Soc Lond B Biol Sci*, 372.

Huang, C., Wang, Y., Li, X., Ren, L., Zhao, J., Hu, Y., Zhang, L., Fan, G., Xu, J., Gu, X., Cheng, Z., Yu, T., Xia, J., Wei, Y., Wu, W., Xie, X., Yin, W., Li, H., Liu, M., Xiao, Y., Gao, H., Guo, L., Xie, J., Wang, G., Jiang, R., Gao, Z., Jin, Q., Wang, J. & Cao, B. (2020). Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. *The Lancet*, 395, 497–506.

Huang, Huaqing. (2019). The rise and fall of middle farmers: accumulation and differentiation in the tea consumption revolution in China. *Canadian Journal of Development Studies / Revue canadienne d'études du développement*, 40, 48–63.

Huang, Y. (2004). *THE SARS EPIDEMIC AND ITS AFTERMATH IN CHINA: A POLITICAL PERSPECTIVE*. *Learning from SARS: Preparing for the Next Disease Outbreak: Workshop Summary*. National Academies Press (US).

Hui, D.S., Azhar, E.I., Madani, T.A., Ntoumi, F., Kock, R., Dar, O., Ippolito, G., Mchugh, T.D., Memish, Z.A., Drosten, C., Zumla, A. & Petersen, E. (2020). The continuing 2019-nCoV epidemic threat of novel coronaviruses to global health — The latest 2019 novel coronavirus outbreak in Wuhan, China. *International Journal of Infectious Diseases*, 91, 264–266.

Hunt, D., Rachel Lombardi, D., Atkinson, S., R. G. Barber, A., Barnes, M., Boyko, C., Brown, J., Bryson, J., Butler, D., Caputo, S., Caserio, M., Coles, R., Cooper, R., Farmani, R., Gaterell, M., Hale, J., Hales, C., Hewitt, C.N., Jankovic, L. & Rogers, C. (2012). *Scenario Archetypes: Converging Rather than Diverging Themes*.

IPBES. (2019). *Global assessment report on biodiversity and ecosystem services*. Intergovernmental Science-Policy Platform on Biodiversity & Ecosystem Services.

IPCC. (2014). *AR5 Climate Change 2014: Impacts, Adaptation & Vulnerability*.

IPCC. (2018a). *IPCC Special Report on Global Warming of 1.5 °C Chapter 3*.

IPCC. (2018b). *IPCC Special Report on Global Warming of 1.5 °C Chapter 5*.

Johns Hopkins University. (2020). COVID-19 Dashboard [WWW Document]. URL https://gisanddata.maps.arcgis.com/apps/opsdashboard/index.html#/bda7594740fd40299423467b48e9ecf6

Johnson, C.K., Hitchens, P.L., Pandit, P.S., Rushmore, J., Evans, T.S., Young, C.C.W. & Doyle, M.M. (2020). Global shifts in mammalian population trends reveal key predictors of virus spillover risk. *Proc. R. Soc. B.*, 287, 20192736.

Jones, B.A., Grace, D., Kock, R., Alonso, S., Rushton, J., Said, M.Y., McKeever, D., Mutua, F., Young, J., McDermott, J. & Pfeiffer, D.U. (2013). Zoonosis emergence linked to agricultural intensification and environmental change. *PNAS*, 110, 8399–8404.

Jones, I.L. & Bull, J.W. (2020). Major dams and the challenge of achieving "No Net Loss" of biodiversity in the tropics. *Sustainable Development*, 28, 435–443.

Jones, K.E., Patel, N.G., Levy, M.A., Storeygard, A., Balk, D., Gittleman, J.L. & Daszak, P. (2008). Global trends in emerging infectious diseases. *Nature*, 451, 990–993.

Jordan, R.E., Adab, P. & Cheng, K.K. (2020). Covid-19: risk factors for severe disease and death. *BMJ*, 368.

Karjalainen, E., Sarjala, T. & Raitio, H. (2010). Promoting human health through forests: overview and major challenges. *Environ Health Prev Med*, 15, 1–8.

Keesing, F., Belden, L.K., Daszak, P., Dobson, A., Harvell, C.D., Holt, R.D., Hudson, P., Jolles, A., Jones, K.E., Mitchell, C.E., Myers, S.S., Bogich, T. & Ostfeld, R.S. (2010). Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature*, 468, 647–652.

Kilpatrick, A.M. & Randolph, S.E. (2012). Drivers, dynamics, and control of emerging vector-borne zoonotic diseases. *The Lancet*, 380, 1946–1955.

Kilpatrick, A.M., Salkeld, D.J., Titcomb, G. & Hahn, M.B. (2017). Conservation of biodiversity as a strategy for improving human health and well-being. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372, 20160131.

Kleinschroth, F. & Healey, J.R. (2017). Impacts of logging roads on tropical forests. *Biotropica*, 49, 620-635.

Knobler. (2004). *Learning from SARS Preparing for the Next Disease Outbreak*.

Kruse, H., Kirkemo, A.-M. & Handeland, K. (2004). Wildlife as Source of Zoonotic Infections. *Emerging Infectious Disease journal*, 10, 2067–2067.

Kubiszewski, I., Costanza, R., Anderson, S. & Sutton, P. (2017). The future value of ecosystem services: Global scenarios and national implications. *Ecosystem Services*, 26, 289–301.

Kung, N.Y., Guan, Y., Perkins, N.R., Bissett, L., Ellis, T., Sims, L., Morris, R.S., Shortridge, K.F. & Peiris, J.S.M. (2003). The Impact of a Monthly Rest Day on Avian Influenza Virus Isolation Rates in Retail Live Poultry Markets in Hong Kong. *Avian Diseases*, 47, 1037–1041.

Lam, T.T.-Y., Shum, M.H.-H., Zhu, H.-C., Tong, Y.-G., Ni, X.-B., Liao, Y.-S., Wei, W., Cheung, W.Y.-M., Li, W.-J., Li, L.-F., Leung, G.M., Holmes, E.C., Hu, Y.-L. & Guan, Y. (2020). Identifying SARS-CoV-2 related coronaviruses in Malayan pangolins. *Nature*.

Lambin, E.F., Meyfroidt, P., Rueda, X., Blackman, A., Börner, J., Cerutti, P.O., Dietsch, T., Jungmann, L., Lamarque, P., Lister, J., Walker, N.F. & Wunder, S. (2014). Effectiveness and synergies of policy instruments for land use governance in tropical regions. *Global Environmental Change*, 28, 129–140.

Langwig, K.E., Voyles, J., Wilber, M.Q., Frick, W.F., Murray, K.A., Bolker, B.M., Collins, J.P., Cheng, T.L., Fisher, M.C., Hoyt, J.R., Lindner, D.L., McCallum, H.I., Puschendorf, R., Rosenblum, E.B., Toothman, M., Willis, C.K.R., Briggs, C.J. & Kilpatrick, A.M. (2015). Context-dependent conservation responses to emerging wildlife diseases. *Frontiers in Ecology and the Environment*, 13, 195–202.

Laurance, W.F. & Arrea, I.B. (2017). Roads to riches or ruin? *Science*, 358, 442-444.

Laurance, W.F., Sloan, S., Weng, L. & Sayer, J.A. (2015). Estimating the Environmental Costs of Africa's Massive "Development Corridors". *Current Biology*, 25, 3202-3208.

Leung, Y.H.C., Lau, E.H.Y., Zhang, L.J., Guan, Y., Cowling, B.J. & Peiris, J.S.M. (2012). Avian influenza and ban on overnight poultry storage in live poultry markets, Hong Kong. *Emerging Infect. Dis.*, 18, 1339–1341.

Li, H., Zhu, G., Zhang, Y., Zhang, L., Hagan, E., Stephanie, M., Chmura, A.A., Francisco, L., Tai, T., Maureen, M. & Daszak, P. (2020). A qualitative study of zoonotic risk among rural communities in Southern China. *International Health*, 12, 1-9.

Li, Y., Wang, Y., Shen, C., Huang, J., Kang, J., Huang, B., Guo, F. & Edwards, J. (2018). Closure of live bird markets leads to the spread of H7N9 influenza in China. *PLoS One*, 13.

Lin, B. (2004). China's domestic animal breeding industry began to take shape. *China Forestry*, 11, 27–28.

Lion Coalition. (2020). Open letter to World Health Organisation [WWW Document]. URL https://lioncoalition.org/2020/04/04/open-letter-to-world-health-organisation/

Lloyd-Smith, J.O., George, D., Pepin, K.M., Pitzer, V.E., Pulliam, J.R.C., Dobson, A.P., Hudson, P.J. & Grenfell, B.T. (2009). Epidemic Dynamics at the Human-Animal Interface. *Science*, 326, 1362–1367.

Lu, D. (2020). The hunt for patient zero: Where did the coronavirus outbreak start? *Scientific American*, 1 April 20.

Ma, W., Kahn, R.E. & Richt, J.A. (2008). The pig as a mixing vessel for influenza viruses: Human and veterinary implications. *J Mol Genet Med*, 3, 158–166.

MacDonald, A.J. & Mordecai, E.A. (2019). Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing. *Proc. Natl. Acad. Sci. U.S.A.*, 116, 22212–22218.

Maldonado, J., Van Reeth, K., Riera, P., Sitjà, M., Saubi, N., Espuña, E. & Artigas, C. (2006). Evidence of the concurrent circulation of H1N2, H1N1 and H3N2 influenza A viruses in densely populated pig areas in Spain. *The Veterinary Journal*, 172, 377–381.

Maruyama, M., Wu, L. & Huang, L. (2016). The modernization of fresh food retailing in China: The role of consumers. *Journal of Retailing and Consumer Services*, 30, 33–39.

McCallum, H. (2012). Disease and the dynamics of extinction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 367, 2828–2839.

McCarthy, A.J., Shaw, M.-A. & Goodman, S.J. (2007). Pathogen evolution and disease emergence in carnivores. *Proceedings of the Royal Society B: Biological Sciences*, 274, 3165–3174.

McCormick, S. (2016). *Health in the Climate Crisis*.

McDaniel, C.J., Cardwell, D.M., Moeller, R.B. & Gray, G.C. (2014). Humans and Cattle: A Review of Bovine Zoonoses. *Vector Borne Zoonotic Dis*, 14, 1–19.

McEvoy, J.F., Connette, G., Huang, Q., Soe, P., Pyone, K.H.H., Valitutto, M., Htun, Y.L., Lin, A.N., Thant, A.L., Htun, W.Y., Paing, K.H., Swe, K.K., Aung, M., Min, S., Songer, M. & Leimgruber, P. (2019). Two sides of the same coin - Wildmeat consumption and illegal wildlife trade at the crossroads of Asia. *Biol. Conserv.*, 238, UNSP 108197.

McKenna, J. (2017). The deadly diseases being released by climate change [WWW Document]. *World Economic Forum*. URL https://www.weforum.org/agenda/2017/05/the-deadly-diseases-being-released-by-climate-change/

McKinnon, M.C., Cheng, S.H., Dupre, S., Edmond, J., Garside, R., Glew, L., Holland, M.B., Levine, E., Masuda, Y.J., Miller, D.C., Oliveira, I., Revenaz, J., Roe, D., Shamer, S., Wilkie, D., Wongbusarakum, S. & Woodhouse, E. (2016). What are the effects of nature conservation on human well-being? A systematic map of empirical evidence from developing countries. *Environmental Evidence*, 5, 8.

Meadows, D. (1999). *Leverage Points: Places to intervene in a system*. The Sustainability Institute, Hartland, VT.

Meadows, D. (2008). *Thinking in Systems: A Primer*. Chelsea Green Publishing, USA.

Mele, C., Ng, M. & Chim, M.B. (2015). Urban markets as a 'corrective' to advanced urbanism: The social space of wet markets in contemporary Singapore. *Urban Studies*, 52, 103–120.

Melin, A.D., Janiak, M.C., Marrone, F., Arora, P.S. & Higham, J.P. (2020). Comparative ACE2 variation and primate COVID-19 risk. *bioRxiv*, 2020.04.09.034967.

Michie, S., van Stralen, M.M. & West, R. (2011). The behaviour change wheel: A new method for characterising and designing behaviour change interventions. *Implementation Sci*, 6, 42.

Mildenstein, T., Tanshi, I. & Racey, P.A. (2016). Exploitation of Bats for Bushmeat and Medicine. In: *Bats in the Anthropocene: Conservation of Bats in a Changing World* (eds. Voigt, C.C. & Kingston, T.). Springer International Publishing, Cham, pp. 325–375.

Mills, J.N., Gage, K.L. & Khan, A.S. (2010). Potential influence of climate change on vector-borne and zoonotic diseases: a review and proposed research plan. *Environ. Health Perspect.*, 118, 1507–1514.

Morens, D.M., Daszak, P. & Taubenberger, J.K. (2020). Escaping Pandora's Box — Another Novel Coronavirus. *New England Journal of Medicine*, 382, 1293–1295.

Morgan, D., Strindberg, S., Winston, W., Stephens, C.R., Traub, C., Ayina, C.E., Ebika, S.T.N., Mayoukou, W., Koni, D., Iyenguet, F. & Sanz, C.M. (2019). Impacts of Selective Logging and Associated Anthropogenic Disturbance on Intact Forest Landscapes and Apes of Northern Congo. *Front. For and Glob. Change*, 2:28.

Morse, S.S., Mazet, J.A., Woolhouse, M., Parrish, C.R., Carroll, D., Karesh, W.B., Zambrana-Torrelio, C., Lipkin, W.I. & Daszak, P. (2012). Prediction and prevention of the next pandemic zoonosis. *The Lancet*, 380, 1956–1965.

Muzemil, A., Fasanmi, O.G. & Fasina, F.O. (2015). African perspectives: modern complexities of emerging, re-emerging, and endemic zoonoses. *J Glob Health*, 8.

Naidoo, R., Gerkey, D., Hole, D., Pfaff, A., Ellis, A.M., Golden, C.D., Herrera, D., Johnson, K., Mulligan, M., Ricketts, T.H. & Fisher, B. (2019). Evaluating the impacts of protected areas on human well-being across the developing world. *Sci. Adv.*, 5, eaav3006.

Nasi, R., Taber, A. & Van Vliet, N. (2011). Empty forests, empty stomachs? Bushmeat and livelihoods in the Congo and Amazon Basins [WWW Document]. URL https://www.ingentaconnect.com/content/cfa/ifr/2011/00000013/00000003/art00008

National Research Council. (1983). *Risk assessment in the Federal Government: manage the process*. The National Academies Press, Washington DC, USA.

Neijman, V. & Nekaris, K. (2014). Trade in wildlife in Bali, Indonesia, for medicinal and decorative purposes. *Traffic Bulletin*, 26, 31–31.

Newbold, T., Hudson, L.N., Hill, S.L.L., Contu, S., Lysenko, I., Senior, R.A., Börger, L., Bennett, D.J., Choimes, A., Collen, B., Day, J., De Palma, A., Díaz, S., Echeverria-Londoño, S., Edgar, M.J., Feldman, A., Garon, M., Harrison, M.L.K., Alhusseini, T., Ingram, D.J., Itescu, Y., Kattge, J., Kemp, V., Kirkpatrick, L., Kleyer, M., Correia, D.L.P., Martin, C.D., Meiri, S., Novosolov, M., Pan, Y., Phillips, H.R.P., Purves, D.W., Robinson, A., Simpson, J., Tuck, S.L., Weiher, E., White, H.J., Ewers, R.M., Mace, G.M., Scharlemann, J.P.W. & Purvis, A. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, 520, 45–50.

Nguyen, T.T.T., Fearnley, L., Dinh, X.T., Tran, T.T.A., Tran, T.T., Nguyen, V.T., Tago, D., Padungtod, P., Newman, S.H. & Tripodi, A. (2017). A Stakeholder Survey on Live Bird Market Closures Policy for Controlling Highly Pathogenic Avian Influenza in Vietnam. *Front. Vet. Sci.*, 4.

Nielsen, M.R., Meilby, H., Smith-Hall, C., Pouliot, M. & Treue, T. (2018). The Importance of Wild Meat in the Global South. *Ecological Economics*, 146, 696–705.

Nijman, V. (2010). An overview of international wildlife trade from Southeast Asia. *Biodiversity Conservation*, 19, 1101–1114.

Olival, K.J., Hosseini, P.R., Zambrana-Torrelio, C., Ross, N., Bogich, T.L. & Daszak, P. (2017). Host and viral traits predict zoonotic spillover from mammals. *Nature*, 546, 646–650.

Olivero, J., Fa, J.E., Real, R., Márquez, A.L., Farfán, M.A., Vargas, J.M., Gaveau, D., Salim, M.A., Park, D., Suter, J., King, S., Leendertz, S.A., Sheil, D. & Nasi, R. (2017). Recent loss of closed forests is associated with Ebola virus disease outbreaks. *Scientific Reports*, 7, 1–9.

O'Malley, P., Rainford, J. & Thompson, A. (2009). Transparency during public health emergencies: from rhetoric to reality. *Bull World Health Organ*, 87, 614–618.

O'Neill. (2016). *Tackling drug-resistant infections globally: final report and recommendations*. Review on antimicrobial resistance.

Onyekuru, A.N., Ezea, C.P. & Ihemezie, E.J. (2018). Assessment of the Structural Effects of Ebola Disease Outbreak on Bush Meat Enterprise in Nigeria: Implications on Biodiversity Conservation. *Journal of Agriculture and Ecology Research International*, 1–13.

Orlik, T., Rush, J., Cousin, M. & Hong, J. (2020). Coronavirus Could Cost the Global Economy $2.7 Trillion. Here's How. *Bloomberg*.

Ostrom, E. (1990). *Governing the Commons: The evolution of institutions for collective action*. Cambridge University Press, New York, NY.

Otte, J., Roland-Holst, D., Pfeiffer, D., Soares-Magalhaes, R., Rushton, J., Graham, J. & Silbergeld, E. (2007). *Industrial Livestock Production and Global Health Risks*. A Living from Livestock Research Report. Pro-Poor Livestock Policy Initiative.

Padgett, D.A. & Glaser, R. (2003). How stress influences the immune response. *Trends in Immunology*, 24, 444–448.

Parker, I.M., Saunders, M., Bontrager, M., Weitz, A.P., Hendricks, R., Magarey, R., Suiter, K. & Gilbert, G.S. (2015). Phylogenetic structure and host abundance drive disease pressure in communities. *Nature*, 520, 542–544.

Parkinson, A.J., Evengard, B., Semenza, J.C., Ogden, N., Børresen, M.L., Berner, J., Brubaker, M., Sjöstedt, A., Evander, M., Hondula, D.M., Menne, B., Pshenichnaya, N., Gounder, P., Larose, T., Revich, B., Hueffer, K. & Albihn, A. (2014). Climate change and infectious diseases in the Arctic: establishment of a circumpolar working group. *International Journal of Circumpolar Health*, 73, 25163.

Pavlin, B.I., Schloegel, L.M. & Daszak, P. (2009). Risk of Importing Zoonotic Diseases through Wildlife Trade, United States. *Emerg Infect Dis*, 15, 1721–1726.

Peiris, M., Cowling, B.J., Wu, J.T., Feng, L., Guan, Y., Yu, H. & Leung, G.M. (2016). Interventions to reduce zoonotic and pandemic risks from avian influenza in Asia. *Lancet Infect Dis*, 16, 252–258.

Pellecchia, U. (2017). Quarantine and Its Malcontents: How Liberians Responded to the Ebola Epidemic Containment Measures. *Anthropology in Action*, 24, 15–24.

Pew Charitable Trusts. (2008). Putting meat on the table: Industrial farm animal production in America. *A Report of the Pew commission on industrial Farm Animal Production*.

Plowright, R.K., Parrish, C.R., McCallum, H., Hudson, P.J., Ko, A.I., Graham, A.L. & Lloyd-Smith, J.O. (2017). Pathways to zoonotic spillover. *Nature Reviews Microbiology*, 15, 502–510.

Pooley, S., Fa, J.E. & Nasi, R. (2015). No conservation silver lining to Ebola. *Conservation Biology*, 29, 965–967.

Pulliam, J.R.C., Epstein, J.H., Dushoff, J., Rahman, S.A., Bunning, M., Jamaluddin, A.A., Hyatt, A.D., Field, H.E., Dobson, A.P. & Daszak, P. (2012). Agricultural intensification, priming for persistence and the emergence of Nipah virus: a lethal bat-borne zoonosis. *Journal of The Royal Society Interface*, 9, 89–101.

Raskin, P.D. (2005). Global Scenarios: Background Review for the Millennium Ecosystem Assessment. *Ecosystems*, 8, 133–142.

Reino, L., Figueira, R., Beja, P., Araújo, M.B., Capinha, C. & Strubbe, D. (2017). Networks of global bird invasion altered by regional trade ban. *Science Advances*, 3, e1700783.

Ritchie, H. & Roser, M. (2017). Meat and Dairy Production [WWW Document]. *Our World in Data*. URL https://ourworldindata.org/meat-production

Robinson, B.E., Holland, M.B. & Naughton-Treves, L. (2014). Does secure land tenure save forests? A meta-analysis of the relationship between land tenure and tropical deforestation. *Global Environmental Change*, 29, 281–293.

Robinson, N.A. & Walzer, C. (2020). Opinion: How Do We Prevent the Next Outbreak? *Scientific American*, March 25,.

Robinson, R.A., Lawson, B., Toms, M.P., Peck, K.M., Kirkwood, J.K., Chantrey, J., Clatworthy, I.R., Evans, A.D., Hughes, L.A., Hutchinson, O.C., John, S.K., Pennycott, T.W., Perkins, M.W., Rowley, P.S., Simpson, V.R., Tyler, K.M. & Cunningham, A.A. (2010). Emerging Infectious Disease Leads to Rapid Population Declines of Common British Birds. *PLOS ONE*, 5, e12215–e12215.

Rohr, J.R., Barrett, C.B., Civitello, D.J., Craft, M.E., Delius, B., DeLeo, G.A., Hudson, P.J., Jouanard, N., Nguyen, K.H., Ostfeld, R.S., Remais, J.V., Riveau, G., Sokolow, S.H. & Tilman, D. (2019). Emerging human infectious diseases and the links to global food production. *Nature Sustainability*, 2, 445–456.

Rohr, J.R., Dobson, A.P., Johnson, P.T.J., Kilpatrick, A.M., Paull, S.H., Raffel, T.R., Ruiz-Moreno, D. & Thomas, M.B. (2011). Frontiers in climate change–disease research. *Trends in Ecology & Evolution*, 26, 270–277.

Rulli, M.C., Santini, M., Hayman, D.T.S. & D'Odorico, P. (2017). The nexus between forest fragmentation in Africa and Ebola virus disease outbreaks. *SCIENTIFIC REPORTS*.

Salkeld, D.J., Padgett, K.A. & Jones, J.H. (2013). A meta-analysis suggesting that the relationship between biodiversity and risk of zoonotic pathogen transmission is idiosyncratic. *Ecology Letters*, 16, 679–686.

Sanjuán, R. & Domingo-Calap, P. (2016). Mechanisms of viral mutation. *Cell. Mol. Life Sci.*, 73, 4433–4448.

Scoones, I. (2010). *Avian influenza: science, policy and politics*. Earthscan, London.

Scoones, I., Stirling, A., Abrol, D., Atela, J., Charli-Joseph, L., Eakin, H., Ely, A., Olsson, P., Pereira, L., Priya, R., van Zwanenberg, P. & Yang, L. (2020). Transformations to sustainability: combining structural, systemic and enabling approaches. *Current Opinion in Environmental Sustainability*, 42, 65–75.

Semenza, J.C. & Menne, B. (2009). Climate change and infectious diseases in Europe. *The Lancet Infectious Diseases*, 9, 365–375.

Shah, H.A., Huxley, P., Elmes, J. & Murray, K.A. (2019). Agricultural land-uses consistently exacerbate infectious disease risks in Southeast Asia. *Nature Communications*, 10, 4299.

Shairp, R., Veríssimo, D., Fraser, I., Challender, D. & MacMillan, D. (2016). Understanding Urban Demand for Wild Meat in Vietnam: Implications for Conservation Actions. *PLoS One*, 11.

Si, Z. & Scott, S. (2019). China's changing food system: top-down and bottom-up forces in food system transformations. *Canadian Journal of Development Studies / Revue canadienne d'études du développement*, 40, 1–11.

Si, Z., Scott, S. & McCordic, C. (2019). Wet markets, supermarkets and alternative food sources: consumers' food access in Nanjing, China. *Canadian Journal of Development Studies / Revue canadienne d'études du développement*, 40, 78–96.

Smith, K.F., Goldberg, M., Rosenthal, S., Carlson, L., Chen, J., Chen, C. & Ramachandran, S. (2014). Global rise in human infectious disease outbreaks. *Journal of The Royal Society Interface*, 11, 20140950.

Sokolow, S.H., Nova, N., Pepin, K.M., Peel, A.J., Pulliam, J.R.C., Manlove, K., Cross, P.C., Becker, D.J., Plowright, R.K., McCallum, H. & De Leo, G.A. (2019). Ecological interventions to prevent and manage zoonotic pathogen spillover. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 374, 20180342–20180342.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J. & Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature*, 562, 519–525.

StartUp Blink. (2020). Global Map of Coronavirus Innovations [WWW Document]. URL https://coronavirus.startupblink.com/innovations

Swei, A., Couper, L.I., Coffey, L.L., Kapan, D. & Bennett, S. (2019). Patterns, Drivers, and Challenges of Vector-Borne Disease Emergence. *Vector-Borne and Zoonotic Diseases*, 20, 159–170.

Symes, W.S., McGrath, F.L., Rao, M. & Carrasco, L.R. (2018). The gravity of wildlife trade. *Biological Conservation*, 218, 268–276.

't Sas-Rolfes, M., Challender, D.W.S., Hinsley, A., Veríssimo, D. & Milner-Gulland, E.J. (2019). Illegal Wildlife Trade: Patterns, Processes, and Governance. *Annual Review of Environment and Resources*.

Taubenberger, J.K. & Morens, D.M. (2019). The 1918 Influenza Pandemic and Its Legacy. *Cold Spring Harb Perspect Med*, a038695.

Teh, L., Zeller, D., Zylich, K., Nguyen, G. & Harper, S. (2016). Vietnam. In: *Global Atlas of Marine Fisheries: A Critical Appraisal of Catches and Ecosystem Impact*. Island Press, Washington DC, USA, p. 455.

Tensen, L. (2016). Under what circumstances can wildlife farming benefit species conservation? *Global Ecology and Conservation*, 6, 286–298.

Tilman, D. & Clark, M. (2014). Global diets link environmental sustainability and human health. *Nature*, 515, 518–522.

Tu, C., Crameri, G., Kong, X., Chen, J., Sun, Y., Yu, M., Xiang, H., Xia, X., Liu, S., Ren, T., Yu, Y., Eaton, B.T., Xuan, H. & Wang, L.-F. (2004). Antibodies to SARS Coronavirus in Civets. *Emerg Infect Dis*, 10, 2244–2248.

Turner, R.A., Addison, J., Arias, A., Bergseth, B.J., Marshall, N.A., Morrison, T.H. & Tobin, R.C. (2016). Trust, confidence, and equity affect the legitimacy of natural resource governance. *Ecology and Society*, 21.

UNEP, U.N. (2017). UNEP Frontiers 2016: Emerging issues of environmental concern [WWW Document]. *UNEP - UN Environment Programme*. URL http://www.unenvironment.org/resources/frontiers-2016-emerging-issues-environmental-concern

Union of Concerned Scientists. (2013). SARS: A Pandemic Prevented [WWW Document]. URL https://www.ucsusa.org/resources/sars-pandemic-prevented

Van Vliet, N., Muhindo, J., Nyumu, J.K. & Nasi, R. (2019). From the Forest to the Dish: A Comprehensive Study of the Wildmeat Value Chain in Yangambi, Democratic Republic of Congo. *Front. Ecol. Evol.*, 7, 132.

Wallace, R. et al. (2020). COVID-19 and Circuits of Capital. *Monthly Review*, March 2020.

Wang, Anderson, D.E., Mackenzie, J.S. & Merson, M.H. (2020a). From Hendra to Wuhan: what has been learned in responding to emerging zoonotic viruses. *The Lancet*, 395, e33–e34.

Wang, L.-F. & Crameri, G. (2014). Emerging zoonotic viral diseases. *Rev. - Off. Int. Epizoot.*, 33, 569–581.

Wang, Wei., Artois, J., Wang, X., Kucharski, A.J., Pei, Y., Tong, X., Virlogeux, V., Wu, P., Cowling, B.J., Gilbert, M. & Yu, H. (2020b). Early Release - Effectiveness of Live Poultry Market Interventions on Human Infection with Avian Influenza A(H7N9) Virus, China - Volume 26, Number 5—May 2020 - Emerging Infectious Diseases journal - CDC.

Webster, R.G. (2004). Wet markets—a continuing source of severe acute respiratory syndrome and influenza? *The Lancet*, 363, 234–236.

Wei, P., Cai, Z., Hua, J., Yu, W., Chen, J., Kang, K., Qiu, C., Ye, L., Hu, J. & Ji, K. (2016). Pains and Gains from China's Experiences with Emerging Epidemics: From SARS to H7N9 [WWW Document]. *BioMed Research International*. URL https://www.hindawi.com/journals/bmri/2016/5717108/

Westley, F.R., Tjornbo, O., Schultz, L., Olsson, P., Folke, C., Crona, B. & Bodin, □rjan. (2013). A Theory of Transformative Agency in Linked Social-Ecological Systems. *Ecology and Society*, 18.

Wiethoelter, A.K., Beltrán-Alcrudo, D., Kock, R. & Mor, S.M. (2015). Global trends in infectious diseases at the wildlife–livestock interface. *Proc Natl Acad Sci USA*, 112, 9662.

Wilcox, B.A. & Gubler, D.J. (2005). Disease ecology and the global emergence of zoonotic pathogens. *Environmental Health and Preventive Medicine*, 10, 263–263.

Williams, T. (2014). Ebola's silver lining - ScienceDirect. *New Scientist*, 223, 26–27.

Woo, P.C., Lau, S.K. & Yuen, K. (2006). Infectious diseases emerging from Chinese wet-markets: zoonotic origins of severe respiratory viral infections. *Current Opinion in Infectious Diseases*, 19, 401–407.

Wood, C.L., Lafferty, K.D., DeLeo, G., Young, H.S., Hudson, P.J. & Kuris, A.M. (2014). Does biodiversity protect humans against infectious disease? *Ecology*, 95, 817–832.

Woolhouse, M.E.J. (2008). Emerging diseases go global. *Nature*, 451, 898–899.

Woolhouse, M.E.J. & Gowtage-Sequeria, S. (2005). Host Range and Emerging and Reemerging Pathogens. *Emerg Infect Dis*, 11, 1842–1847.

World Bank. (2012). *The Economics of One Health* (Vol 2). People, Pathogens & Our Planet. World Bank, Washington DC, USA.

World Health Organization. (2004). *Report of the WHO/FAO/OIE joint consultation on emerging zoonotic diseases*. World Health Organization.

World Health Organization. (2014). *A brief guide to emerging infectious diseases and zoonoses*. WHO Regional Office for South-East Asia.

World Health Organization. (2016). Ebola Situation Report [WWW Document]. URL https://apps.who.int/ebola/current-situation/ebola-situation-report-16-march-2016

World Health Organization. (2018). Antibiotic resistance [WWW Document]. URL https://www.who.int/news-room/fact-sheets/detail/antibiotic-resistance

World Health Organization. (2019). Summary of probable SARS cases with onset of illness from 1 November 2002 to 31 July 2003 [WWW Document]. *WHO*. URL https://www.who.int/csr/sars/country/table2004_04_21/en/

World Health Organization. (2020a). Disease Outbreaks [WWW Document]. *WHO*. URL http://www.who.int/emergencies/diseases/en/

World Health Organization. (2020b). SARS (Severe Acute Respiratory Syndrome) [WWW Document]. *WHO*. URL https://www.who.int/ith/diseases/sars/en/

Wu, P., Jiang, H., Wu, J.T., Chen, E., He, J., Zhou, H., Wei, L., Yang, J., Yang, B., Qin, Y., Fang, V.J., Li, M., Tsang, T.K., Zheng, J., Lau, E.H.Y., Cao, Y., Chai, C., Zhong, H., Li, Z., Leung, G.M., Feng, L., Gao, G.F., Cowling, B.J. & Yu, H. (2014). Poultry Market Closures and Human Infection with Influenza A(H7N9) Virus, China, 2013–14. *Emerg Infect Dis*, 20, 1891–1894.

Wuethrich, B. (2003). INFECTIOUS DISEASE: Chasing the Fickle Swine Flu. *Science*, 299, 1502–1505.

Yong, E. (2014). Giant virus resurrected from 30,000-year-old ice. *Nature News*.

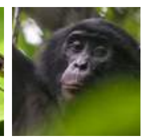
Yu, H., Wu, J.T., Cowling, B.J., Liao, Q., Fang, V.J., Zhou, S., Wu, P., Zhou, H., Lau, E.H.Y., Guo, D., Ni, M.Y., Peng, Z., Feng, L., Jiang, H., Luo, H., Li, Q., Feng, Z., Wang, Y., Yang, W. & Leung, G.M. (2014). Effect of closure of live poultry markets on poultry-to-person transmission of avian influenza A H7N9 virus: an ecological study. *The Lancet*, 383, 541–548.

Photo credits

Cover: © naturepl.com / Andy Rouse / WWF
Page 2: © Jonathan Caramanus / Green Renaissance / WWF-UK
Page 3: Left to right: © Luis Barreto / WWF-UK; © Shutterstock.com; © Shutterstock.com; © Karine Aigner / WWF-US; © Greg Armfield / WWF-UK
Page 4: © Martin Harvey / WWF
Page 5: © Shutterstock.com
Page 8: © Luis Barreto / WWF-UK
Page 9: © WWF
Page 10: © Luis Barreto / WWF-UK
Page 11: © Shutterstock.com
Page 13: © © Edward Parker / WWF
Page 15: © Shutterstock.com
Page 17: © Adriano Gambarini / WWF Living Amazon Initiative
Page 18: © Luis Barreto / WWF-UK
Page 20: © Shutterstock.com
Page 21: Left: © Ronald Petocz / WWF; right: © Global Warming Images / WWF).
Page 22: © Thomas Nicolon / WWF DRC
Page 24: © Minzayar Oo / WWF-US
Page 26: © Shutterstock.com
Page 27: © Brent Stirton / Getty Images / WWF-UK
Page 28: © Luis Barreto / WWF-UK
Page 31: © Karine Aigner / WWF-US
Page 32: © Pixaby.com
Page 33: Top: © Brent Stirton / Reportage by Getty Images / WWF, bottom: © Luis Barreto / WWF-UK
Page 35: © WWF / Simon Rawles
Page 37: © WWF / James Morgan
Page 39: © Ola Jennersten / WWF-Sweden
Page 40: © James Frankham / WWF
Page 41: © Sean Rayford / Stringer / Getty Images
Page 42: Top: © Greg Armfield / WWF-UK; bottom: © Paul Weinberg / WWF
Page 44: © Luis Barreto / WWF-UK
Page 45: © Luis Barreto / WWF-UK
Page 46: © Shutterstock.com
Page 47: © WWF / Yunaidi Joepoet
Page 49: © Shutterstock.com
Page 51: © Shutterstock.com
Page 53: © James Frankham / WWF
Page 55: © André Bärtschi / WWF
Page 56: © Greg Armfield / WWF-UK
Page 67: © Shutterstock.com

Beyond Boundaries

Insights into emerging zoonotic diseases, nature, and human well-being

WWF