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COVID-19 RESPONSE

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CGIAR

PREVENTING THE NEXT PANDEMIC

Zoonotic diseases and how to break the chain of transmission

A Scientific Assessment with Key Messages for Policy-Makers

A Special Volume of UNEP's *Frontiers* Report Series

ISBN No: 978-92-807-3792-9
Job No: DEW/2290/NA

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Suggested citation

United Nations Environment Programme and International Livestock Research Institute (2020). Preventing the Next Pandemic: Zoonotic diseases and how to break the chain of transmission. Nairobi, Kenya.

Production

Science Division | United Nations Environment Programme | P.O. Box 30552, Nairobi, 00100, Kenya
Tel: +254 20 7621234 | Email: unep-publications@un.org | www.unep.org

A Special Volume of UNEP's *Frontiers* Report Series

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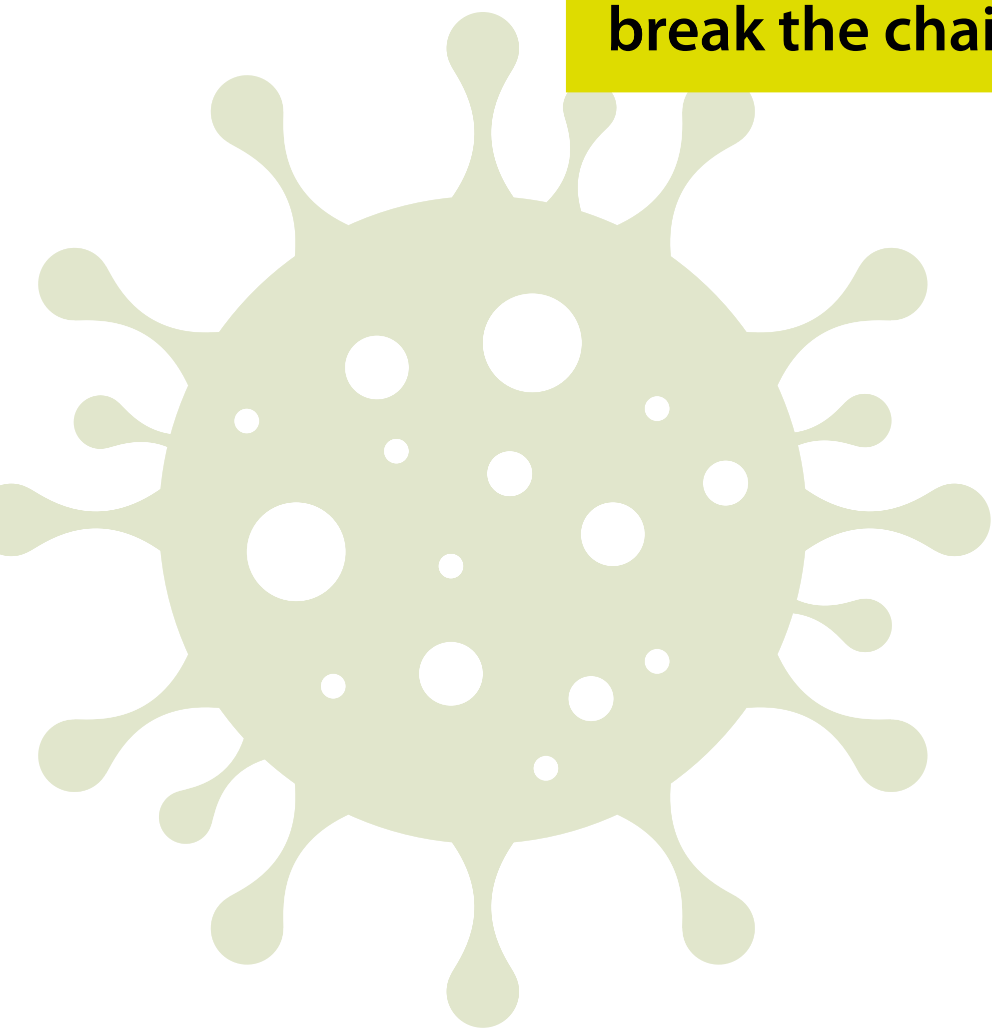

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Acknowledgements

The United Nations Environment Programme (UNEP) would like to thank the authors, reviewers and the supporting organizations for their contribution to the preparation of this rapid scientific assessment report.

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Thanks also to:

Jimmy Smith (ILRI); Judith Akoth, Inger Andersen, Magda Biesiada, Alexander Caldas, Harsha Dave, Angeline Djampou, Sandor Frigyik, Tito Kimathi, Emily Kilonzi, Rachel Kosse, Fred Lerionka, Jian Liu, Lu Liu, Janet Macharia, Isabel Martínez, Nada Matta, Joyce Mavoungou, Abdelmenam Mohamed, Joyce Msuya, Pascil Muchesia, Jane Muriithi, Daniel Nthiwa, David Osborn, Rafael Peralta, Julia Rugo, Nandita Surendran, Ying Wang, Edoardo Zandri and Jing Zheng (all: UNEP, Nairobi, Kenya); and David Berman (independent).

Partners

The United Nations Environment Programme would like to express its gratitude to the International Livestock Research Institute (ILRI, Nairobi, Kenya), the South African Medical Research Council (SAMRC, Pretoria, South Africa) and the Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals (CMS, Bonn, Germany) for their extraordinary support to the development, launch and communication of this rapid scientific assessment report.

UNEP and ILRI are thankful for the support received from the following organisations:

UNEP AEWA

CEBioS

Convention on Biological Diversity

CGIAR

CMS

EcoHealth Alliance

EUROBATS

EMORY UNIVERSITY

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OIE
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RVC Royal Veterinary College
University of London

SAFOSO

National Council for Science and the Environment

SAMRC advancing life

South African NATIONAL PARKS

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Contents

Abbreviations and Acronyms

AIDS	acquired immune deficiency syndrome
BSE	bovine spongiform encephalopathy
CBD	Convention on Biological Diversity
CGIAR	A global partnership for a food secure future
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
CMS	Convention on Migratory Species (Bonn Convention)
COP	Conference of the Parties
COVID-19	coronavirus disease 2019
DNA	deoxyribonucleic acid
EID	emerging infectious disease
FAO	Food and Agriculture Organization of the United Nations
GDP	gross domestic product
HCoV-OC43	human coronavirus subtype OC43
HIV/AIDS	human immunodeficiency virus/acquired immune deficiency syndrome
HPAI	highly pathogenic avian influenza
IBD	inflammatory bowel disease
ILRI	International Livestock Research Institute
MERS	Middle East respiratory syndrome
MERS-CoV	Middle East respiratory syndrome coronavirus
OIE	World Organisation for Animal Health
PED	porcine epidemic diarrhoea
RNA	ribonucleic acid
RVF	Rift Valley fever
SARS	severe acute respiratory syndrome
SARS-CoV	severe acute respiratory syndrome coronavirus
SARS-CoV-2	severe acute respiratory syndrome coronavirus 2
SIV	simian immunodeficiency virus
TGE	transmissible gastroenteritis
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children’s Fund
WHO	World Health Organization

Foreword by the Executive Director of UNEP

COVID-19 has caused profound damage to human health, societies and economies in every corner of the world. This illness is zoonotic, a type of disease that transmits between animals and humans. It may be the worst, but it is not the first. We already know that 60 per cent of known infectious diseases in humans and 75 per cent of all emerging infectious diseases are zoonotic. Ebola, SARS, the Zika virus and bird flu all came to people by way of animals.

As we seek to build back better after COVID-19, we need to fully understand the transmission of zoonoses, the threats they pose to human health and how to minimize the risk of further devastating outbreaks. This requires an ambitious line of enquiry, in which this report, Preventing the next pandemic: Zoonotic diseases and how to break the chain of transmission, is a crucial first step.

The report—produced in partnership with universities, research institutions, UN agencies and the secretariats of several multilateral environmental agreements—identifies key anthropogenic drivers for the emergence of zoonoses, from agricultural intensification and increased demand for animal protein to the conversion of land and climate change. These drivers are destroying natural habitats and seeing humanity exploiting more species, which brings people into closer contact with disease vectors. Once established in humans, these diseases quickly spread across our interconnected world, as we have seen with COVID-19.

Understanding these drivers is essential to inform effective strategies and policy responses to prevent future outbreaks. This report makes many recommendations, all based on the One Health approach, which unites experts from multiple disciplines—public health, animal health, plant health and the environment —to deliver outcomes that improve the health of people, wildlife and the planet.

The recommendations include expanding scientific enquiry into zoonoses, regulating and monitoring traditional food markets, incentivizing the legal wildlife trade and animal husbandry to adopt zoonotic control measures, and radically transforming food systems. Above all, governments, citizens and the private sector need to work together. This is a global challenge that nobody can hide from. It crosses every discipline and every border. The drivers of pandemics are often also the drivers of climate change and biodiversity loss—two long-term challenges that have not gone away during the pandemic.

At the heart of our response to zoonoses and the other challenges humanity faces should be the simple idea that the health of humanity depends on the health of the planet and the health of other species. If humanity gives nature a chance to breathe, it will be our greatest ally as we seek to build a fairer, greener and safer world for everyone.

Inger Andersen
Executive Director
United Nations Environment Programme
July 2020

UN environment programme

Foreword by the Director General of ILRI

I am honoured to introduce this collaborative report by scientists of the United Nations Environment Programme (UNEP), the International Livestock Research Institute (ILRI) and the South African Medical Research Council in partnership with other UN and multilateral agencies and leading universities and research institutions. It is altogether fitting that environment, livestock and medical expertise should join up to help understand and stem the rise of human contagions.

This report will deepen the reader's understanding of the virus causing the global COVID-19 pandemic and other pathogens that have similarly jumped species from their animal to human hosts. These 'zoonotic' diseases are increasing as the world's growing human population broadens and deepens interactions among people, animals and environments.

To date, most efforts to control zoonotic diseases have been reactive rather than proactive. COVID-19 has made us all aware that it's time to change that. To prevent future outbreaks of novel zoonotic diseases, we need to address the root causes of their emergence. We need among other things to break down disciplinary and organisational silos, to invest in public health programmes, to farm sustainably, to end the over-exploitation of wildlife, to restore land and ecosystem health and to reduce climate change.

The only way to achieve all of this is to boost collaboration among agencies that work on environment, animal and human health. In the past two decades, 'One Health'—a holistic, inter-sectoral and interdisciplinary approach that focuses on where the health of people, animals and environments converge—has emerged as the most promising way to prevent and manage zoonotic diseases. I have long championed use of 'One Health', but while experts agree that it is the optimal way to ensure a healthier future for all of us, this approach needs to be strengthened and mainstreamed everywhere, particularly the environment aspects of One Health, and it needs to receive vastly greater financial and institutional support. We must work in productive and novel ways across the human, animal and environment sectors and at every level—from village to ministry to global. This collaborative work by leading environment, livestock and human health organisations is an example of such vital cross-sector work.

United and proactive in moving a healthy people-animal-environment development agenda forward, governments, agencies and communities together can stop future zoonoses from happening. At the same time, these new coalitions will enable us to 'build back' healthy ecosystems while also meeting the world's Sustainable Development Goals, with historic and enduring returns on investment. This report is an early attempt to outline ways by which institutions of all kinds—in government, business and civil society—might work together to create such a legacy.

Jimmy Smith
Director General
International Livestock Research Institute
July 2020

ILRI INTERNATIONAL LIVESTOCK RESEARCH INSTITUTE

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Key messages

This evidence-based scientific assessment has identified the following ten key messages for decision-makers:

1. **DE-RISKING FOOD SYSTEMS:** Many new science-based policy reports continue to focus on the global public health emergency caused by the COVID-19 pandemic, following the fast spread of the infectious SARS-CoV-2 virus of zoonotic origin. We need more evidence-based scientific assessments, such as this one, to examine the environmental and zoonotic context of the current pandemic, as well as the risk of future zoonotic disease outbreaks.
2. **URGENCY:** Diseases are emerging more frequently from animals. Rapid action is necessary to fill the science gap and fast-track the development of knowledge and tools to help national governments, businesses, the health sector, local communities and other stakeholders—especially those with limited resources—to reduce the risk of future pandemics.
3. **REPORT AUDIENCE:** To help fill this gap, a scientific assessment was conducted to explore the role of wild and domesticated animals in emerging zoonotic infectious diseases. This rapid assessment is designed for decision-makers in government, business and civil society at all levels and in all regions.
4. **SCOPE OF THE PROBLEM:** About 60 per cent of human infections are estimated to have an animal origin. Of all new and emerging human infectious diseases, some 75 per cent "jump species" from other animals to people. Most described zoonoses happen indirectly, e.g. via the food system.
5. **OUTBREAK FREQUENCY AND PREDICTABILITY:** The frequency of pathogenic microorganisms jumping from other animals to people is increasing due to unsustainable human activities. Pandemics such as the COVID-19 outbreak are a predictable and predicted outcome of how people source and grow food, trade and consume animals, and alter environments.
6. **CONNECTIVITY AND COMPLEXITY:** The links among the wider environment, biodiversity and emerging infectious diseases are complex. While wildlife is the most common source of emerging human disease, domesticated animals may be original sources, transmission pathways, or amplifiers of zoonotic disease. Such linkages—as well as the interconnectedness with issues such as air and water quality, food security and nutrition, and mental and physical health—should inform policies that address the challenges posed by current and future emerging infectious diseases, including zoonoses.
7. **DISEASE DRIVERS:** Seven human-mediated factors are most likely driving the emergence of zoonotic diseases: 1) increasing human demand for animal protein; 2) unsustainable agricultural intensification; 3) increased use and exploitation of wildlife; 4) unsustainable utilization of natural resources accelerated by urbanization, land use change and extractive industries; 5) increased travel and transportation; 6) changes in food supply; and 7) climate change.
8. **IMPACT AND COST:** Emerging zoonotic diseases threaten human and animal health, economic development and the environment. The greatest burden of zoonotic disease is borne by poor people, but emerging infectious diseases impact everyone, with monetary losses of emerging infectious disease much greater in high-income countries. Given that a single zoonotic outbreak can incur trillions of US dollars in costs across the globe, prevention is significantly more cost-effective than response.
9. **POLICY OPTIONS:** This assessment recommends ten policy response options to reduce the risk of future zoonotic pandemics and to 'build back better': (i) raise awareness of health and environment risks and prevention; (ii) improve health governance, including by engaging environmental stakeholders; (iii) expand scientific inquiry into the environmental dimensions of zoonotic diseases; (iv) ensure full-cost financial accounting of the societal impacts of disease; (v) enhance monitoring and regulation of food systems using risk-based approaches; (vi) phase out unsustainable agricultural practices; (vii) develop and implement stronger biosecurity measures; (viii) strengthen animal health (including wildlife health services); (ix) build capacity among health stakeholders to incorporate environmental dimensions of health; and (x) mainstream and implement One Health approaches. These policy options are discussed in detail in Section Five of this report.
10. **ONE HEALTH:** This report confirms and builds on the conclusions of the FAO-OIE-WHO Tripartite Alliance and many other expert groups that a One Health approach is the optimal method for preventing as well as responding to zoonotic disease outbreaks and pandemics. Adopting a One Health approach, which unites medical, veterinary and environmental expertise, will help governments, businesses and civil society achieve enduring health for people, animals and environments alike.

Introduction

As the UN Framework for the Immediate Socio-economic Response to COVID-19, published in April 2020, says:

> "The success of post-pandemic recovery will also be determined by a ***better understanding of the context and nature of risk.***[1] In view of the COVID-19 crisis, this includes developing and maintaining a global mapping of encroachment, illegal trade, wet markets, etc. that are ***pathways for future pathogen transmission and thus potential future zoonoses*** identified. It will also mean supporting efforts to arrest ecosystem encroachments and harmful practices, restore degraded ecosystems, close down illegal trade and illegal wet markets, while protecting communities that depend on these for their food supply and livelihoods. This will be delivered in part by adhering to existing guidance by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the Convention on Migratory Species (CMS), as well as by delivering an ambitious agreement at the Fifteenth Conference of the Parties (COP15) of the Convention on Biological Diversity (CBD)."

By mid-2020 though, while the world grapples with the COVID-19 pandemic, most new papers and guidelines focus on the public health responses to the novel SARS-CoV-2 virus and the pandemic it caused. These articles and reports emphasize the prevention and treatment of this contagious disease, or discuss ways to safeguard livelihoods, secure nutrition and re-build national or regional economies that are facing recessions. However, there are almost no scientific assessments that evaluate the issues that may hamper our global efforts to reduce the risk of future zoonotic pandemics in a post-COVID-19 world.

In the spirit of the above-mentioned UN Framework for the Immediate Socio-economic Response to COVID-19, the United Nations Environment Programme (UNEP)—the leading global environmental authority and advocate—has teamed up with the renowned International Livestock Research Institute (ILRI) and other key partners to develop an evidence-based assessment report on the risk of future zoonotic outbreaks.

This report is one of the first that specifically focuses on the environmental side of the zoonotic dimension of disease outbreaks during the COVID-19 pandemic. It tries to fill a critical knowledge gap and provide policymakers with a better understanding of the context and nature of potential future zoonotic disease outbreaks. It examines the root causes of the COVID-19 pandemic and other "zoonoses," which the World Health Organization defines as human diseases or infections that are naturally transmissible from vertebrate animals to humans. The report also looks at where zoonoses come from and how we can reduce the likelihood of their occurrence. The report explores the role of animals, and in particular non-domestic animals, in emerging infectious human diseases. This is essential for our global efforts to improve our response preparedness because the frequency of spillover of pathogenic organisms jumping from animals to humans has been increasing considerably, due to the growing magnitude of our unsustainable natural resource use in today's world.

The relationship between the environment, biodiversity, human society and human diseases is complex.[2] While wildlife may be a source of human disease, domesticated animal sources may act as amplifiers of pathogens emerging from the wild. Moreover, as noted in this report, most emerging infectious diseases—whether in wildlife, domestic animals, plants or people—are driven by human activities such as agricultural intensification, wildlife use and mis-use, and human-induced landscape changes, interacting in unpredictable ways that can have negative outcomes.

Against this backdrop, it is important to recognize that disease emergence is not only about the relationship between domestic animals or wildlife and people, but also about the complexity of the system as a whole and the interactions between biotic and abiotic components. Biodiversity, and the complexity of our landscapes and seascapes, is integral to social and ecological resilience.[3] It is also important to take into account the complex relationship between biodiversity and our mental and physical health, including non-communicable diseases as well as infectious diseases. The many linkages here include those related to air, water, food security, and nutrition.[2]

Accordingly, the Convention on Biological Diversity has developed a biodiversity-inclusive One Health Guidance,[3] which looks at the One Health concept as a key ingredient for conservation and sustainable use of biodiversity. The WHO defines One Health as an approach to designing and implementing programmes, policies, legislation and research in which multiple sectors communicate and work together to achieve better public health outcomes.

This science-for-policy report provides examples of the application of the One Health approach and related policy response options that can be implemented by governments, civil society and the business sector in their efforts to tackle the drivers of zoonotic diseases with the ultimate goal to minimize the risk of future zoonotic disease outbreaks.

Section One

Overview of emerging infectious diseases including zoonoses

I

The emergence of the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) at the end of 2019 and the vast global public health and economic impacts this novel coronavirus is causing in 2020 are treated as a crisis. While pandemics such as this are sometimes seen as a "black swan"—an extremely rare event—they are actually a widely predicted consequence of how people source food, trade animals, and alter environments.

To manage emerging infectious diseases (EID), including zoonoses, and reduce the risk of them becoming epidemics and pandemics, we need to understand their origins, their various types and importance in different communities, and their drivers. This section introduces the general reader to emerging diseases and zoonoses, before we take a deeper dive into the world of coronaviruses in Section Two.

What are emerging diseases and what are zoonoses?

People and other animals share many microorganisms and diseases; such co-existence is natural, common and important to health. Only a few of these cause disease. Considering the millions of species of microorganism on Earth, pathogens (microorganisms that harm the host) are extremely unusual. Only about 1,400 microorganisms are known as potential causes of human infections.

New diseases in humans can emerge either as a result of a change in the nature or behaviour of commensal microorganisms that cause disease, or through infection by novel organisms, usually through contact with animals and the environment, where most microorganisms exist.

About 60 per cent of human infections are estimated to have an animal origin,[4] and of all new and emerging human infectious diseases, some 75 per cent "jump species" from (non-human) animals to people.[5] In high-income countries, direct infection with a zoonosis is probably a rare event,[6] with most described zoonoses happening indirectly, e.g. through insect vectors or, more frequently, via the food system.[7] Domesticated animal species share an average of 19 (range of 5–31) zoonotic viruses with people, and wild animal species share an average of 0.23 (range of 0–16) viruses with people.[8] So, unsurprisingly, the vast majority of animals involved in historic zoonotic events or current zoonosis are domestic (livestock, domesticated wildlife and pets), which is logical as the contact rates are high. The emergence of a new wildlife zoonosis is extremely rare, but can be very significant.

Around 80 per cent of pathogens infecting animals are "multi-host," meaning that they move among different animal hosts,[9] including occasionally humans. Domestic animals and peri-domestic wildlife also act as bridges for the emergence of human diseases; this can occur in an evolutionary sense, or the animal could serve as a physical transmitter.

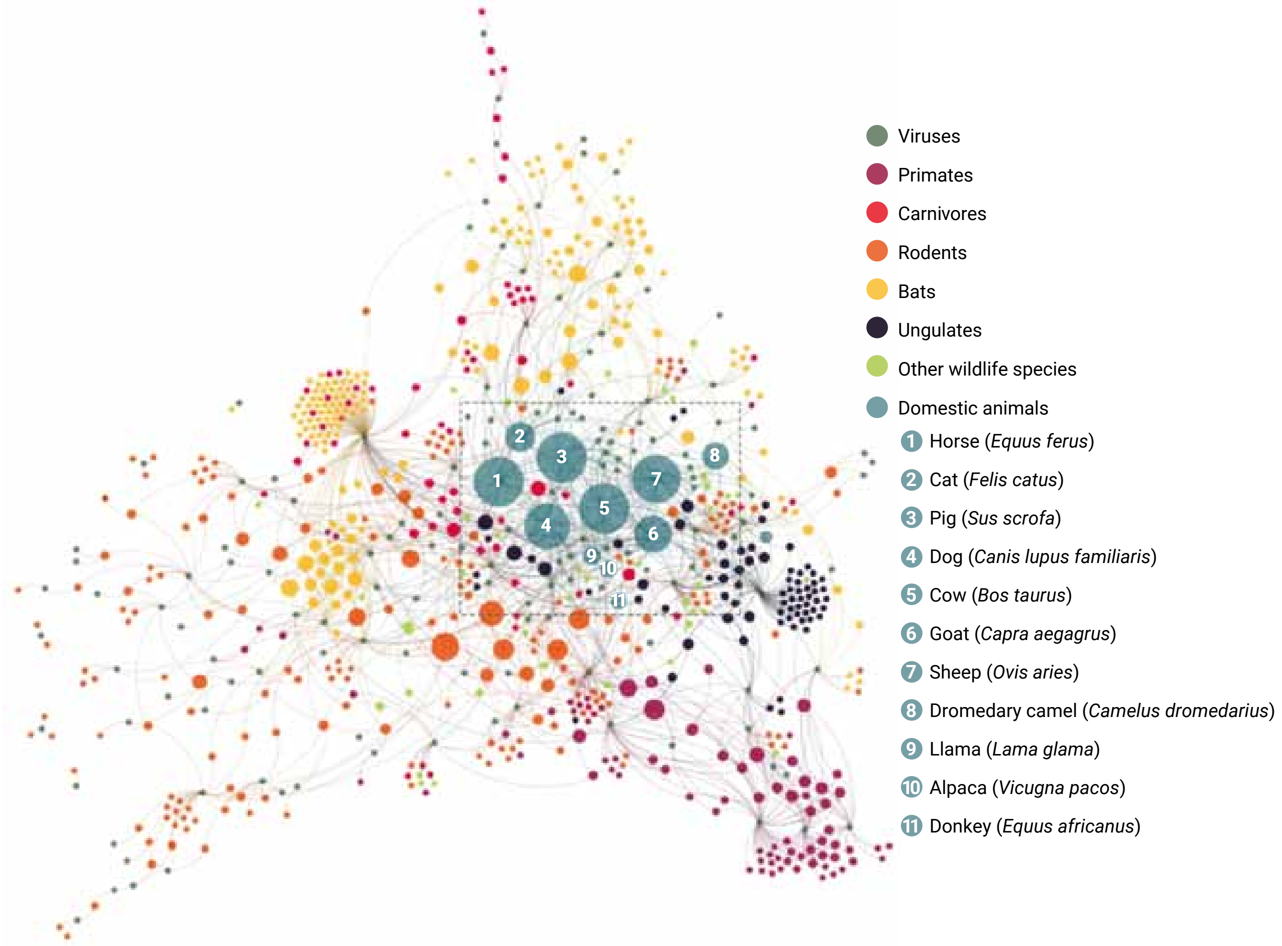
Some of these viruses generated in bio-insecure industrial and intensive agricultural systems result in zoonotic forms of the virus. An example is the highly pathogenic avian influenza (HPAI), an important economic disease of domestic poultry that evolves from low-pathogenic viruses that circulate commensally in the environment in wild bird populations. Another example is Rift Valley fever (RVF), where domestic livestock have served as amplifying hosts for the human- and animal-pathogenic virus that originally circulated between wild animals and mosquitos. The reservoir is the wild animal, while the domestic animal is the bridging host to human infection.

True human pandemic influenza viruses (rather like COVID-19) have a more complex evolution with mixing of viruses in different domestic animal compartments, usually pigs and poultry and interacting with human influenzas to produce highly pathogenic human influenza pandemics.

While we are in the midst of an ongoing pandemic of COVID-19, recent decades have seen other headline-hitting and dramatically destructive novel diseases. Amongst the more prominent examples are: zoonotic influenza (Bird Flu), pandemic human influenza (H1N1), Middle East respiratory syndrome (MERS), and severe acute respiratory syndrome (SARS), most of which have a proven or suspected domestic animal involvement in transmission; only SARS has a suspected peri-domestic wildlife reservoir, though yet unproven.

Other diseases, such as re-emerging West Nile fever, yellow fever and Zika virus diseases are indirect zoonoses. In recent decades, emerging diseases of zoonotic origin have had direct costs of more than USD100 billion; it was earlier estimated that if these outbreaks had become

The bipartite network of zoonotic viruses sharing among domestic and wild mammalian hosts



Johnson *et al.* (2020)[8] analysed data on wild and domesticated mammalian species that share viruses with humans. The resulting bipartite diagram demonstrates the association between zoonotic viruses and mammalian host species. Host species harbouring the same zoonotic virus are linked by a virus node ( ). Mammalian species nodes are coloured by domestication status and taxonomic order for non-domesticated terrestrial wildlife. Species node size is relative to the zoonotic virus richness calculated in that species. Humans, who are host to all viruses, are not shown in the diagram.

Source: Johnson et al. (2020)[8] published by the Royal Society under the Creative Common license (CC BY 4.0). The diagram legend has been modified for readability.

human pandemics, the losses would have amounted to several trillion dollars.[10] And this is likely to be the case for the current COVID-19 pandemic. Despite the massive real and potential socio-economic impacts of emerging zoonotic diseases, and despite the general consensus that prevention is better than cure, investments and political will to control them at their source have been insufficient to date.

Emerging diseases are of course hugely problematic, with some becoming *epidemic* (affecting a large number of people within a region), others becoming *pandemic* (spread over several countries and continents and affecting large numbers of people around the world). COVID-19 is now a pandemic spread across the planet, sickening and killing people and sending billions into lockdowns of various kinds as health services struggle to cope and killing hundreds of thousands by June 2020.

Also, of great importance to some countries and regions of the world are *endemic* zoonotic diseases. The so-called “neglected zoonoses” are continuously present in affected (mainly impoverished) populations, yet receive much less international attention and funding than emerging zoonotic diseases.[11] Among the important neglected zoonoses widespread in developing countries are anthrax, bovine tuberculosis, brucellosis, rabies, cysticercosis (pig tapeworm), echinococcosis (hydatid disease), Japanese encephalitis, leptospirosis, Q fever, rabies, Lassa fever virus and trypanosomiasis (sleeping sickness). Most of these are spread by domestic animals, but several have a wildlife interface, or wildlife is of occasional importance (brucellosis, leptospirosis, rabies, alveolar echinococcosis and bat-associated rabies). Only Lassa fever has exclusively a wildlife host (the multi-mammate rat).

Neglected zoonoses persist in communities experiencing complex development problems—typically a mix of poverty, poor sanitation, poor access to water and waste removal services, isolation, socio-political insecurity, political marginalization, low literacy levels, gender inequality and degraded natural resources. These communities often have a high dependence on livestock and high contact with wild or peri-domestic wildlife, which increases their exposure to pathogens. Another often neglected category of diseases with mainly domestic animal origins are those that are foodborne. For poor people, some of the responses made to control outbreaks may inadvertently cause harm, for example by reducing access to animal source food, important for nutrition, as a result of large-scale culling of domestic animals.[12]

Remarkably, a recent study by the World Health Organization (WHO) found the burden of a selection of important food-borne diseases to be comparable to that of "the big three" major infectious diseases: HIV/AIDS (human immunodeficiency virus-acquired immune deficiency syndrome), malaria and tuberculosis.[13]

Between 2018 and 2019, for example, South Africa experienced the world's largest outbreak of listeriosis, with more than 1,000 laboratory-confirmed cases and more than 200 fatalities of people who got infected after eating contaminated food products.[14]

When do zoonoses become human disease outbreaks?

Historically, the emergence of new human diseases from animals has been associated with major societal change. For example, during the Neolithic transition from hunter-gathering to agricultural societies, humans lived shorter lives, ate less and poorer-quality foods, were smaller in size and were sicker than their hunter-gatherer ancestors. With the advent of agriculture, the dramatic rise in population and the settlement of people in close proximity to their waste led to increases in human disease; the domestication of animals led to livestock pathogens jumping species into people, where they became the probable cause of diseases such as diphtheria, influenza, measles and smallpox.[15,16]

Subsequent major plagues or outbreaks, associated with major societal stresses and upheavals, were linked with zoonoses or diseases that had originally jumped species from animals to people, but had subsequently become transmitted mainly from person to person. Some of the most dramatic ones are:

1. The true zoonotic bubonic plague or pest (Black Death caused by the bacteria *Yersinia pestis*) of the mid-fourteenth century killed millions in Eurasia and North Africa, wiping out a third of Europe's population.

Types of zoonotic diseases

Emerging zoonotic diseases

are those that newly appear in human populations or have existed previously but are now rapidly increasing in incidence or geographical range. Fortunately, these diseases are often not highly lethal and most do not spread widely. But some emerging diseases have enormous impacts. Ebola, HIV/AIDS and now COVID-19 are well-known examples of emerging zoonoses particularly harmful to human health and the economy.

Ebola outbreak of 2013-2016 in Guinea, Liberia and Sierra Leone

11,323 deaths

USD 2.8 billion in economic losses

Zika virus outbreak 2015-2016 in the Americas

1 in 7 babies of pregnant women infected with Zika virus develops neurological problems

USD 912,000 life-time cost per case of Zika-associated microcephaly

Epidemic zoonoses

typically occur intermittently and are mostly domestic in origin. Examples are anthrax, leishmaniasis and Rift Valley fever. Epidemic zoonoses are often triggered by events such as climate variability, flooding and other extreme weather, and famines. The overall health burden of outbreak/epidemic zoonoses is much less than that of neglected zoonoses, but because epidemic zoonoses cause 'shocks' to food production and other systems, they can significantly reduce the resilience of affected impoverished communities

The 2015-2016 El Niño induced **Rift Valley fever** outbreaks in Mauritania

Extended periods of **permafrost thaw** played a key role in the 2016 anthrax outbreak on the Siberian Yamal Peninsular

Neglected zoonotic diseases

are mostly domestic in origin, and continuously present to a greater or lesser degree in certain populations. These common diseases affect mostly poor populations and are commonly neglected by the international donor, standard-setting and research communities alike as well as by national governments. It is likely that poor detection and surveillance of these diseases diminish their recognition and hence prioritization by researchers and policymakers.

Impact of **pig tapeworm**

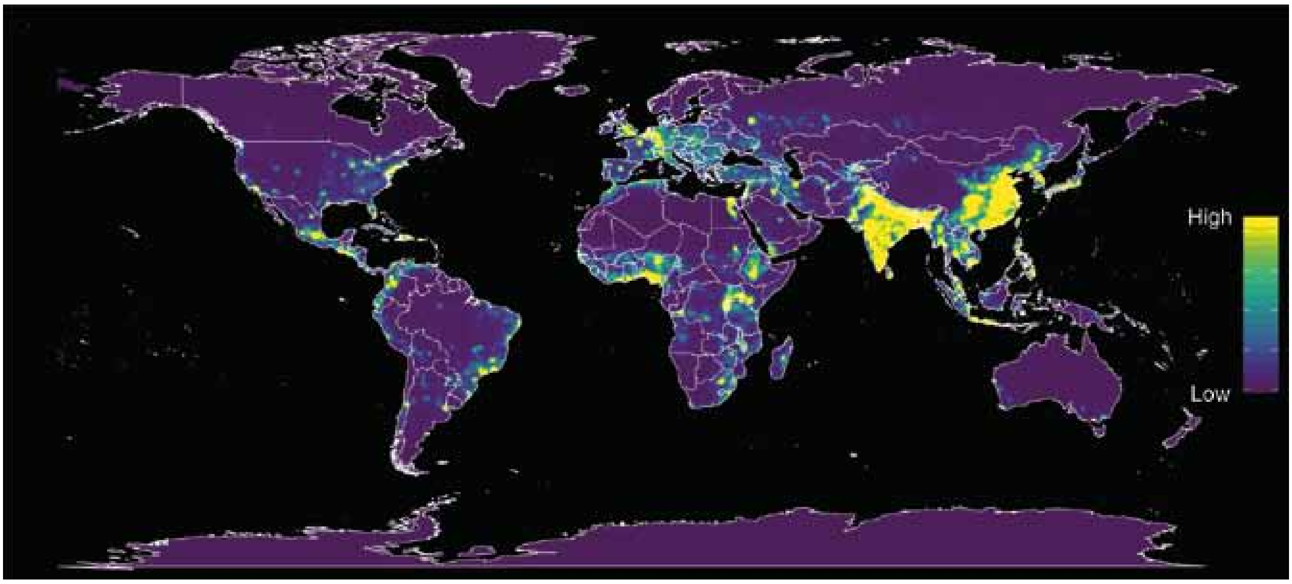
50 million people affected globally

80% of them live in developing countries

USD 150 million annual cost to India

For references see page 60.

Global hotspot map of estimated risk in zoonotic disease emergence



Allen *et al.* (2017)[23] analysed emerging infectious diseases (EID) of wildlife origin based on a broad set of predictors, such as the distribution of tropical forested regions, human population density, mammal species richness, agricultural land use, and others. The resulting heat map shows the global spatial patterns of estimated risk of zoonotic EID events after factoring out reporting bias.

2. Epidemics of European diseases in the Americas shortly after the arrival of Europeans in the sixteenth century were responsible for the deaths of up to 95 per cent of the indigenous populations and accelerated the destruction of their ancient civilizations.[17] It is thought that more infectious diseases of the temperate zone emerged in the Old World, compared to the New World, because diverse species of animals capable of harbouring ancestral pathogens were domesticated in the Old World.[16]
3. The tuberculosis outbreak of the nineteenth century, associated with the industrialization in Western Europe and over-crowding, killing up to one in four people. Unlike the current situation, where most illness is caused by non-zoonotic tuberculosis, a substantial proportion of the nineteenth-century outbreak was thought to be caused by zoonotic tuberculosis.[18]
4. The expansion of colonial rule in Africa facilitated outbreaks of zoonotic sleeping sickness that killed one third of the population in Uganda and up to one fifth of the people living in the Congo River Basin in the first decade of the twentieth century.[19]
5. The 1918 influenza pandemic killed some 40 million people in the last months of World War I and the following years (1918–1921).

The global human population has increased from about 1.6 billion in 1900 to about 7.8 billion today. The population of the domesticated animals that provide people with food, and of pests or "peri-domestic animals" (such as rats) that thrive in new environments created by people, increased in parallel. In general, these exploding human, livestock and pest populations have reduced the size of wildlife populations while paradoxically increasing contacts among people, livestock and wildlife (with more people hunting fewer wild animals in diminished and degraded ecosystems, and an increasing number of human-wildlife conflicts worldwide).

However, this broad-brush picture conceals some great regional and local differences. Some countries have declining rather than expanding human populations. And over the last century, "natural environments" have returned to depopulated rural areas (e.g., parts of the northeastern United States) as small farms proved unviable and farmlands reverted to forested lands. Despite these exceptions, overall there have been significant increases in human populations, encroachment of humans and livestock into wildlife habitats, and concurrent massive decreases in natural environments. These changes have important implications for ecosystem, animal and human health alike. One of these consequences is an increase in emerging zoonoses. Many of these diseases are emerging in high-income settings, but there is an increasing trend for these diseases to emerge in low- and middle-income countries.[20-22]

While still imperfect, our understanding of the factors favouring emerging diseases is growing. For example, one study makes the case that the risk of zoonotic emerging infectious diseases is elevated in forested tropical regions where land use is changing and wildlife diversity, in terms of mammalian species richness, is high.[23]

Seven major anthropogenic drivers of zoonotic disease emergence

A broad range of studies on zoonotic disease emergence implicates the following seven main drivers of their emergence.[20,24-26] Many of these drivers are now occurring in the same places, amplifying their impact. A description of each of these drivers is provided below.

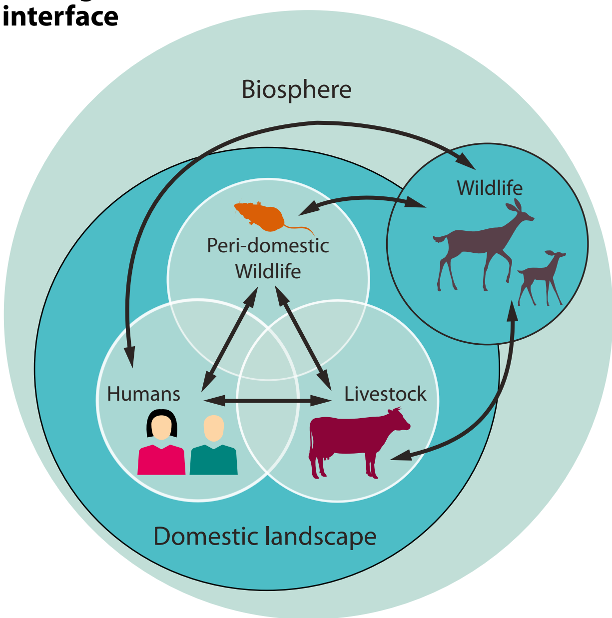
1. Increasing demand for animal protein

High-income countries have experienced little change in consumption of animal source foods during the last four decades. In contrast, Southeast Asia has seen a rapid increase: Since the 1960s, the share of the region's daily food supply of proteins from animal products has doubled to 21 per cent; from fish, it has increased by half to 15 per cent. The share of total calories from both fish and animal products doubled to total of 12 per cent of the supply. Meanwhile, South Asia has also seen an increase in animal protein consumption, but not as strong. Sub-Saharan Africa has also followed the pattern seen in Southeast Asia, although it has been less marked. This per capita increase in animal protein consumption in many low- and middle-income countries has been accompanied by significant growths in population. Together, these factors have driven a strong growth in meat production (+260 per cent), milk (+90 per cent), and eggs (+340 per cent) over the last 50 years. This trend is predicted to continue in the coming decades, with most growth in animal-source food consumption occurring in low- and middle-income countries. Compared with other protein sources, livestock product consumption is rising rapidly, whereas the long-term trend for pulses is of sustained consumption levels.

2. Unsustainable agricultural intensification

Increasing demand for animal-source foods stimulates the intensification and industrialization of animal production. The intensification of agriculture, and in particular of domestic livestock farming (animal husbandry), results in large numbers of genetically similar animals.
These are often bred for higher production levels; more recently, they have also been bred for disease resistance. As a result, domestic animals are being kept in close proximity to each other and often in less than ideal conditions. Such genetically homogenous host populations are more vulnerable to infection than genetically diverse populations, because the latter are more likely to include some individuals that better resist disease. Factory farming of pigs, for example, promoted transmission of swine flu due to a lack of physical distancing between the animals.[27]
In poorer countries, there are additional risk factors in that livestock production often occurs close to cities, while biosecurity and basic husbandry practices are often inadequate, animal waste is often poorly managed, and antimicrobial drugs are used to mask poor conditions or practices. Since 1940, agricultural intensification measures such as dams, irrigation projects and factory farms have

Pathogen flow at the wildlife-livestock-human interface



Source: Adapted from Jones et al. (2013)[25]

been associated with more than 25 per cent of all—and more than 50 per cent of zoonotic—infectious diseases that have emerged in humans.[28] Moreover, around one third of croplands are used for animal feed. In some countries, this is driving deforestation.[29]

3. Increased use and exploitation of wildlife

There are many ways in which wildlife are used and traded. Section three provides more detail on the complexities. However, in general, an increasing use and exploitation of wildlife includes the following:

1. Harvesting wild animals (wild meat, sometimes called "bushmeat") as a source of protein, micronutrients and money for the poor;
2. Recreational hunting and consumption of wildlife as a status symbol;
3. Consumption of wildlife in the belief that wild meat is fresh, natural, traditional and safe;
4. Trade in live animals for recreational use (pets, zoos) and for research and medical testing; and
5. Use of animal parts for decorative, medicinal and other commercial products.

In general, use and trade in live and dead animals can lead to increased close contact between animals and people throughout the supply chain, which increases the risk of zoonotic disease emergence. In some regions, as human populations and wealth have increased, there has also been an increased demand for wild animals and their products. In West Africa, for example, exploitation of wildlife for food has increased over the last 10 years.[30]

Infrastructural development can often facilitate wildlife exploitation: new roads in remote areas can increase human access to wildlife and help spread diseases within and between countries more rapidly. As animals in the wild become scarcer, attention has turned to the farming of some species of wild animals.[31] While this might have the potential to reduce the pressure on wildlife, farming wildlife or "ranching" is often more costly than harvesting or hunting animals from the wild, and less preferred by local communities; it also may create cover for the "laundering" of wild animals.[32] In addition, any significant increase in the farming of wild animals risks "recapitulating" the increases in zoonoses that likely accompanied the first domestication of animals in the Neolithic era, some 12,000 years ago.[16]

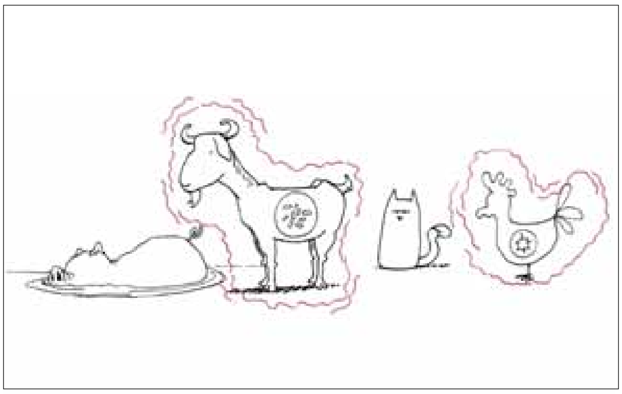
4. Unsustainable utilization of natural resources accelerated by urbanization, land use change and extractive industries

Rapid urbanization, especially when unplanned and with poor infrastructure, creates novel and diverse contacts among wildlife, livestock and people. The greater movement of people, animals, food and trade that is associated with accelerated urbanization often provides favourable grounds for the emergence of infectious diseases, including zoonoses. For example, irrigation systems encourage some vector-borne zoonoses to spread; deforestation and fragmentation of ecosystems and wildlife habitats encourage contacts at the human-livestock-wildlife ecosystem interface;[32] and increased human settlements and fencing constrain herding and migratory movements of both domesticated and wild animals. Ecological tourism and human settlements near caves and forested areas, particularly those with poor housing conditions, can increase human-wildlife contacts and human exposure to insects, ticks and other vectors of wildlife pathogens.

Infrastructure development, including new roads and railways, transformation of natural areas to commercial and retail use, and other drivers of land-use change can also contribute to the destruction and fragmentation of wildlife habitats and increase human-wildlife contact and conflict.

Video: How can animals make you ill?

Video Link: https://www.youtube.com/watch?v=J5qLKWUTNM4 | © RIVM/Government of the Netherlands



Encroachment into wildlife habitats that are altered for the purpose of extracting their natural resources—e.g., mining, oil and gas extraction, logging but also harvesting bat *guano*—also encourages new or expanded interactions between people and wildlife. These activities often come with other changes, such as new human settlements, road building and movements of people and products, which further increase human access to wilderness areas and often provoke changes in how local communities acquire and store their food (e.g., via wildlife hunting, introduction of livestock rearing, and keeping food stocks that attract pest animals).

5. Travel and transportation

Diseases can now move around the world in periods shorter than their incubation periods (the time between exposure to a pathogen and the first clinical sign of illness). The increasing amounts of human travel and trade, including the increasing handling, transport and (legal and illegal) trade of animals and animal products, increases the risk of zoonotic diseases emerging and spreading.

6. Changes in food supply chains

Food supply chains are lengthening and diversifying, especially in low- and middle-income countries. This trend—which is being driven by increased demand for animal source food, new markets for wildlife food, and poorly regulated agricultural intensification—is creating additional opportunities for disease transmission. These include the following:

1. There are increased opportunities for cross-contamination.
2. It can be more difficult to identify where a given food comes from. Traceability challenges make it harder for officials to follow up quickly on any potential problems.
3. Changes in processing can encourage the proliferation of zoonotic diseases (e.g., the formation of biofilms—microbial ecosystems—in food processing plants).
4. Rapidly expanding and poorly managed informal wildlife and fresh produce markets (including so-called "wet" markets) bring products along poorly regulated supply chains to supply rapidly growing cities. While traditional markets provide many benefits, especially for poor people—including their convenience, lower costs, sales of traditional foods, and support of livelihoods (especially women)—their levels of hygiene are often low, and biosecurity is poor, increasing the risks of disease. The same is often true along the supply chains from rural areas to the markets in the cities.
5. Industrial meat processing plants can also be sites of disease transmission. Food from modern retail outlets is not always safer than that from informal markets.[33] For example, there have been many

Impacts of climate change on zoonoses

Caster bean tick, deer tick or sheep tick (*Ixodes ricinus*) is a well-known vector of Lyme disease in Europe
Photo credit: Dagmara_K / Shutterstock.com

Climate change is a major factor in disease emergence. The survival, reproduction, abundance and distribution of pathogens, vectors and hosts can be influenced by climatic parameters affected by climate change. For example, climate variability tends to affect the many diseases transmitted by insects, ticks and other arthropod vectors. Warmer temperatures could also increase the incidence of disease both by increasing the vector population size and distribution and by increasing the duration of the season in which infectious vector species are present in the environment. Many newly emerging infectious diseases arise in tropical regions where the warm temperatures suit the lifecycles of both pathogen and vector.[16] The impacts of climate change on zoonotic diseases as well as on food and economic insecurity and other problems are predicted to be harshest in low- and middle-income countries, where disease surveillance and data are particularly scarce.[37]

Climate change is a force of growing importance that influences the future geographic distribution and abundance of species such as bats, monkeys and rodents, including those in which zoonotic pathogens often originate; and of mosquitos and other vectors that transmit viruses such as the chikungunya virus and West Nile virus. Climate change can increase or decrease the incidence of the insect-transmitted Chagas disease, sand-fly transmitted leishmaniasis, and other vector-borne and zoonotic diseases, generally with greater illness occurring at higher degrees of warming.[38] In 2010 in Africa, an outbreak of Rift Valley fever, a mosquito-borne zoonotic disease, occurred with higher than average seasonal rainfall; other outbreaks have occurred even with short periods of heavy rainfall.[16]

An extensive literature review of emerging diseases in Brazil revealed relationships between infectious diseases outbreaks and (1) extreme climate events (El Niño, La Niña, heatwaves, droughts, floods, increased temperature, higher rainfall), the frequency of which might be affected by climate change; and (2) environmental changes (habitat fragmentation, deforestation, urbanization, wild meat consumption).[39]

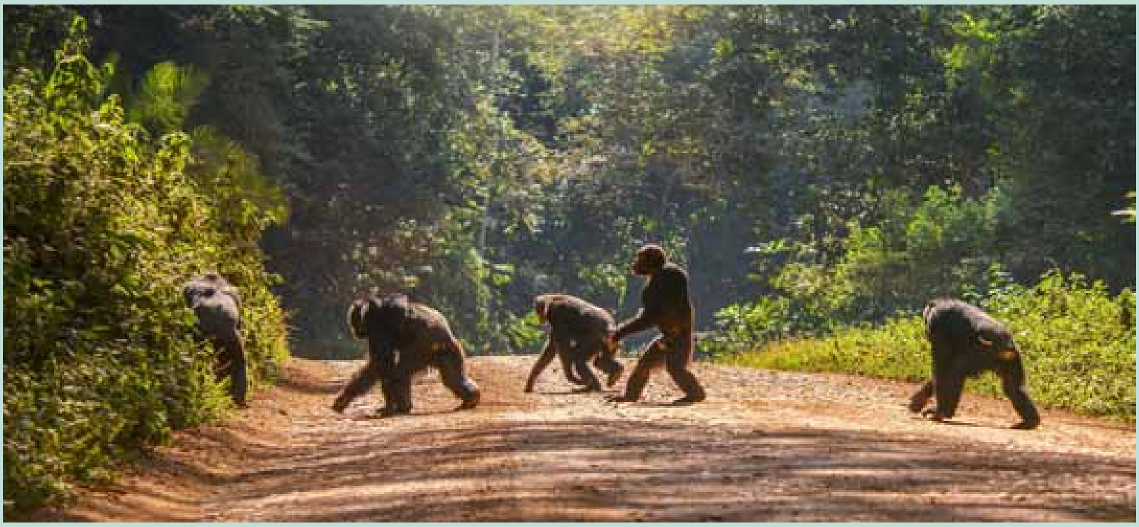
Arctic and subarctic regions are especially vulnerable to climate change due to the thawing of the permafrost, which significantly transforms soil structures, vegetation and habitats. Degradation of the permafrost can expose historic burial grounds, enabling the revival of deadly infections from the past.[40] Rising temperatures are raising the risk of zoonotic diseases in the vast Republic of Sakha (Yakutia) which makes up one fifth of Russia's territories. Extended growing periods and expanded habitats are providing some zoonotic pathogens and their vectors with more favourable living conditions.

outbreaks of COVID-19 from the massive, crowded, artificially chilled industrial meat plants in Europe and America, but much fewer from smaller, naturally ventilated meat plants in many low- and middle-income countries. Thus, it cannot always be assumed that the modernization of food value chains will reduce risk. Moreover, especially in low- and middle-income countries, people are consuming more animal-source foods than in the past, which results in potential exposure to pathogens, including zoonotic pathogens.[34]

7. Climate change

Many zoonoses are climate sensitive and a number of them will thrive in a warmer, wetter, more disaster-prone world foreseen in future scenarios.[35] Some pathogens, vectors and host animals probably fare more poorly under changing environmental conditions, disappearing in places and resulting in the loss of their population-moderating effects or the establishment of other species in the new ecological niches created by their departure. There is some speculation that the SARS-CoV-2 may survive better in cooler, drier conditions when outside the body.[36]

Immunodeficiency disorders in primates



Chimpanzees in Uganda
Photo credit: CherylRamalho / Shutterstock.com

Two of the most significant zoonotic disease transmissions in recent history are the human immunodeficiency viruses, HIV-1 and HIV-2, the etiologic agents for acquired immune deficiency syndrome (AIDS) in humans.[41,42]

The closest relatives of HIV-1 are simian immunodeficiency viruses (SIVs) that infect wild-living chimpanzees (*Pan troglodytes troglodytes*) and gorillas (*Gorilla gorilla gorilla*) in Western Equatorial Africa. Chimpanzees were the original hosts of this clade of viruses. Four lineages of HIV-1 have arisen by independent cross-species transmissions to humans and one or two of those transmissions may have been via gorillas.[43]

On the other hand, the closest relatives of HIV-2 are simian immunodeficiency viruses in a monkey, the sooty mangabey (*Cercocebus atys*), whose natural range is in west Africa.[44] SIV-HIV species crossing seem to have occurred originally at least six times between sooty mangabeys (primate) and humans.[45] Sooty mangabeys and chimpanzees are both often kept as pets and used for food, thus resulting in their frequent direct contact with humans.[46,47]

More than 40 species of African monkeys are infected with their own, species-specific SIV.[47-49] These viruses are of relatively low pathogenicity and they do not induce an AIDS-like disease in their natural hosts, suggesting that they have associated and evolved with their hosts over an extended period of time. However, recent evidence shows that SIVcpz can cause AIDS-like disease and reduced fertility in Eastern Chimpanzees.[50]

The conclusion that HIV-1 was derived from a virus infecting chimpanzees is of particular interest, because chimpanzees and humans are so closely related. This raises a number of interesting questions: 1) as to the origin of the chimpanzee virus; 2) whether adaptation of SIVcpz to infecting chimpanzees made the virus more capable of infecting humans; and 3) whether SIVcpz infection of chimpanzees is of low pathogenicity or not.[43] Based on the analysis of strains found in four species of monkeys from Bioko Island in Equatorial Guinea, which was isolated from the mainland by rising sea level about 11,000 years ago, it has been concluded that SIV has been present in monkeys and apes for at least 30,000 years, and probably much longer. Therefore, it is thought that SIV may have previously crossed the species barrier into human hosts multiple times throughout history, but it was not until relatively recently at the advent of modern transportation and global travel that HIV spread regionally and globally beyond decimations in local populations.[51]

Other factors playing a role in zoonotic disease emergence

The seven main drivers of zoonoses emergence, described above, are all anthropogenic, that is, the result of human action. Other factors, of course, also affect disease emergence, particularly the agent type, virulence and modes of transmission of the pathogen; the susceptibility of the pathogen's host; and the longevity and range of the pathogen's animal reservoir. Pathogens that are widely distributed, mutate rapidly and are multi-host are considered most likely to jump species. RNA viruses mostly lack the "proofreading" mechanisms of DNA viruses and hence develop many more mutations as they evolve, some of which may make the virus better able to infect a new host. Pathogens that spread using the respiratory functions of the host (which are over-represented among emerging diseases) have fewer barriers to moving from one host to another than pathogens spread via other routes.

Certain people are more susceptible than others to infection with pathogens. Age, health, sex, physiology, nutritional status, exposure history, simultaneous infection with more than one pathogen, immunocompetence, genetics and underlying diseases all influence an individual's susceptibility to infection. Certain animals, in their turn, are more likely to harbour zoonotic or potentially zoonotic pathogens based on their physiological characteristics, ecosystem niche, social behaviour and relatedness to humans. Some studies detected higher numbers of zoonotic viruses in animal species that have become abundant and have expanded their range by adapting to human-dominated landscapes.[8] Livestock, rodents, bats, carnivores and non-human primates have been identified as of special concern in several studies. However, as with all animals, they are not risks in and of themselves, and it is only when there is close contact with people that there is the potential for this risk to be realized.

Baby owls in a cage sold in an animal market in Yogyakarta, Indonesia
Photo credit: Ibenk_88 / Shutterstock.com

Section Two

Coronaviruses in a One Health context

In this second section, we move from zoonoses in general to the specific alarming and ongoing pandemic of COVID-19, a disease caused by a zoonotic coronavirus. The section starts with some background on coronaviruses and continues from the One Health perspective, reflecting both veterinary and medical experiences and commonalities between important coronavirus diseases and pandemics.

What are coronaviruses?

Coronaviruses are a large group of viruses that infect many animals and humans and are responsible for numerous diseases. They are named "corona" for the crown-like arrangement of the spike-shaped proteins on the surface of their membranes. Some human coronaviruses usually cause mild upper respiratory illness like the common cold. They can also cause serious diseases such as infectious peritonitis in cats and respiratory and enteric infections in cattle. The only known serious human coronavirus diseases are SARS, MERS, COVID-19, and possibly the Asian Flu from the late 19th century; all are likely to have zoonotic origins. In addition to these well-known, sporadic, locally important and long-established diseases, there have been at least six major outbreaks of novel coronaviruses in the last century, all of which imposed high costs across several continents:

1. **Infectious bronchitis virus (IBV)** causes infectious bronchitis in poultry. It emerged in the 1930s and is still one of the main causes of economic losses in the poultry industry, with repeated waves of disease caused by different strains.[52]
2. **Transmissible gastroenteritis (TGE)** virus was first reported in the United States in 1946 and subsequently spread to Europe, Africa, South America and China.[53]
3. **Porcine epidemic diarrhoea (PED)** virus emerged in 1971 as a pig disease causing a global pandemic of enormous cost and is still a major problem in piglets. Since then different strains have caused waves of disease in Asia, Europe and the Americas.[54]
4. **SARS-CoV**, the coronavirus that causes severe acute respiratory syndrome, or SARS, was first reported in China in February 2003 and likely originated from bats, probably then spreading to other animals (likely civet cats) and then to humans. The illness then spread to more than two dozen countries in North America, South America, Europe and Asia before it was contained. Over 8,000 cases were reported and nearly 800 people died of the disease. Since 2004 there have not been any reported cases.[55]
5. **MERS-CoV**, the coronavirus that causes Middle East respiratory syndrome, or MERS, was first reported in Saudi Arabia in 2012 and has a higher mortality rate than SARS. MERS-CoV can occur zoonotically from human contact with camels but has secondary cycles of spread from ill people to other people through close contact. To date, there have been around 2,500 laboratory confirmed cases mostly human to human, of which more than one third proved fatal. Sporadic cases continue to occur as the infection remains present in dromedary camels.[56]
6. **SARS-CoV-2**, the coronavirus that causes a severe acute respiratory syndrome known as COVID-19, already has had its genome compared to the genetic sequences of more than 200 other coronaviruses from around the world that infect various animals. SARS-CoV-2 appears to be a recent mix, or genetic recombination, of coronaviruses.[57] As a result of this recombination, one of the proteins of SARS-CoV-2 enables the virus to enter the cells of humans. Other research has shown the virus to be 96 per cent identical to a previously identified bat coronavirus, with a common ancestor about 50 years ago. It is hypothesized that this is the origin of the unknown pathway that resulted in the transmission of SARS-CoV-2 to humans in 2019.[58]

Family of Coronaviruses

Coronaviruses are diverse. They belong to the Coronavirinae subfamily in the Coronaviridae family. The Coronavirinae subfamily comprises four genera:

Alphacoronavirus
Alphacoronaviruses cause respiratory tract illnesses and common colds in humans, and gastroenteritis in animals.

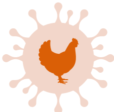
Betacoronavirus
Betacoronaviruses affect mainly mammals, and include those that cause MERS, SARS and COVID-19.

Gammacoronavirus
They infect mainly avian species and sometimes mammals including cetaceans. IBV is a gammacoronavirus that causes avian infectious bronchitis.

Deltacoronavirus
They are found primarily in birds and some mammals. Porcine deltacoronavirus (PDCov) recently emerged, causing severe diarrhoea in newborn piglets.

For references see page 60.

Emergence of significant diseases caused by coronaviruses and other pathogens

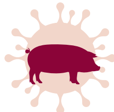


1931

Avian infectious bronchitis

Pathogen: Infectious bronchitis virus (IBV)
Genus: *Gammacoronavirus*
Host: Chickens
Place of emergence: North Dakota, USA

IBV causes an acute, highly contagious respiratory disease in chickens. It can also damage the reproductive tract, causing decreased egg quality and production. First documented in USA, the disease is now prevalent in all countries with an intensive poultry industry.

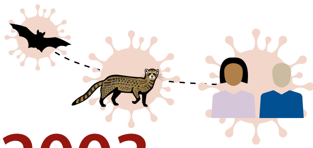


1971

Porcine epidemic diarrhoea (PED)

Pathogen: Porcine epidemic diarrhoea virus (PEDV)
Genus: *Alphacoronavirus*
Host: Pigs
Place of emergence: United Kingdom

Following the first appearance in the UK, it spread to other European countries and Asia. A highly virulent PEDV strain emerged in 2013 and caused nationwide outbreaks in the US, and rapidly spread to North, Central and South American countries. The virus is not zoonotic and poses no risk to humans, or food safety.



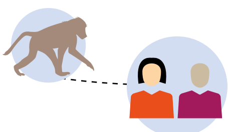
2003

Severe acute respiratory syndrome (SARS)

Pathogen: SARS coronavirus (SARS-CoV)
Genus: *Betacoronavirus*
Natural reservoir: Horseshoe bats
Intermediate host: Masked civet cats
Place of emergence: Guangdong, China

This pneumonia-like infection spread from Guangdong, China, to more than 26 countries in Asia, Europe, North America and South America before it was contained. SARS-like coronavirus has been found in horseshoe bats, suggesting that bats are natural reservoirs.

1920 1930 1940 1950 1970

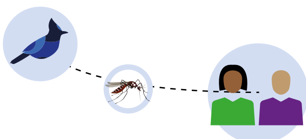


1920s

Human Immunodeficiency Virus (HIV) infection

Pathogen: HIV
Genus: *Lentivirus*
Natural reservoir: Chimpanzee for HIV type 1, and Sooty Mangabey for HIV type 2
Place of emergence: Kinshasa, Democratic Republic of Congo

Based on genetic sequencing and historical records, the emergence of HIV is traced back to 1920s in Kinshasa, DRC. It is thought that simian immunodeficiency viruses (SIVs) in primates crossed over to humans at the time, presumably as a result of hunting and meat consumption. SIVs then adapted to the new human host to become HIV.

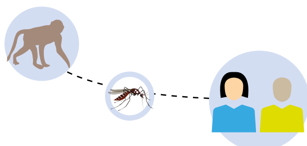


1937

West Nile fever

Pathogen: West Nile virus
Genus: *Flavivirus*
Host: Birds
Place of emergence: West Nile district, Uganda

Mosquitoes serve as disease vectors carrying the virus from infected birds to people and some mammals. Humans are usually incidental and dead-end hosts for the virus. The first recognized outbreak occurred in Israel in 1951, then Egypt. The virus re-emerged in Romania in 1996, and has established itself in the US since 1999. West Nile virus belongs to the same genus as dengue virus and yellow fever virus.

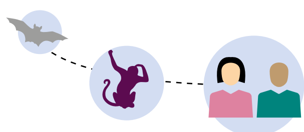


1947

Zika virus disease

Pathogen: Zika virus (ZIKV)
Genus: *Flavivirus*
Natural reservoir: Primates including humans
Place of emergence: The Zika forest, Uganda

ZIKV was first discovered in a febrile sentinel rhesus monkey from the Zika forest, and in the *Aedes africanus* mosquito from the same forest a year later. The first human cases were detected in Uganda and Tanzania in 1952. An outbreak occurred in the Yap Islands, Federated State of Micronesia in 2007, followed by a major epidemic in the Americas in 2015-16.



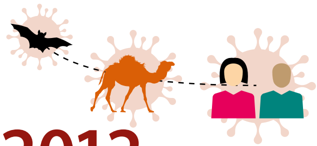
1976

Ebola virus disease

Pathogen: Ebola virus
Genus: *Ebolavirus*
Natural reservoir: Unconfirmed but likely to be African fruit bats of the *Pteropodidae* family
Intermediate host: Apes and monkeys
Place of emergence: Two simultaneous outbreaks in Democratic Republic of Congo (DRC) and South Sudan

The largest outbreak in history occurred primarily in Guinea, Liberia and Sierra Leone from 2014 to 2016, killing 11,323 people. The virus also recently re-emerged in eastern DRC from 2018 to 2019. Case fatality ratio of Ebola varied from 25% to 90%.

For references see page 61.

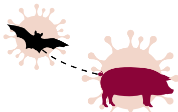


2012

Middle East respiratory syndrome (MERS)

Pathogen: MERS coronavirus (MERS-CoV)
Genus: *Betacoronavirus*
Natural reservoir: Probably bats
Intermediate host: Dromedary camels
Place of emergence: Saudi Arabia

First reported in Saudi Arabia, MERS has spread to 27 countries with a large outbreak in Korea in 2015. A study in 2018 shows high prevalence of MERS-CoV strains in local camels in Saudi Arabia, compared to imported camels from Africa.

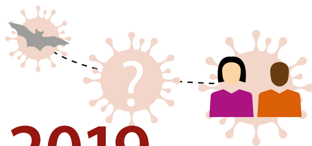


2016

Swine acute diarrhoea syndrome (SADS)

Pathogen: SADS coronavirus (SADS-CoV)
Genus: *Alphacoronavirus*
Natural reservoir: Probably bats
Host: Pigs
Place of emergence: Guangdong, China

SADS-CoV caused severe and acute diarrhoea and vomiting in newborn piglets. The outbreak killed nearly 25,000 piglets in Guangdong. Case fatality ratio: 90% in piglets less than five days old. This coronavirus did not appear to jump to humans.



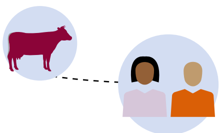
2019

Coronavirus disease 2019 (COVID-19)

Pathogen: SARS-CoV-2
Genus: *Betacoronavirus*
Natural reservoir: Probably bats
Intermediate host: Unknown
Place of emergence: Wuhan, China

SARS-CoV-2 appears to be a recent mix, or genetic recombination, of two coronaviruses. Genome sequencing suggests that SARS-CoV-2 is 96% identical to a coronavirus in horseshoe bats.

1980 1990 2000 2010 2020

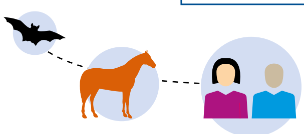


1986

Bovine spongiform encephalopathy or mad cow disease

Agent: Pathogenic prions
Host: Cattle
Place of emergence: United Kingdom

Mad cow disease is a progressive, fatal neurological disorder in cattle. The human form of the mad cow disease known as variant Creutzfeldt-Jakob disease is linked to consumption of beef from cattle infected with the disease.

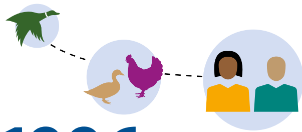


1994

Hendra virus infection

Pathogen: Hendra virus
Genus: *Henipavirus*
Natural reservoir: Large fruit bats (*Pteropus* spp.) or flying fox
Host: Horses
Place of emergence: Hendra, Australia

Sporadic outbreaks have occurred in Australia over the years since its initial appearance in 1994. So far, no cases have been reported outside Australia. Case fatality ratio is 75% in horses, and 50% in humans. Hendra virus belongs to the same genus as Nipah virus.

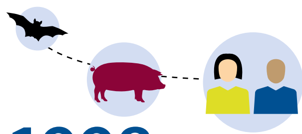


1996

Highly pathogenic avian influenza (HPAI) or bird flu

Pathogen: HPAI virus subtype H5N1
Genus: *Alphainfluenzavirus*
Natural reservoir: Wild waterfowl
Host: Poultry
Place of emergence: Guangdong, China

First human cases found in Hong Kong in 1997 were traced back to wild and domestic waterfowl in Guangdong in 1996. Re-emerging in Hong Kong in 2002, the virus spread rapidly to South East Asian countries. Over 100 million domesticated chickens and ducks either died of the disease or were culled to stop the outbreak in Asia.



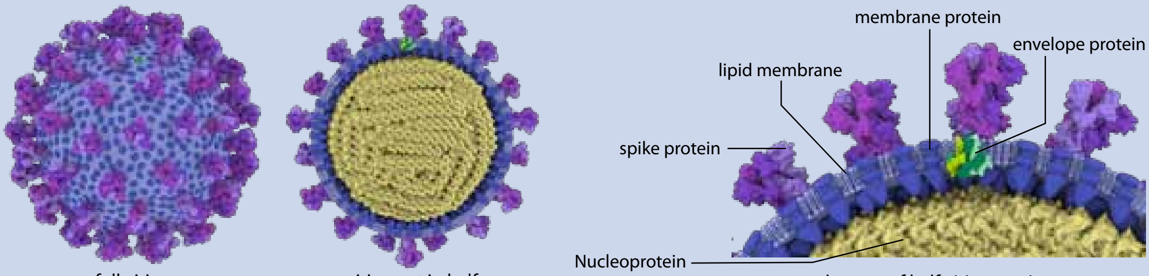
1998

Nipah virus infection

Pathogen: Paramyxovirus
Genus: *Henipavirus*
Natural reservoir: Large fruit bats (*Pteropus* spp.) or flying fox
Host: Pigs
Place of emergence: Guangdong, China

Nipah virus emerged as a respiratory and neurologic disease in pigs, and then spread to humans. A large outbreak in Malaysia from 1998 to 1999 was followed by five outbreaks in Bangladesh from 2001 to 2005. To control the outbreak in Malaysia, at least one million pigs were culled.

SARS-CoV-2



full virion | virion cut in half | close up of half virion section

SARS-CoV-2 is an enveloped virus, meaning that its RNA is packaged within an outer **lipid (fatty) membrane**. The lipid membrane is stable enough to protect the RNA from the surrounding environment, but also able to break open inside the host cell to release the RNA. This balance means the membrane is susceptible to being destroyed by detergent.

The membrane contains several virus proteins. The large **spike (S) proteins** allows the virus to bind to and enter host cells. The distinctive 'corona' of spikes gives the virus its name.

Seven human coronaviruses have been identified so far, of which three are capable of invading deep into the lungs and causing more severe disease. One possible reason is that the S protein of SARS-CoV-2, like SARS-CoV (the virus responsible for SARS), binds to ACE-2 receptors on human cells. ACE-2 receptors are found throughout the body but are particularly concentrated in the upper and lower airways of the lungs.

SARS-CoV-2 also binds to ACE2 particularly well. It is 10–20 times more likely to bind ACE2 than SARS-CoV. The **membrane (M) proteins** give shape and integrity to the virus particle. They are also thought to help assemble new virus particles inside the host cell.

The **envelope (E) proteins** are thought to assist virus growth and ability to cause disease. They may form small pores that alter the properties of the host membranes, prevent M protein from clumping together, and assist in assembly of new viral particles inside the host cell.

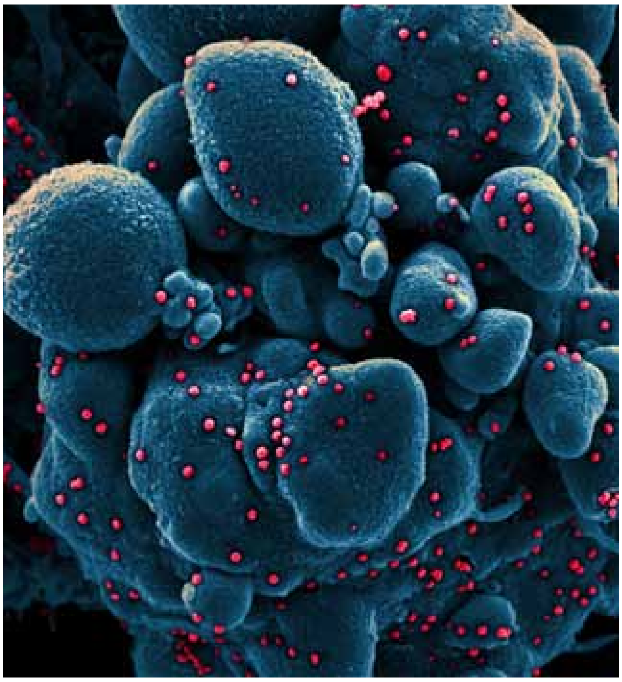
Inside the viral envelope is the viral RNA, which is bound to the nucleoprotein (N). N proteins form a tight spiral that wraps and coils the RNA, protecting it from damage. When the RNA is first released into the host cell, the N protein also reduces the host cell's natural defences against the virus.

The coronavirus **RNA** molecule is 30,000 'letters' long, making it one of the largest RNA viruses discovered. While RNA viruses have a high mutation rate, coronaviruses also possess a genomic proofreading mechanism. This can keep them from accumulating negative mutations that would weaken them. Coronaviruses can also swap blocks of RNA with each other, potentially trading useful mutations.

While the new coronavirus likely originated from bats, it is not yet known whether or which mutations allowed this jump from animals to humans. The RNA of SARS-CoV-2 is 96% similar to a virus found in a bat in China. However, the bat virus contains key differences in its S protein, and is not able to infect humans. It is also likely that SARS-CoV-2 viruses will contain **host cell proteins** from previous host cells. The virus also makes additional proteins following host cell entry that allow it to multiply and make new virus particles. In addition to vaccine efforts targeting the S-protein on the virus particle, these intra-cellular proteins are potential targets for intervention.

Prepared by Annabel Slater, ILRI.

For references see page 62.



Colourized scanning electron micrograph of a cell (blue) infected with SARS-COV-2 virus particles (red)

Photo credit: US National Institute of Allergy and Infectious Diseases

Common elements and origins of coronavirus pandemics

The six coronavirus pandemics named above share some of the following common elements.

Bats

Bats are natural reservoir hosts as well as vectors of many microbes that can affect animals and people. Contact between bats and other animals, including humans, allows for inter-species transmission of the pathogens they harbour, potentially resulting in disease outbreaks. Most of the recent coronavirus pandemics have been hypothesized to have an initial origin in bats. More than 200 novel coronaviruses have been found in bats and they are likely the source and natural hosts for all coronavirus lineages.[59] Bats are also associated with many other important zoonoses such as Ebola, Nipah (via bridging with pigs or indirectly through contamination of domesticated plants) and very rarely rabies. Bat species harbour at least 61 potential zoonotic viruses.[60] They can resist, provide opportunities for recombination, and spread many serious zoonoses as a result of their unique physiological features (bats are the only mammals able to fly), ecology and immunology. At the same time, bats provide many ecosystem services such as flower pollination and seed dispersal for hundreds of species of plants, and aid in controlling insect populations; they also maintain ecosystems by providing food for predators such as owls, hawks and snakes.[61]

Agricultural intensification and increased demand for animal protein

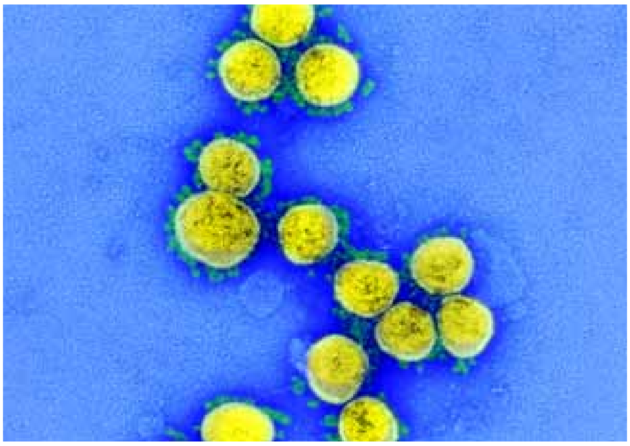
These coronavirus disease outbreaks followed rapid intensification of agricultural practices and systems, and dramatic changes in the ways animals were kept or farmed, many of which were made without proper precautionary measures being taken. As mentioned previously, this was a demand driven process, associated with increasing wealth, allowing people to consume more animal source food. For instance, the emergence of infectious bronchitis virus in the United States was associated with post-World War I intensification of poultry systems based on bird confinement (resulting in greater stress and more frequent contacts) and new breeding techniques (resulting in less genetic variation and disease resistance). In addition, the transmissible gastroenteritis (TGE) virus and porcine epidemic diarrhoea (PED) virus were associated with post-World War II increases in intensive pig production systems and a related decline in pig health, similar to the case of industrialization of poultry production.

SARS-CoV and SARS-CoV-2 may be associated with wildlife harvest, trade practices and the intensification of wildlife farming in East Asia. The latter has been actively encouraged in some countries; by 2006, nearly 20,000 wildlife breeding and farming ventures were established in China.[62] As wealthy consumers tend to prefer wild-caught animals, the meat from these farms is often consumed by China's rapidly growing middle class.[63]

There is concern that many wildlife farms are prone to low biosecurity and that they also enable illegally poached wildlife to be "laundered"—presented and sold as legally farmed animals.[31] Both factors would increase the risk of zoonotic disease outbreaks.

Video: Novel coronavirus

Video Link: https://www.youtube.com/watch?v=mOV1aBVYKGA | © WHO



SARS-CoV-2 virus particles

Photo credit: US National Institute of Allergy and Infectious Diseases

Flying foxes or fruit bats (*Pteropus* sp.)
Photo credit: nutsiam / Shutterstock.com

MERS-CoV was associated with increases in dromedary camel numbers and a shift from extensive to intensive camel production systems. An analysis of potential drivers of MERS-CoV emergence in Qatar suggests that the socio-economic transformation in the last three decades and the growing popularity of camel racing triggered major changes in camel farming practices.[64] Camels were raised in designated camel complexes in a high-density environment alongside the workers who fed and took care of them. Races and contests in the Gulf region also required camels to travel frequently and extensively, both across borders and within the country. These factors played an important role in the transmission of MERS-CoV from camels to humans.

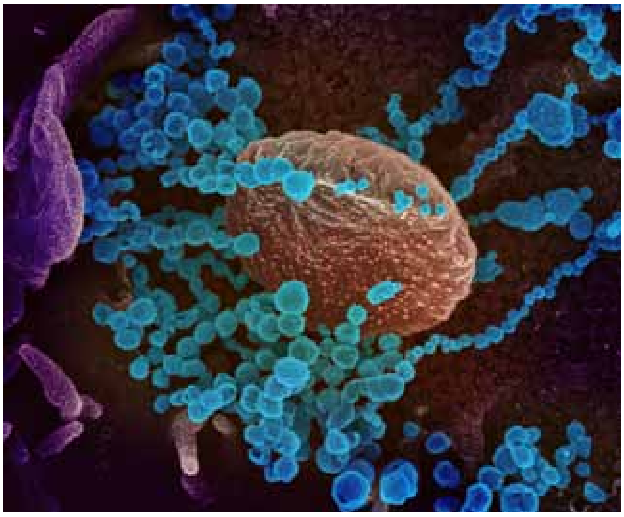
Traditional markets

Both SARS-CoV and SARS-CoV-2 have been associated with traditional informal markets or fresh produce markets (sometimes called wet markets). These markets sell fresh meat, fish and other perishable agricultural produce. Some of these informal markets sell live poultry and other domesticated animals; many sell live aquatic products (fish and shellfish); and some sell live or dead wild animals. The products can be sourced from many different places, including from distant parts of the world.

SARS-CoV was associated with civet cats sold in informal markets. SARS-CoV-2 has been associated with a traditional food market where wildlife was purported to be sold. Other studies, however, have cast doubt on the initial emergence event leading to human infection.[65,66] There is general consensus that informal markets can be epidemiologically risky, especially those selling live domesticated animals or live or dead wild animals and those with poor hygiene.[67,68] However, expert opinions differ as to whether live animal markets should be regulated more strictly, gradually upgraded with buy-in from vendors, or banned completely in order to reduce disease transmission risk. It should be noted that strict regulation of food has proven difficult in governance-poor contexts and banning desired products often

Video: How do viruses jump from animals to humans?

Video Link: https://www.youtube.com/watch?v=xjcsrU-ZmgY | © *TED-ED*



Electron microscope image of the novel coronavirus, SARS-CoV-2 (round blue spheres) in cell culture.

Photo credit: US National Institute of Allergy and Infectious Diseases

shifts the market underground.[69] As mentioned earlier, informal, traditional or fresh produce markets have many benefits for people, including low prices, ease of access, the availability of preferred fresh and traditional foods, income-earning opportunities for women, worker independence, and attractions for tourists. However, these need to be weighed against the wider benefits to humanity (including local people) of preventing disease outbreaks and global pandemics. Ideally, solutions would be found that preserve the benefits while mitigating the risks of traditional markets.

High economic costs

The three recent human coronavirus outbreaks (MERS, SARS and COVID-19) have shown a relatively low human population mortality rate compared to historic plagues (some of which killed up to 90 per cent of the populations affected); relatively high lethality in comparison to colds or seasonal influenza; and intense social disruptions. All six coronavirus pandemics (IBD, PED, TGE, SARS, MERS, COVID-19) have had high economic costs and, for some diseases, very high animal mortality rates.

As of 29 June 2020, there were more than 10 million confirmed cases of COVID-19, including more than 500,000 reported deaths. These figures are likely to be great underestimations of the true numbers of infections and deaths. With medical staff and facilities in frontline disease regions in or near overwhelm, COVID-19 may also be responsible for many more indirect deaths due to sick people choosing not to seek medical care because of their concerns about contracting COVID-19 in hospitals or not wanting to overwhelm health services. Reported to occur in 216 countries and territories (as of mid-June 2020) and on every continent other than Antarctica, the disease initially concentrated in "disease hotspots" experiencing especially high disease burdens. These included, among others, Wuhan in China, Lombardy in northeast Italy, New York City in the United States, Madrid in Spain, London in the United Kingdom, and Rio de Janeiro and São Paulo in Brazil.

The huge health impacts of this new coronavirus necessarily imply enormous economic impacts. The International Monetary Fund predicts that the global economy will shrink by 3 per cent in 2020, a downgrade of 6.3 percentage points from estimates in January 2020. The Fund also estimates that over the next two years, cumulative output losses from the COVID-19 pandemic could reach USD9 trillion.

The International Labour Organization estimates that COVID-19 will wipe out 6.7 per cent of working hours globally in the second quarter of 2020—equivalent to 195 million full-time workers. The Chinese economy shrank 6.8 per cent in the first three months of 2020, the country's first such contraction on record. With the modern global economy so closely interconnected, much up- and downstream damage is anticipated. Among the more serious harms are the potential impacts on food systems, which could lead to more than a quarter of a billion people suffering acute hunger by the end of 2020, according to the World Food Programme. Countries highly reliant on food imports, such as Somalia, and those highly reliant on food exports, such as Nigeria, are equally vulnerable. The impacts of this disease are already being felt across many sectors. According to UNESCO, for example, more than one billion students worldwide missed attending school or university in April 2020.

A market in Guangzhou, China

Photo credit: tostphoto / Shutterstock.com

Section Three

Understanding the linkages between habitat loss, the trade and use of wildlife, and the emergence of novel zoonoses

III

This section considers how human activity contributes to the emergence of diseases at the environment-wildlife interface. Building from the anthropogenic drivers outlined in Section One, this section focuses on land-use change and the use or exploitation of wildlife; discusses evidence regarding the consumption, trade and other uses of wild animals; describes the driving forces behind these behaviours and actions; and focuses on the specific risks associated with wildlife use and consumption.

Habitat and biodiversity loss

The FAO Global Forest Resources Assessment 2020 indicates that deforestation continues globally at a rate of 10 million hectares a year.[70] Rapid increases in the world's human population from around one billion two centuries ago to over 7.8 billion today, has meant more and more encroachment of humans into natural habitats, which has brought humans and animals into ever-closer contact and increased the risk of animal-to-human disease transmission. Deforestation, particularly in tropical regions, has been associated with an increase in infectious diseases such as dengue fever, malaria and yellow fever, to name a few.[71] This section discusses the association between habitat/biodiversity loss and the emergence of zoonotic diseases.

Anthropogenic land-use changes in Australia have contributed considerably to the rise of emerging and re-emerging mosquito-borne diseases, while forest fragmentation has increased the risk of humans contracting Lyme disease.[32,72] An examination of circumstances surrounding outbreaks of rodent-borne haemorrhagic fevers suggests that anthropogenically disturbed, low-diversity habitats present the greatest risk for humans to contract hantaviruses, causing potentially fatal illnesses, or arenaviruses, which cause Lassa fever and other illnesses.[73] Rodent populations are increasing in many areas. One explanation for this is that many predators that fed on rodents no longer inhabit disturbed habitats. An increase in the transmission of flea-borne diseases via small mammals due to human disturbance of habitats has been shown in several ecosystems.[74] A study of zoonotic malaria, transmitted by macaques in Malaysian Borneo, confirmed the link between zoonotic spillovers and deforestation but showed complex and different effects of forest degradation at different scales.[75] In general, increases in malaria prevalence may be associated with certain forms of landscape conversion, such as partial draining of wetlands, shrub height changes favoured by certain species, and changes in mosquito prey that affect mosquito abundance.

Several hypotheses attempt to explain the association between habitat or biodiversity loss and emerging infectious diseases. First, disturbed habitats often favour opportunistic or generalist species that happen to be reservoirs for viruses. Second, through a process called the "dilution effect," more virus transmission events occur within a single species in communities that have low species diversity than in communities that have greater species diversity. In such cases, the single species is usually an opportunistic species that is the specific host of the virus. The dilution effect occurs because communities with more species dilute transmission events by reducing the number of susceptible animals. For example, in communities of higher biodiversity, disease-transmitting vectors feed on a larger variety of hosts that are poor reservoirs for the pathogen (e.g., West Nile virus and tick-transmitted Lyme disease).[76] Nonetheless, ecological systems are complex, and empirical evidence for the dilution effect hypothesis has been inconsistent. The outcome depends on the pathogen transmission mode, among other factors. Dilution effects occur for most frequency-transmitted pathogens and amplification effects occur for density-dependent pathogens.[77] Moreover, while more biodiversity means greater viral richness, the risk of pathogen spillover stems from increased exposure, for example as more humans visit environments where pathogens are present.[23,78]

Hunter prepares Bonobo bushmeat over a fire in Kilima, DR Congo
Photo credit: © Terese Hart / Flickr License CC BY-NC 2.0

Respiratory infections and primates

A bonobo (*Pan paniscus*) in a forest of DR Congo
Photo credit: Sergey Uryadnikov / Shutterstock.com

Human respiratory pathogens have been transmitted to wild great ape populations many times, sometimes causing extensive ape mortality. Some of these pathogens tended to cause mild disease in adult humans but severe and even lethal outcomes in great apes, such as the human respiratory syncytial virus (HRSV) and human metapneumovirus (HMPV), as well as human coronavirus subtype OC43 infections of wild chimpanzees in 2016.[79,80]

Whether ape morbidity and mortality associated with the new coronavirus, SARS-CoV-2, could be similar to that in humans is unknown. The fact that mild cases occur in humans is cause for grave concern for the great apes because asymptomatic visitors could pass the virus on to great apes.[81] Governments, policymakers, conservationists, researchers and great ape tourism professionals are being encouraged to take actions to reduce the risk of SARS-CoV-2 being introduced in endangered ape populations. Many protected area authorities in Africa and Asia have already taken action, with tourism suspended at almost all great ape sites. The Primate Specialist Group, Section on Great Apes, and the Wildlife Health Specialist Group of the International Union for the Conservation of Nature (IUCN) refer in a joint statement of 15 March 2020 to best practice guidelines for great ape disease control and tourism.[82,83]

Other diseases have had devastating impacts on both humans and great apes. Ebola, discovered in 1976 in the Democratic Republic of Congo and in South Sudan, can afflict chimpanzees and gorillas as well as people. Pre-2005 Ebola outbreaks occurred deep in the rainforest biomes but subsequently shifted to more transitional forests in Uganda, DR Congo and Guinea, where forest loss might have played a role.[84,85]

Previous Ebola outbreaks in Gabon and the Republic of Congo in the mid-1990s killed more than 90 per cent of the gorillas and chimpanzees in some areas, and additional outbreaks in these countries from 2000 to 2005 killed thousands of great apes.[86] It is estimated that it will take gorilla populations that experienced 95 per cent mortality more than 130 years to recover.[87]

Another hypothesis, known as the "coevolution effect," which is rooted in ecology and evolutionary biology, proposes to explain the underlying mechanisms that drive this association between habitat or biodiversity loss and emerging infectious diseases.[88] This theory suggests that as humans alter landscapes and former intact habitats are lost, forest fragments serve as islands harbouring wildlife hosts of pathogens that undergo rapid diversification, leading to greater probability that one of these pathogens will spill over into human populations, where they will cause new disease outbreaks.[88,89] Maintaining healthy, well-connected ecosystems is important for migratory and resident species and also should help reduce the prevalence of infectious diseases.[89]

Viral diversity is also associated with species diversity.[78] New research has predicted high rates of mammalian viral sharing in the tropics, particularly among rodents and bats, depending on their taxonomic similarity and overlap in geographic range.[90] While the specific transmission mechanisms may differ by pathogen and interaction, the shared drivers of biodiversity loss, ecosystem change and disease emergence reinforce how biodiversity and wildlife conservation can play critical roles in protecting humans from emerging infectious diseases.

The roles of wildlife harvesting, farming and trade in pathogen spread

As noted above, wild animals are hunted and captured for human subsistence, for recreation and for the sale of body parts and their derivatives.[91,92] They are also farmed for the production of food and products.

Wild meat hunting

Hunting has been part of many cultures for millennia. However, an important disease transmission interface between the environment and people is through the harvesting of wild animals.

It is estimated that about 6 million (metric) tonnes of wild meat is harvested annually in Latin America and Africa.[93] One analysis found that, in Central Africa, meat supply from wild meat hunting might be higher (at 48g per person per day) than supply from domesticated animals (34g per person per day).[94] A recent survey of nearly 8,000 rural households in 24 countries across Africa, Latin America and Asia found that 39 per cent of households harvested wild meat and almost all consumed it.[95] Animals that are often hunted for meat include large herbivores, primates, rodents, snakes and other reptiles. Mammals represent more than 90 per cent of the wild meat sold in markets in Central Africa.

The hunting of aquatic species has taken place for generations, but it is clear that many poorer coastal communities are becoming newly reliant on aquatic wild meat to satisfy their daily dietary requirements. These communities have also turned to this harvest for alternative sources of income.[96]

Aquatic wild meat includes products derived from aquatic mammals and reptiles, including species of dolphins, whales, manatees, crocodiles and turtles, that are used for subsistence food, bait for fisheries and traditional uses. The products include shells, bones and organs as well as meat. Aquatic wild meat is obtained through unregulated, and sometimes illegal, hunts as well as from stranded (dead or alive) animals or through "bycatches" of non-target animals caught by fishermen incidentally.

A leopard cat sold in a market

Photo credit: MemoryMan / Shutterstock

Migratory species and zoonotic diseases

Wild ducks
Photo credit: aaltair / Shutterstock.com

Zoonotic pathogens are found in a variety of migratory species of wild animals (e.g., bats, ungulates, and waterfowl). While some zoonotic diseases in humans appear to have been tied to spillovers from migratory species, most of these events have resulted from human activities, such as direct consumption of wild animals, harvesting, handling and increased proximity of humans and livestock to natural habitats.

In the case of the current pandemic, while a bat species is a likely reservoir of the precursor to SARS-CoV-2, there is wide consensus that bats do not carry or transmit COVID-19 to humans. Misinformation has led to an unfortunate culling of bat populations in some parts of the world.

Some migratory species have been associated with the spread of zoonoses. Yet migration has also been shown to reduce transmission in some species.[97] In particular, reduction of length or suppression of migration has been associated with increased load in pathogens.[98] As climate change and habitat loss and fragmentation are profoundly affecting migratory behaviour, there is an urgent need to further investigate links between animal migration and disease infection dynamics.[99]

The conservation status of many migratory species is declining worldwide. Many factors related to the increased occurrence of zoonotic diseases are the same as those that threaten the survival of migratory species.

A preliminary analysis of the status of migratory animals listed under the Convention on Migratory Species (CMS) identified consumptive use as the threat affecting most species.[100] Consumptive use includes both legal and illegal trade, illegal killing, subsistence harvesting and recreational hunting. Overexploitation of wildlife has also been associated with an increased risk of pathogen spillover.[8] Habitat loss and fragmentation is another major cause of migratory species decline. The loss of ecological connectivity, vital for migratory species, is of particular concern. Habitat loss and fragmentation have also been found to increase the likelihood of a spillover.[101] Maintaining healthy, well-connected ecosystems is important for migratory species and also should help reduce the prevalence of infectious diseases.[89]

Prepared by the Secretariat of the Convention on the Conservation of Migratory Species of Wild Animals.

Driving forces of wild meat consumption

The increasing consumption of wild meat in certain regions is driven by the following factors: [92,102]

1. An increasing human population is demanding more protein-rich food and income that cannot be met with traditional resources—land, labour, livestock, capital—alone. Global population densities are increasing, especially in Africa, which has the world's highest rate of population growth and is expected to account for more than half of the world's population growth between 2017 and 2050.[103]
2. Local communities have few incentives to conserve wildlife and wildlife habitats, and there are few attractive substitutes for these wildlife resources. In many cases, development projects such as chicken and pig farms have provided employment and animal protein to local communities, but failed to reduce pressure on populations of wild species.[104] In other cases, attempts to introduce domesticated animals into communities were unsuccessful. The wild meat trade also serves as a safety net in times of hardship, as it generates both protein and income for poor households.[105]
3. In some regions, there is a growing demand for wild meat among wealthy urban elites, for whom consumption of wild animals is a status symbol or a luxury good—or they simply prefer the rich taste. A survey estimated that around 83 per cent of sampled households in Brazzaville, Republic of the Congo, consumed wild meat.[106] Less well-off city dwellers may also prefer wild meat, perhaps choosing less exotic or less expensive types.
4. Increasing connectivity between rural and urban populations is increasingly bringing poor and rich worlds together. In Asia and Africa, much wild meat as well as live wild animals are sold in informal markets. The lack of adequate biosafety measures makes these markets, where live wild animals are mixed together for their sale, a particular risk for zoonotic disease emergence.

Wild meat farming and ranching

Over the last 60 years, wild meat production from both illegal and legal production of farms has been steadily increasing. Wild meat is also harvested from more extensive production systems in rangelands in the tropics, temperate regions and the arctic. The total global legal production reached 2.11 billion (metric) tonnes in 2018. In South Africa, wild meat contributes nearly USD500 million (ZAR9 billion) annually to the country's GDP and employs over 100,000 people while also providing a considerably better return on investment than livestock production.[107] In Europe, the value of game meat (including deer and boar) was USD347 million (EUR321 million) in 2014. Game meat also contributes significantly to local livelihoods and food security around the world.[97,108-111] In these cases, using and trading wildlife is an economically viable land-use option that helps to keep habitats intact.

There are also concerns about zoonotic disease transfer to humans from both wildlife farms and more extensive rangeland management systems. In theory, wildlife farms could provide proper sanitary conditions that reduce the risk of disease transmission. But in reality, the risk of disease transmission with wildlife farms is significant and more efforts to reduce risks are needed.[31,112]

Wildlife trade

Live animals and animal products are brought into close proximity with people in different forms, as part of national and international legal and illegal wildlife trades—as food, sale items, pets or medicines.[112] A mix of animal species are traded in markets—wild, captive-bred, farmed and domesticated—in transport vehicles and in market cages. Viruses transmitted to people during practices that facilitate the mixing of diverse animal species such as in markets have been shown to have significantly higher 'host plasticity'—a taxonomically and ecologically diverse host range.[113]

The close contact between humans and different species of wildlife in the global wildlife trade can facilitate animal-to-human spillover of new viruses that are capable of infecting diverse host species. This can trigger emerging disease events with higher pandemic potential because these viruses are more likely to amplify via human-to-human transmission, and thus spread widely.

Dried Tokay gecko (*Gekko gecko*) traded for traditional medicine
Photo credit: Orvar Belenus / Shutterstock.com

Zoonotic risks of wildlife use, trade and consumption

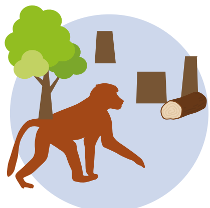
The potential health risks of harvesting, trading and consuming wild meat and of trading live animals are discussed in more detail in the following paragraphs. Disease transmission can occur through direct contact with any of the following:

1. Hunted and consumed wild animals;
2. Traded wild animals (including at markets);
3. Wild animals kept as pets or in zoos, sanctuaries or laboratories (not covered in this report); and
4. Domestic animals (covered in Section One).

With wild vertebrates being reservoirs of a large repertoire of zoonotic pathogens, wild meat harvesting and trade in live animals enhances several pathways of zoonotic pathogen spillover. Hunters in many forested regions risk disease if injured by an animal during its capture, when carrying their prey back home, or if they cut themselves

Forest destruction and disturbance increase human exposure to zoonotic disease reservoirs. A spillover of ebolaviruses to humans is more likely to occur in highly disturbed forested areas. An analysis of large-scale deforestation and fragmentation in West and Central Africa from 2001 to 2014 shows that the Ebola virus outbreaks along the edge of the forest was associated with the loss of the dense forests, especially those with high canopy cover, that happened within the previous two years.

A study of the effect of landscape fragmentation in Brazil's Atlantic Forest found that the re-emergence of Chagas disease, caused by the parasitic protozoan *Trypanosoma cruzi*, was associated with reduced mammal diversity and increased abundance of competent reservoir species, such as the common opossum and other marsupials. Moreover, *T. cruzi* was found to be more prevalent in small mammalian species in forest fragments than in continuous forest.



Habitat disturbances can alter the dynamics of cross-species pathogen transmission. When scientists examined *Escherichia coli* bacteria in humans, livestock and wildlife near Kibale National Park in Uganda, they found that *E. coli* from humans and livestock were genetically more similar to those collected from primates living in forest fragments, than the bacteria from primates living nearby in undisturbed forest areas. Another study in Bwindi Impenetrable National Park also found that *E. coli* from gorillas with frequent human contacts were genetically similar to *E. coli* from people and livestock.

Encroachment of natural habitats brings people into greater contact with wildlife, allowing pathogens to jump from wildlife hosts to other species. The emergence of bat-associated viruses in Australia including Australian bat lyssavirus, Hendra virus and Menangle virus is linked to agricultural and urban development. Bats are sensitive to human disturbances. Landscape transformation and fragmentation reduced feeding and roosting habitats of *Pteropus* sp. fruit bats or flying foxes, driving them to search for alternative feeding and roosting sites in peri-urban landscapes.

For references see page 63.

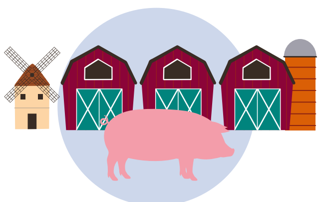
when butchering the animal.[114] These facilitate the transfer of body fluids from the animal to the hunter.[115]

Investigations into the diversity of human T-lymphotropic virus (HTLV) among Central Africans reporting contact with non-human primate blood and body fluids through hunting and butchering showed that these hunters were infected with a wide variety of HTLVs associated with many human illnesses.[116] A study found simian foamy virus infections in Central African hunters and concluded that retroviruses can cross into human populations via contact when hunting and butchering.[117] An extensive survey of the prevalence and genetic diversity of SIVs in primate wild meat provides insights into the risk for potential new cross-species transmissions.[118]

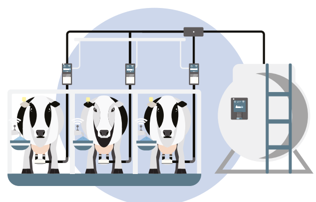
It is noteworthy that Ebola in Central Africa was spread among hunters opportunistically harvesting and handling infected gorilla and chimpanzee cadavers for meat consumption.[119] While there is a risk in consuming wild

Rodents are associated with more than 80 zoonotic diseases. They are highly adaptable to habitat disturbances. A meta-analysis of 58 case studies from eight countries suggests that land use change is more favourable to rodent species that harbour zoonotic pathogens. Reservoir rodents were found to be more abundant in modified habitats, and more non-reservoir rodents in natural habitats. Experiments in a savanna system show that rodent abundance increased when large wildlife— either rodent predators or competitors—were removed, leading to an increased risk of rodent-borne disease.

West Nile virus was introduced to the United States in 1999 and is now endemic. Wild and peri-domestic birds serve as virus hosts, and mosquitoes as disease vectors. The introduction of the exotic virus has substantially reduced numbers of native bird populations, with some species showing no signs of recovery. A national-scale study found that prevalence of West Nile virus infection in vector mosquitos and humans increased as bird diversity decreased. Bird communities with rich diversity tended to be less competent pathogen reservoirs.



Land-use change can facilitate contact between species that usually have little or no prior interaction, allowing pathogens to cross the species barrier. Nipah virus emerged from a large intensive pig farm in Ipoh, Malaysia, in 1997. Studies suggest that Nipah virus spilled over to pigs from infected fruit bats searching for food in cultivated fruit orchards adjacent to the pig farm. Infected pigs were then sold to other commercial pig farms in the south, resulting in the 1998-1999 outbreak in pigs and piggery workers.



Changes in the pathogens can occur as they evolve to exploit new hosts or adapt to changing evolutionary pressures. Antimicrobial resistance is the result of pathogens being exposed to antimicrobial drugs and building resistance over their short-lived generations. Antimicrobials are widely used, or misused, in veterinary medicine, often as preventives. Drug resistance is growing in domesticated animals, especially in industrialized agriculture, and can increase risks of disease emergence in livestock and humans.

Video: Hotbed of Disease

Video Link: https://www.youtube.com/watch?v=9kGH7iC-7TQ | © Frontline PBS

Bwindi Impenetrable National Park, Uganda

Photo credit: Travel Stock/Shutterstock.com

meat without applying minimum hygiene rules, this is not the only factor. The biggest Ebola outbreaks in West Africa and now Eastern DR Congo are about secondary epidemiological cycles, which underscores the fact that human conditions and actions, not "chance spillovers," are the central factor in zoonotic disease transmission. In low-density and widely dispersed human communities, Ebola was a sporadic, low-impact (if distressing) disease of little socio-economic consequence until it found its way into urban spaces with their dense, and densely connected, human populations.

The pathogen transmission pathway from a wild animal to a human—starting with a small number of rural hunters and moving to large numbers of wild-meat consumers, in both rural and urban areas, is an important factor.[112,120] Recent studies conducted in the western part of the Serengeti, in Tanzania, showed that regardless of the wildlife species, the samples of wild meat screened had DNA signatures of potentially dangerous zoonotic pathogens such as *Bacillus, Brucella* and *Coxiella* spp.[121]

The meat samples screened were from the highly preferred large mammals such as buffalo, wildebeest, eland, gazelle, giraffe, warthog and zebra, as well as porcupine. Infections from such endemic pathogens generally do not develop into epidemics, but such infections can be used to identify risk pathways that could be used by pathogens of higher consequence.

A risk assessment of zoonotic disease in markets in Cambodia found that the combination of high wildlife volumes, high-risk taxa for zoonoses and poor biosafety increases the potential for pathogen presence and transmission.[122] In North America, several studies have documented the potential disease transmission pathway associated with the import of live animals in trade.[120,123] The first reported occurrence of monkeypox outside Africa, in 2003, was due to human infection by pet prairie dogs that had become infected by African rodents imported to the US.[124] In 2017, an outbreak of *Salmonella Agbeni* infections was linked to pet turtles.[125]

Camels at the camel sales market in Cairo, Egypt

Photo credit: Buhairi Nawawi / Shutterstock.com

Early warning systems and monitoring wildlife

Bat research at Joshua Tree National Park in California, United States
Photo credit: US National Park Service/Hannah Schwalbe

Animal and environmental indicators can provide a valuable tool for disease early warning systems:

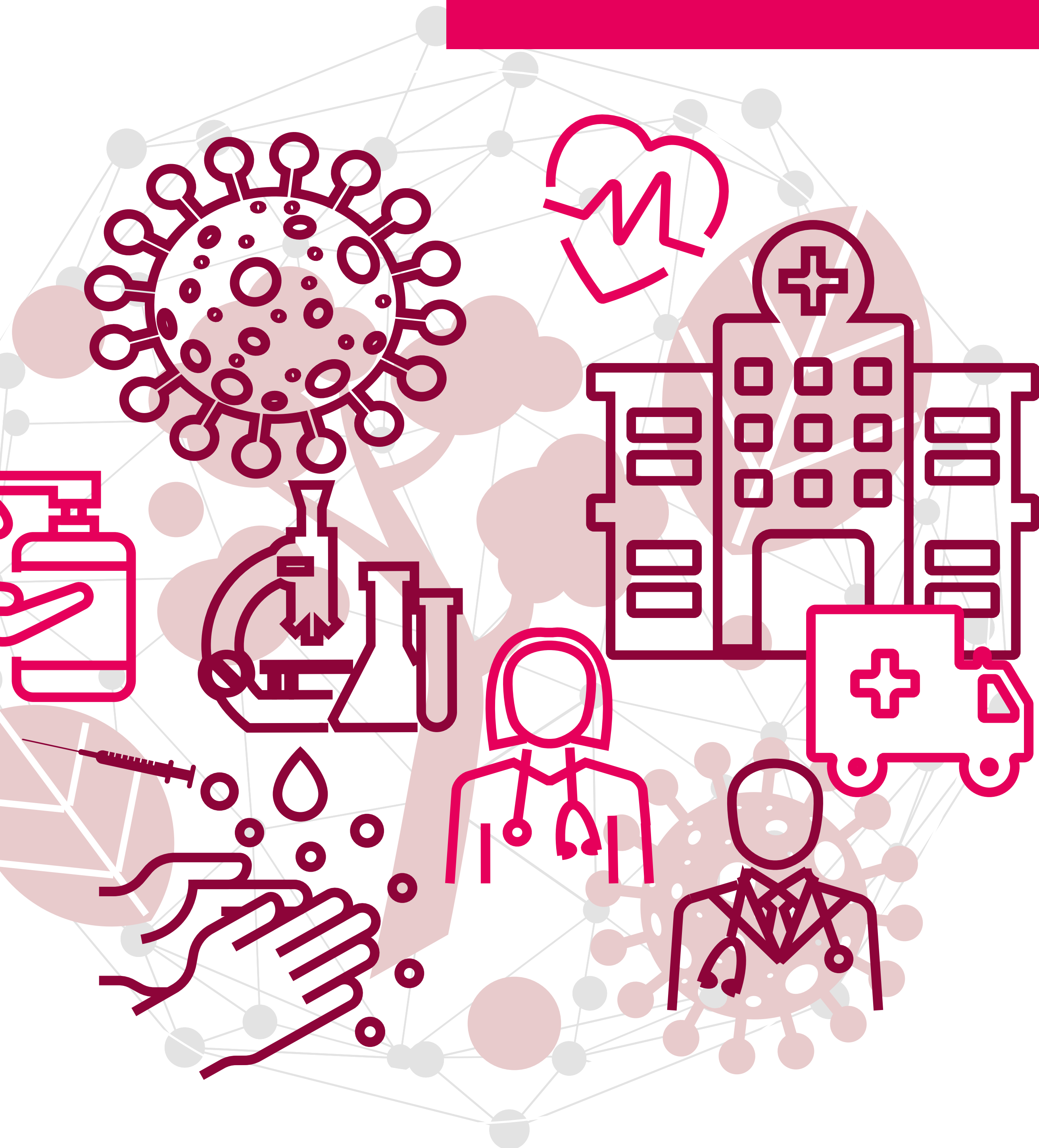
Monitoring microbial diversity in wildlife, either in a given region or certain species, can be a good indicator for detecting potential disease outbreaks, particularly for coronaviruses, filoviruses and paramyxoviruses. Consistent monitoring of wildlife morbidity or mortality events can also provide indicators of active circulation of disease or outbreaks. For example, an investigation of dead howler monkeys found near a wildlife sanctuary in Bolivia led to the detection of yellow fever virus. This provided vital alert information and activation of vaccination campaigns to prevent human cases.[126]

Sentinel surveillance approaches that select a smaller and targeted group of health workers to gather data have been utilized effectively to get ahead of potential spillover events for the detection of West Nile virus in birds and equids, Ebola virus in great apes, and monkeypox in chimpanzees in Cameroon.

Targeted environmental indicators may also be useful for forecasting risk alerts. Examples have included prolonged periods of rainfall, which are associated with elevated risk of Rift Valley fever outbreaks in some regions, or flooding events, which are associated with leptospirosis. As certain species are known to serve as hosts or transmitters of zoonotic diseases, monitoring species distribution can offer important indications of potential risks to human health. For example, a change in species range or introduction of invasive species that has the potential to serve as a host can signal potential risks. Consistent monitoring and sharing of this information among wildlife, livestock and human health agencies is important to improve risk assessment and prevention for zoonotic disease threats.

There are other examples of zoonotic diseases known to be transmitted by aquatic animals. If left untreated, zoonoses transmitted from seals, whales and other marine mammals that rely on marine ecosystems can induce life-threatening systemic diseases that could pose public health risks. Consumption of raw or undercooked meat from pinniped (seal, walrus) or cetacean (whale, dolphin, porpoise) mammals has caused serious bacterial (e.g. *salmonellosis* and botulism) and parasitic (*trichinellosis* and *toxoplasmosis*) diseases in humans.[96]

While this section focuses on the direct risks of zoonotic disease transmission faced by humans in contact with wild animals, there are also significant secondary impacts to such wild animal-human interactions. As noted at the beginning of this section, where wild animal trade is unsustainable and wildlife populations are significantly reduced or made locally extinct, that ecosystem loses not only its biodiversity but also a protective "biodiverse buffer" against the emergence and spread of novel zoonotic diseases.



Section Four

Managing and preventing zoonoses: How One Health can help

IV

This section sets out the One Health approach as the most promising way to manage and prevent zoonoses; it also gives examples of its past successes and discusses some of the potential barriers to a wider uptake. Lessons from managing previous zoonotic outbreaks, including pandemics, are shared and discussed.

The One Health approach to controlling zoonoses

Humanity's experience in public health over the past centuries allows us to draw some broad lessons about effective management of zoonoses. As explained earlier in this report, the One Health approach can be defined as the collaborative effort across multiple disciplines to attain optimal health for people, animals and the environment. This approach has emerged as a key tool for preventing and managing diseases occurring at the interface of human, animal and environment health. At the same time, a closely related approach, known as "EcoHealth" has been defined as a set of systemic, participatory approaches necessary to understanding and promoting both health and well-being in the context of social and ecological interactions. Both the One Health and EcoHealth approaches emphasize multidisciplinary collaboration for holistic interventions that attain not only human health goals but also animal and environment health targets, the latter two of which are central to improving the control of neglected and emerging infectious diseases, many of which are zoonoses.[127]

Though both One Health and EcoHealth approaches sit at the nexus of human, animal and environmental interactions, they have subtle differences: One Health, as generally practiced, emphasizes biomedical animal and human health, while EcoHealth pays more attention to the broader relations between health and ecosystems, focusing on the environment and related socio-economic systems.[128] A third concept, "Planetary Health," focuses on human health in relation to global sustainability.[129] As none of these terms has an agreed or standardized definition, and given their convergence and similarities[130], this assessment report adopts One Health as the umbrella term, as it can be most easily understood by decision-makers and the general public.

As we have seen, zoonotic diseases involve and affect human health, animal health and environment health.

One Health

The pathogens originate in animals, and the emergence or spillover of the diseases they cause in humans is usually the result of human actions, such as intensifying livestock production or degrading and fragmenting ecosystems, or exploiting wildlife unsustainably (see Sections One and Three). As such, their management should be inter-sectoral. At the global level, three intergovernmental organisations, from different sectors, have specific mandates that address zoonotic diseases: the World Health Organization (WHO), the World Organisation for Animal Health (OIE), and the Food and Agriculture Organization (FAO).

In response to the bird flu (HPAI) pandemic, these three intergovernmental organisations along with UNICEF, the United Nations System Influenza Coordination (UNSIC), and the World Bank developed a strategic framework for reducing the risks of emerging zoonoses.[131] This framework has five strategic elements that remain relevant today:

1. Build robust and well-governed public and animal health systems compliant with the WHO International Health Regulations (the amendment entered into force in July 2016) and OIE international standards through the pursuit of long-term interventions.
2. Prevent regional and international crises by controlling disease outbreaks through improved

national and international emergency response capabilities.
3. Promote wide-ranging collaboration across sectors and disciplines.
4. Develop rational and targeted disease control programmes through the conduct of strategic research.
5. Better address concerns of the poor by shifting the focus from developed to developing economies, from potential to actual disease problems, and through a focus on the drivers of a broader range of locally important diseases.

In 2010, FAO, OIE and WHO started collaborative work to address risks at the human-animal-ecosystems interface as described in the FAO/OIE/WHO Tripartite Concept Note.[132] In 2019, they updated their joint 2008 tripartite guide on zoonoses and other One Health issues. Other intergovernmental organisations also have interests in environment, animal and human health, notably the United Nations Environment Programme (UNEP), some Multilateral Environmental Agreements (MEAs) and the World Bank. The Convention on Biological Diversity has developed Biodiversity-inclusive One Health Guidance.[133] And there are many other organisations, institutes, programmes, government agencies and nongovernmental organisations working in this space. CGIAR, for example, is the world's largest global agricultural innovation network; one of CGIAR's constituent centres, the International Livestock Research Institute (ILRI), has programmes working on livestock and human health and sustainable livestock systems.

In general, environment health initiatives have been less well represented than animal, livestock and human health initiatives in global zoonoses prevention and control programmes. But the environment is key to the emerging One Health approaches that are spearheading zoonoses risk reduction and control at regional and national levels. Applying these multi-sector approaches has had

Role of environmental health and its practitioners in Uganda's One Health programmes

A butcher shop in Kampala, Uganda
Photo credit: Black Sheep Media / Shutterstock.com

Environmental health practitioners in Uganda have significantly helped to reduce sickness and deaths caused by zoonotic disease outbreaks such as Ebola. These practitioners work at the frontlines of disease surveillance. Their tasks include the following:

- Inspecting livestock before slaughter as well as the meat in slaughterhouses and butcheries;
- Monitoring the destruction of condemned meat;
- Investigating zoonotic disease outbreaks and monitoring disease control programmes;
- Ensuring the control of disease vectors and vermin such as rats, fleas, mosquitoes and monkeys;
- Providing communities with health education on pertinent issues such as vaccination of children and pets;
- Involving themselves in all matters related to food safety; and
- Helping to enforce Uganda's public health legislation.

In short, Uganda's environmental health practitioners are the very embodiment of the One Health approach to healthy people, animals and the environment. To stop disease outbreaks in the future, Uganda will be relying on this remarkable group of "environmental health activists" to advise on, plan, implement, manage and monitor the country's many One Health activities.[134]

some notable successes, such as in controlling rabies in the Serengeti ecosystem in Tanzania; understanding the human and animal burden of brucellosis in Mongolia; elucidating the transmission dynamics of Rift Valley fever and forecasting its outbreaks; and building capacity in One Health disease control in Southeast Asia.[135]

Track record in managing zoonoses

There have been many cases of successful management of endemic zoonotic diseases. Several developed countries have succeeded in reducing zoonotic foodborne diseases over relatively short periods by instituting control mechanisms all along the food value chain, with an emphasis on reducing disease in the animal host.

Similarly, many campaigns have managed to reduce endemic zoonoses such as pig tapeworm and rabies. For example, preventable epilepsy in humans caused by the parasitic pig tapeworm, which is ingested by people consuming pork in Madagascar, is being effectively controlled by combining a roll-out of anti-worm medication and educational campaigns. It is important to emphasize that such successes in disease control need to be sustained: If the control measures are not maintained, the diseases will recur after an initial suppression. For this reason, several high-priority zoonoses have been targeted for "progressive control towards elimination" (where possible), including HPAI, pig tapeworm and rabies. Much progress has been made in reducing or even eliminating zoonoses from richer countries; considerable achievements have been made in less wealthy countries as well. In Bangladesh, for example, a canine rabies elimination programme has focused on dog bite management and mass dog vaccination since 2011; as a result, human rabies deaths in the country have been cut in half.

The track record in managing emerging zoonoses is much more mixed. The rapid containment of SARS is considered to be one of the biggest success stories in public health in recent years. In 2003, the WHO alerted the world that a severe acute respiratory syndrome (SARS) of unknown cause was rapidly spreading from southern China. Within six months, this entirely new disease had been identified as a coronavirus, with its transmission and risk factors elucidated, treatments developed and the disease spread stopped.

The more recent Ebola epidemic in West Africa, however, shows how difficult it can be to control a zoonotic outbreak. The 2013–2016 Ebola outbreak at the intersection of Guinea, Liberia and Sierra Leone affected some of the world's poorest and least developed countries. The outbreak grew larger than all previous outbreaks combined, with the virus reportedly infecting 28,646 people and killing 11,323 of them. It took more than three months just to confirm that Ebola was the cause of many severe illnesses and untimely deaths in the region, and by then large numbers of people were already infected. War, population growth, poverty, suboptimal communications and community engagement, and poor health infrastructure all likely contributed to the unprecedented spread, duration and size of the epidemic.[136] Even when individual epidemics are successfully declared over, the threat of recurring spillover events will remain as long as a strategy to address disease risks at their source is lacking: Since Ebola viruses were first detected in 1976, there have been approximately 30 known outbreaks.

With rapidly advancing information and communication technologies, a surge in novel surveillance and reporting tools is drawing on a wide range of field reports. These tools include the Program for Monitoring Emerging Diseases (ProMed), GeoChat, the Global Early Warning System for Major Animal Disease Including Zoonoses (GLEWS), the Global Outbreak Alert and Response Network (GOARN), the World Animal Health Information Database (OIE/WAHIS) and Interface (currently being updated), the Emergency Prevention System for Animal Health (EMPRES-AH), and HealthMap. Although wildlife diseases are included in several of these systems, wildlife disease monitoring and reporting remains highly limited at global and national scales. There is a need for information systems for wildlife disease and pathogen surveillance information, paired with effective connections to public health and domestic animal health systems to ensure effective coordination and timely use of information.

Advances in biotechnology and molecular epidemiology have made it much easier to develop diagnostics that can identify and track the transmission of zoonoses as well as support the development of vaccines and therapeutics.[137] Another noteworthy trend is the democratization of disease control. Increasing participation in zoonotic disease control from an increasingly wide range of people—including "community animal health workers" and "citizen scientists"—has introduced new perspectives and agendas to the disease control community, such as ensuring animal welfare and assessing the impacts of both disease and disease control programmes on women and poor farmers.

For example, gender plays a significant role in shaping both infectious disease outbreaks and our responses to control them. Biological, economic, cultural and political factors influence how men and women are affected by, and are made vulnerable to, diseases and related health risks.[138] Women in particular tend to be more vulnerable than men to disease outbreaks, including zoonoses (though COVID-19 may be an exception). In Liberia, for instance, the government reported that 75 per cent of epidemic victims were women, as they are more often than not at the forefront of human-animal interactions.[139]

One Health approach—What can we learn from past zoonotic disease outbreaks?

Chickens sold at the Ganeshguru livestock market, Guwahati, India
Photo credit: ILRI/Stevie Mann

Given that COVID-19 is only one of a series of emerging zoonoses, the experiences of the past can inform strategies for the future. Overall efforts to strengthen systems for prevention, detection and response to emerging infectious diseases in Asia have had mixed results. Significant investment has been made by development partners and developing countries following the epidemic of highly pathogenic avian influenza virus of type A and subtype H5N1 (HPAI [H5N1]) in 2004. Surveillance and diagnostic capacity have been built but HPAI remains endemic in key countries across much of Southeast Asia and in Egypt. Efforts to strengthen capacity in Africa to detect and manage pandemic threats have only just started and services lag behind Asia. The One Health approach has been advocated by many, but its uptake and institutional support is uneven. More investment and support is required before such approaches can be implemented routinely. In addition, a standardized set of metrics to measure the effectiveness of One Health interventions may also help to increase uptake of the approach.[140]

Recognizing the instrumental role women could play in controlling disease outbreaks, there has been a series of "Women and One Health Workshops" highlighting the pressing need for a more inclusive and gender-sensitive approach to One Health policies, particularly in a developing-country context.[139] These workshops aim to build a foundation for effective policies addressing gender inequalities that so often underlie zoonotic-disease-related risk factors.

While few would argue against setting up programmes to respond to zoonotic outbreaks, there are concerns that, first, our responses may end up costing more than the diseases themselves, and, second, that these costs may be borne disproportionately by the world's poorest people.

During the bird flu pandemic, which started in 1997, there were several attempts to "restructure" the poultry industry, which in effect meant discouraging poor "backyard" poultry farmers, many of whom were women with few other ways to generate an income.[141] And a recent study in Egypt found that large-scale culling of poultry in response to an outbreak of bird flu (HPAI) was associated with an increase in childhood malnutrition.[142] Likewise, bans on wildlife trade, while sometimes successful, have in other cases led to unintended consequences, such as when a ban on polar bear products impoverished livelihoods in indigenous Arctic communities and reduced the communities' tolerance for polar bears near their communities and participation in shared management initiatives.[143] Response measures inappropriately targeting wildlife—such as poisoning or depopulation efforts—may threaten biodiversity and ecosystem services. These lessons reinforce the notion that interventions must weigh possible benefits with potential trade-offs; such an approach can help to optimize resource use and ensure equitable solutions.

Lessons from managing previous coronavirus outbreaks

Because we are in the midst of an ongoing pandemic, it will require some time before clear conclusions can be drawn on the best ways to manage COVID-19. Already, we can see the need for rapid learning, uptake of good practices such as real-time surveillance data, and global solidarity around resources. However, lessons learned from previous coronavirus epidemics and pandemics in animals and people suggest the following.

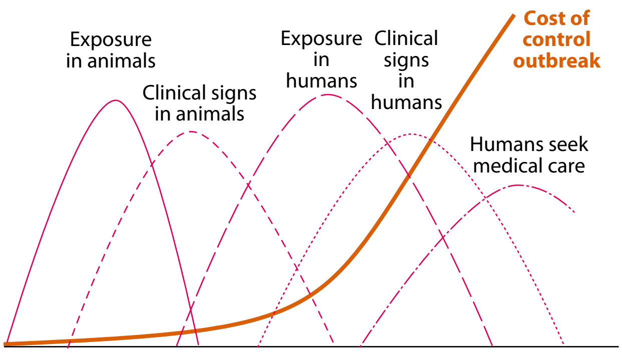
Like all viruses, over time, coronaviruses mutate into new strains possessing different degrees of pathogenicity (the ability to invade and cause disease within the host), virulence (severity of the disease in infected hosts) and infectiousness (capability of being transmitted). Coronaviruses have a slower mutation rate than some other RNA viruses, which means that once an effective vaccine is produced, it will likely provide protection against the virus for much longer than, say, that provided by today's annual influenza vaccines.

It has been difficult, however, to develop effective vaccines against livestock coronavirus-caused diseases of high economic cost. Because outbreaks of novel coronavirus diseases occur fairly regularly—as noted, six recent global coronavirus outbreaks have all spread widely, affecting several continents—coronaviruses should have higher priority among the viruses that need study and surveillance.

Previous coronavirus outbreaks have entailed enormous financial costs and social disruption. The human health burden of zoonotic coronaviruses has been relatively low, but with the potential to be much higher. Risk assessment, mitigation and communication must be improved. And in many countries, most of the direct and indirect burden of disease control has fallen on the poorest, indicating a pressing need to provide people with better social protection and increased resilience to disease.

Compared with the SARS epidemic, both the scientific and public health responses to COVID-19 have been communicated differently, but incentives for countries to declare outbreaks early remain weak, especially in developing and emerging economies. That needs to change in order to facilitate both global readiness and effective international collaboration.

The economic impacts of COVID-19 by June 2020 appear to be many times worse than those of previous known coronavirus outbreaks. The economic losses linked to an outbreak include both direct and indirect losses. When pandemics have a relatively low population mortality rate (perhaps much less than 10 per cent as appears to be the case of COVID-19), the indirect costs of the pandemic tend to be much higher than the direct costs. These indirect costs include loss of jobs, disrupted food supply chains, border closings, restricted mobility, restricted tourism, reduced education opportunities, business closures/ bankruptcies, a rise in fatalities because health services are overwhelmed or people avoid them, and many other complex downstream effects. Many ongoing and proposed actions are addressing these costs but they are not within the remit of this paper.

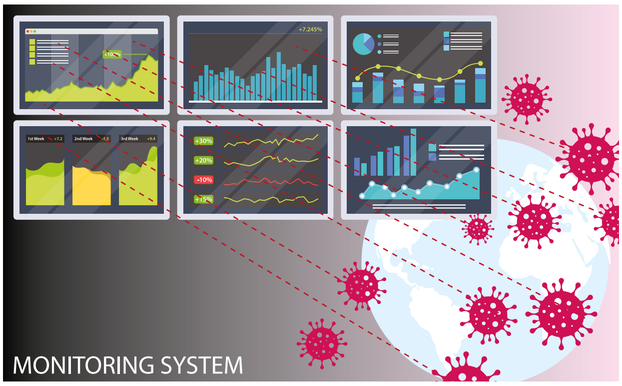


Effective control of zoonotic diseases requires early detection and accurate diagnosis at the animal source. Disease surveillance in animals is critical for preventing the spread of disease between animal populations, and minimizing the risk of transmission to human populations. The cost of disease control increases exponentially once the disease spreads among humans.[10]

Source: World Bank (2012)

Video: WAHIS: Protecting animals, preserving our future

Video Link: https://www.youtube.com/watch?v=M5PuNtcBh14 | *© OIEVideo*



Control of coronavirus and other zoonotic infections in farmed domestic animals, farmed and captured wildlife and companion animals is difficult in all countries and perhaps impossible in many developing countries. The best veterinary practice requires combined applications of vaccines, biosecurity protocols, movement controls and husbandry management, all of which are very difficult to implement in poorer countries. Because vaccines used for porcine epidemic diarrhoea are not always effective, strict biosecurity is the most effective measure to prevent the introduction and spread of the virus. This has almost never been successfully applied to smallholder farms supplying mass domestic markets. Vaccines are also unsatisfactory in preventing infectious bronchitis in chickens and feline infectious peritonitis. Infectious bronchitis and porcine epidemic diarrhoea have been better controlled in Europe than in China but remain global pandemics. Coronaviruses that are well-adapted to their hosts are difficult to eradicate.

While SARS appears to be eliminated, MERS continues to cause human deaths, because the virus still circulates in the intermediate host (dromedary camels). Vaccines were initiated for SARS but did not progress beyond phase-one human trials. Vaccines are currently under development for MERS but not yet approved. A race is now on among the large private pharmaceutical companies, academic units and small biotech companies to develop a vaccine for COVID-19. More than one hundred companies are involved in this work, but there remain real challenges, not only to developing an effective vaccine for this novel coronavirus, but also for quickly mass-producing it in sufficient quantities, and ensuring that it is available to all regardless of income, to protect every one of the 7.8 billion people living today on planet Earth.

V

Section Five

Preventing future zoonotic pandemics: What more could be done?

This final section looks at additional policy and practice responses that can help prevent the inevitable next emerging zoonosis to appear on the horizon. Again, it focuses on the One Health approach as the preferred framework for zoonoses risk reduction and control and discusses how this could add value to attempts to mitigate the seven anthropogenic drivers of zoonoses emergence identified in Section One. It makes ten concrete, One-Health-based recommendations that could address the underlying causes, while also supporting a more effective, coordinated response to future pandemics.

One Health aspects of zoonoses control and prevention

Controlling and preventing zoonotic outbreaks requires coordinated interdisciplinary responses across human, animal and environment health. Our responses to both controlling the ongoing COVID-19 pandemic and to reducing the risk of future zoonotic disease outbreaks must address a range of areas.

In the immediate crisis, a public health response must be mounted, financed and managed. Maintaining the global food system is a top priority, as is providing additional social protection for poor, vulnerable and marginalized populations. A clear exit strategy from pandemic responses is needed, as are sustainable ways of re-building damaged economies while not sacrificing long-term social and environmental achievements. There are many reports, guidelines and suggestions addressing these issues. This report, and this section in particular, takes a broader view and recommends ways to prevent and mitigate the risks posed by zoonotic diseases, with a particular focus on animal and environment health aspects. It will be critical to incorporate these aspects in short-term recovery packages, as well as in longer-term policy and development planning.

As noted, zoonoses are complex; responsibility for their prevention and control falls across several sectors—environment, agriculture, health, trade and commerce. Approaches to dealing with these diseases to date have been inadequately coordinated across these multiple dimensions.[144] Institutionally speaking, zoonoses can find themselves outside conventional health fields (falling between different siloed sectors of human and veterinary health) and, in the worst cases, ignored. One Health thinking and research offers an approach to break down traditional sectoral barriers to achieve effective control of zoonoses. A promising development in the wake of the bird flu pandemic is the establishment of joint zoonoses working groups in many countries and other international collaborations.[145]

Successful control of zoonoses requires strong policy frameworks and judicious legal mechanisms to accompany policy frameworks. It also demands well-functioning institutions that have adequate capacity, adequate financing and a clear plan for implementing interventions.

In the case of emerging diseases, up-front investments in surveillance and in coordinated human, animal and environment health services are needed to ensure that 'emergence events' do not turn into full-scale epidemics, or pandemics. In economic terms, the World Bank estimated eight years ago that an annual investment of USD3.4 billion in animal health systems worldwide would avert losses incurred through delayed or inadequate responses to zoonoses—losses estimated at almost double the preventative investment.[10] The loss of human life, and economic and social costs of the COVID-19 crisis clearly indicate the value—and the necessity—of increased investment in surveillance, prevention measures and coordinated cross-sectoral early response to ensure we do everything possible to prevent this from happening again.

Video: What is One Health?

Video Link: https://www.youtube.com/watch?v=kfluP-tFC2k |
© *Simpleshow foundation*

Improved interdisciplinary science will help to inform the prevention and control of zoonotic diseases. It is important not to study pathogens in isolation, but rather to better understand how human social behaviour impacts the natural world, as well as the emergence and spread of disease.[146] These relations are non-linear and involve complex systemic relationships that must be factored into both research and effective decision-making.

Success will require addressing the root causes and drivers of disease emergence, which in turn will require changing our behaviour and our actions in relation to ecosystems. While some of the basic ecological factors of disease emergence are known, these factors need to be integrated fully into country-level surveillance and response programmes with relevant expertise included in inter-sectoral teams.

Many zoonotic diseases can occur along with other infectious diseases within a given environment or host.[147] This can complicate disease management if each pathogen requires a different measure to control it. It is also critical to understand these interactions and identify opportunities to control multiple pathogens or vectors with a single intervention.

Addressing the anthropogenic drivers of zoonoses emergence

A major constraint to moving towards a pandemic-free world is that most efforts to control infectious diseases are still reactive rather than proactive. During any disease crisis, much effort is spent in developing immediate responses. However, much less investment is made in building communities' resilience to future outbreaks and, even more importantly, in addressing the underlying structural problems or drivers that are causing the recurrence of animal and human epidemics and pandemics.

Our present crisis in 2020 provides us with an opportunity to "build back better." Collectively, we need to shift from short-term political responses to long-term political commitments to secure human, animal and environment health. Sustaining all life on Earth depends on it.

The following table returns to the anthropogenic drivers identified in Sections One and Three and gives examples of possible actions, both general and One Health-oriented, that could address these in a successful way.

Many of these seven drivers have shared underlying causes. For example, the growing demand for food can cause agricultural systems to intensify, and pay insufficient attention to important consequences related to environmental and human health,[148] changes to food value chains, and increased utilization of wildlife.

The COVID-19 crisis has highlighted vulnerabilities in the current global food system. These range from strains on local, regional and global supply chains due to "lockdowns," to very specific problems, such as

Commuters wearing masks during the COVID-19 pandemic in Bangkok, Thailand

Photo credit: The Escape of Malee / Shutterstock.com disruption in crop production that have occurred due to interruptions in the transport of commercial beehives to supply critical pollination services.[149] Many local food markets have been forced to close because of perceived high risks of COVID-19 due to the density of people and animal products and low abilities to enforce hygiene and social distancing measures. These market closures have increased food insecurity, according to the International Panel of Experts on Sustainable Food Systems (April 2020).

Increased support is necessary to build resilient agroecological food systems that rely on natural synergies and harness biological diversity for food production while protecting important wildlife habitats. This is needed not only to decrease the risks of potential zoonotic outbreaks but also to build resilience in human communities to withstand the impacts of zoonotic outbreaks. Investments in local supply chains, including strengthening local abilities to meet food safety regulations, are also part of the necessary transformation to sustainable food systems. Lastly, a farm-to-fork approach must be taken with regards to reducing risk from zoonotic diseases along the entire consumptive chain, from production to processing, and transport to consumption of food. Many of these issues are examined in more depth later in this section.

Strengthening the environment dimensions of the One Health approach

All seven anthropogenic drivers of zoonotic disease listed above have a strong environmental dimension. However, environmental science, scientists and practitioners as well as environmental policies have been inadequately incorporated in the One Health approach, while environmental considerations have been insufficiently mainstreamed in its development and implementation. These oversights have significantly limited the success of the One Health approach to date.[3]

Moving forward, we must further invest in understanding the underlying environmental links with infectious zoonotic diseases and the emergence of those diseases. We must work to monitor zoonotic disease in human-dominated environments (where live animals may be sold), in areas where human settlements are encroaching on wildlife habitats, as well as in intact ecosystems that are home to important wildlife species. Such work will help us to establish essential baselines. We also need to investigate how the transformation and degradation of habitats—whether due to urbanization, risk-averse fire policies, inappropriate agriculture or other development, restoration or re-wilding of areas, or other forms of environmental change and degradation—are affecting the emergence of diseases. A deeper understanding of how existing stressors, including pollution and climate change, exacerbate risks and impacts from zoonotic disease is also warranted. In particular, we must further

Video: Controlling zoonotic diseases through One Health approach preserving our future

Video Link: https://youtu.be/RL0izxaUoMk | © ILRI

A farmer and her pigs in Tete province, Mozambique
Photo credit: ILRI/Stevie Mann

strengthen research capacity-building, and further investigate the links between wildlife exploitation, zoonotic disease emergence, and the potential risk of an epidemic or pandemic.

An example of studying the complex relationship between biodiversity and infectious disease outbreaks is provided by the Great Apes Survival Partnership (GRASP) programme. Working with conservation partners and through implementation at the level of local communities, for instance, this programme developed protocols to monitor human and wildlife health in the Republic of Congo. Results from this project led to recommendations for African great ape range states.[150] This technical approach could be replicated in other regions to monitor the outbreak and spread of human and wildlife diseases at different stages of habitat alteration and identify hotspots where interventions aiming to reverse or halt natural and biodiversity losses are required.

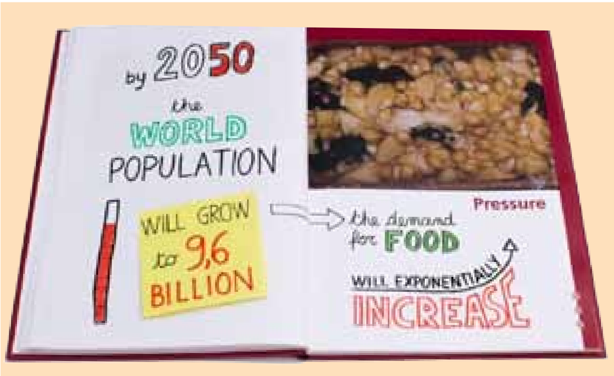
Leveraging innovations and new technologies

Without more fundamental knowledge of pathogen epidemiology and more rapid and inexpensive genome sequencing, every new serious emerging disease will continue to take us by surprise. However, additional investments in new technologies, particularly biotechnologies and information and communication technologies, could stimulate the innovation of "game-changers" in disease surveillance, rapid response and control.

Specific improvements in biosecurity are critical for detecting, preventing and controlling zoonotic disease outbreaks, and for implementing rapid and adequate emergency responses. These include preventive measures designed to reduce risk of infectious disease transmission

Video: FAO: Changing disease landscapes - Towards a Global Health approach

Video Link: https://www.youtube.com/watch?v=vHVSW5HwmZM | © FAO



in crops, livestock, quarantined pests, invasive alien species and living modified organisms. While several studies found that biosecurity advice and policy are often sound, there is limited implementation of biosecurity measures, especially among small-scale livestock keepers, due to a lack of resources and incentives.

Some impediments to implementing biosecurity interventions include a lack of awareness in farmers of the risk and the cost and convenience of protective measures.[151,152] A study in Uganda found that even though implementing biosecurity practices would reduce losses from African swine fever, it would also reduce farmer profit margins by 6 per cent per year.[153] We need new approaches that rely more on incentives, systemic understanding, and equitable sharing of risk.

However, while innovation is key to pandemic solutions, improved biosecurity is also needed in laboratories that research emerging infectious diseases. While there is no evidence that this played any role in the COVID-19 pandemic, there are many documented incidences of laboratory-acquired infections and even accidental escapes of highly pathogenic organisms from laboratories.[154,155]

Responding to public and policy demand for the prevention and control of zoonoses

While further research and innovation are critical, a number of effective strategies to control neglected zoonoses have already been identified. A main barrier to the wide uptake of these strategies is a lack of investment in disease control, particularly in developing countries. The costs of preventing or controlling a zoonotic disease can seem high when compared to the direct public health benefits of such actions.

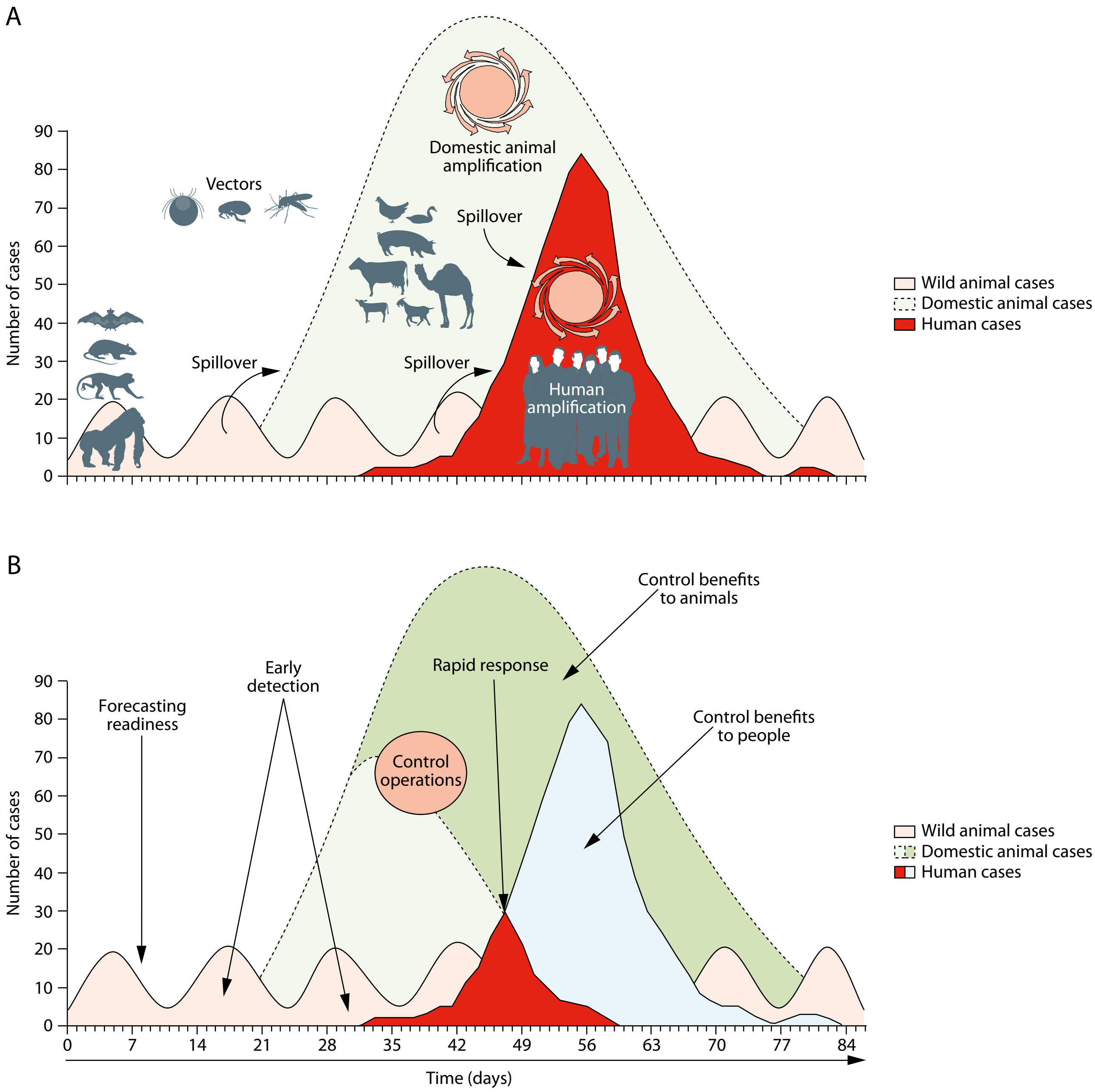
However, the costs of prevention are easily outweighed by the benefits. This becomes evident when a full analysis of the social, economic and ecological consequences of a potential outbreak across multiple sectors is undertaken, including losses of livestock, wildlife, tourism, forestry, trade, employment and other areas.[156] COVID-19 has made this clear.

Effective policy responses to mitigate threats from zoonotic diseases require concerted policy action to stem the multiple drivers of their emergence, which include habitat loss and degradation, overexploitation of wildlife, and land-use changes, among other factors. This will be particularly important in cases where fragmented habitats are thought to play a role in stimulating rapid evolutionary processes and diversification of diseases. These land-use change and habitat-associated policy responses must be considered in the context of potential climate change risks. This is especially important for any policies aiming to mitigate risk from pathogens that spend part of their life cycle outside of their hosts, as is the case for vector-borne diseases, which have proven to be more climate sensitive.[157]

Transforming and re-governing food systems

Preventing future zoonotic disease outbreaks also requires improvements in policy, regulation and monitoring of traditional food markets. Millions of people depend on informal food markets that occur in public spaces where small-scale retailers come together to sell fresh produce, fish and meat from domesticated animals, and in some cases, from wild animals. While many recent zoonotic pandemics originated in wildlife,[158] a similarly large number originated in livestock. To reduce risks of future zoonotic diseases, meat from both wild and domesticated origin—and the places in which the meat is sold—should be subject to similarly strict sanitary standards.

Dissecting infected ticks in ILRI's Tick Laboratory
Photo credit: © ILRI / David White



Clinical relevance of disease ecology
(A) Transmission of infection and amplification in people (bright red) occurs after a pathogen from wild animals (pink) moves into livestock to cause an outbreak (light green) that amplifies the capacity for pathogen transmission to people. (B) Early detection and control efforts reduce disease incidence in people (light blue) and animals (dark green). Spillover arrows shows cross-species transmission.[167]

Source: Reprinted from The Lancet, Vol.380, Karesh et al., Ecology of zoonoses: natural and unnatural histories, Page 1942, Copyright (2012), with permission from Elsevier.

Furthermore, strengthened sanitary regulations must go beyond public food markets and include the entire supply chain for domesticated and wild meat, including both farmed and captured wildlife. Better enforcement of these standards is absolutely essential to reduce risk. WHO has developed guidelines for healthy food markets.[159] Adoption of animal welfare standards for the care, housing and transport of live animals along the entire supply chain is also needed to reduce risk of zoonotic disease transmission.[160] Additional restrictions on which species can be legally sold should also be considered, as is being done in Asia in the wake of the COVID-19 crisis. Additional options for reducing risk, including bans on the highest-risk markets, must also be considered if there is evidence that such measures would be effective in preventing future pandemics.

Any consideration of additional regulations on informal markets, including those involving legally consumed wild meat, must consider social equity and human vulnerability. Some populations may be disproportionately dependent on these sources of protein to meet their food security needs.

Sustainable use of wild resources and Multilateral Environmental Agreements

Sustainable use of biodiversity or wild natural resources —a critical component of the Convention on Biological Diversity (CBD)—includes non-consumptive uses of wildlife, such as sustainable tourism and wildlife viewing, as well as consumptive uses. Consumption, handling and trading of wildlife—including for food, pets, zoos and medical research—can be a factor in the transmission of zoonotic diseases.

The Convention on Migratory Species (CMS) addresses the conservation and management of migratory species that are endangered or whose conservation status is unfavourable, and the taking and use of such species. It established an expert group on wildlife diseases in 2005. Sustainable use is central to the economic and social sustainability of wildlife and its habitats. The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) has established a non-detriment finding mechanism to ensure that international trade in wildlife is biologically sustainable. Additional measures to ensure safety for human health components as part of trade regulations, and improved application of all these measures at national levels, would benefit zoonotic disease control.

Demand management for consumption of wildlife, and associated policies to incentivize such shifts in demand, have been indicated as a possible and appropriate response to reduce zoonotic risk. Demand management interventions are most successful when they are based on a clear understanding of the social, economic and cultural aspects of wild meat consumption along the entire value chain, from producer (or hunter) to consumer.[107] Demand management measures should be put in place as part of a comprehensive package of policies and interventions that address all aspects of human, animal and environment health. The human and animal dimensions of health include disease transmission aspects but also nutrition, welfare and food security components. In cases where human nutrition and livelihoods are dependent on the consumption and/or trade in wild meat or live animals, careful consideration must be given to viable alternatives, particularly for poor or marginalized people. This becomes even more critical when bans of wild meat or live animal marketing are being considered. Expansion of diversified income sources is often an essential component to shift incentives along the wild meat supply chain to grow economic resilience and ensure continued incentives for wildlife conservation. Diversification should be based on a thorough understanding of the dynamics of the system

A villager and her sheep in Fakara, Niger

Photo credit: ILRI / Stevie Mann

Commuters at Shinagawa train station in Tokyo, Japan
Photo credit: StreetVJ / Shutterstock

and clear business planning for alternative means of generating income.[170,171]

The Collaborative Partnership on Sustainable Wildlife Management describes some of the key factors to ensure sustainability of wild meat consumption, including careful monitoring of animal populations, strengthened tenure and management rights for local populations, and provision of technical expertise to support the management of animal populations as well as to implement stringent sanitary measures for the sale, transport and consumption of wild animals and meat. Management measures, such as temporary bans to allow wildlife population recovery as well as removal of non-productive animals, may also be effective.

Interventions at the human-livestock interface

Many zoonoses can be best tackled through interventions involving the livestock hosts of the disease pathogens.[172] Improved and sustained collaboration between medical, veterinary and wildlife authorities is necessary to improve surveillance and control of zoonotic diseases. While these authorities may come together during a crisis to collaborate and share resources, as is the case now where many veterinary laboratories are supporting testing for the current novel coronavirus, these collaborations are not fully institutionalized and often discontinue in non-crises periods. Intensive livestock production systems would benefit from stringent biosecurity and veterinary control measures. Extensive livestock production systems, including pastoralism, can provide proteins efficiently while also providing environmental co-benefits and reduced zoonotic disease risk. The control of coronavirus and other zoonotic infections in farmed domestic animals, captured wild animals and companion animals is difficult in many developing countries. This generally requires combined applications of vaccines, biosecurity protocols, movement controls, slaughter of affected animals and quarantine of premises, and husbandry management, among other measures.

Towards evidence-informed policy

A stronger evidence base and greater capacity-building is needed to understand complex risk profiles and to assess the costs, benefits, acceptability and scalability of such interventions. In addition, many interventions to curb zoonotic disease in animals that were promising in a project context have not been taken up by development programmes or the public sector. For example, a review of different ecosystem and animal interventions to control sleeping sickness in five African countries found they worked well during the project, but that the disease re-emerged after the project ended.[164] Future efforts must ensure that proven preventive measures that mitigate zoonotic disease transmission among livestock are incorporated in policy frameworks. Disease discriminates, with the burden of neglected zoonotic diseases falling heaviest on poor, vulnerable and marginalized people.[165] To be effective, zoonoses control programmes must find ways to reduce the barriers that disadvantaged groups face in managing diseases in the animals they keep, and in accessing disease control services for themselves and their animals.

Key actors in implementing the recommendations of this report include research institutions, national and local governments, intergovernmental organisations, non-governmental organisations and businesses. A clear interdisciplinary research agenda on zoonotic diseases has been described. The aim of this agenda is not only to improve understanding of the human, animal

Seafood at a fish market

Photo credit: Vladimir Krupenkin / Shutterstock.com

and environmental dimensions of health, but also to pursue applied research on the socio-economic policy dimensions of addressing these factors in integrated ways. While many One Health approaches are employed by interdisciplinary teams at national levels, it is important that the approaches are fully employed at local governance levels using the best available science.

Non-governmental organisations provide critical technical assistance and multidisciplinary support in rolling out One Health approaches. Intergovernmental organisations have an important role in the coordination of the response to global pandemic threats, including collating information, providing guidelines and advice, developing response strategies and sharing lessons learned for improved preventive actions. WHO works in close collaboration with FAO and OIE to promote cross-sectoral collaboration to address risks from zoonoses and other public health threats at the human-animal-ecosystem interface, and to provide guidance on how to reduce these risks. UNEP, the science-based global environmental authority of the United Nations, and the Secretariats of the Multilateral Environmental Agreements (MEAs) that it administers, have a clear role to play in expanding the environmental dimensions of this approach, including strengthening environmental laws and their enforcement. Several examples of possible entry points have been identified in voluntary guidance on biodiversity-inclusive One Health approaches.

The World Bank recently issued guidelines for operationalizing One Health in existing and future projects undertaken by the Bank and its client countries and technical partners.[166] These guidelines can serve as a model for other financial institutions to incorporate in planning processes for development and infrastructure projects. Furthermore, the business sector must assess its investments, incentive structures and business practices to understand the material risks of creating zoonotic pathogen spillovers.

For example, reformed risk assessments that incorporate potential hazards from zoonotic spillovers and diminished forest-associated health benefits can be combined with sustainability commitments as part of up-front financing for forest-converting commodities, such as soy or palm oil.

Greater efforts must be made to raise awareness among politicians, particularly with regards to the importance of investing in interdisciplinary surveillance, detection and preventive measures. The current crisis clearly demonstrates the much greater cost of not investing in detection, prevention and early response. However, curbing zoonotic disease outbreaks and their impacts does not stop with national decision-makers, but requires increased awareness-raising of risks and proactive mitigation steps at the level of communities, farmers, and individual consumers of animal and other food products.

Ten key policy recommendations

As of June 2020, most papers and guidelines that discuss policies and actions to tackle the novel SARS-CoV-2 virus and COVID-19 pandemic focus on how to prevent and treat the disease, or how to safeguard livelihoods, secure nutrition and re-build national and regional economies. This paper focuses on recommendations based on the One Health approach. The recommendations set forth here can help governments, businesses and other actors not only to respond to and mitigate future disease outbreaks, but also to reduce the risk of their emergence. To this end, the following ten science-based policy recommendations are proposed:

1. **AWARENESS:** Raise awareness and increase understanding (knowledge) of zoonotic and emerging disease risks and prevention (where appropriate), at all levels of society to build widespread support for risk-reduction strategies.

2. **GOVERNANCE:** Increase investments in interdisciplinary approaches including the One Health perspective; strengthen the integration of environmental considerations in the World Health Organization (WHO)/Food and Agriculture Organization (FAO)/World Organisation for Animal Health (OIE) Tripartite Collaboration.

3. **SCIENCE:** Expand scientific enquiry into the complex social, economic and ecological dimensions of emerging diseases, including zoonoses, to assess risks and develop interventions at the interface of the environment, animal health and human health.

4. **FINANCE:** Improve cost-benefit analyses of emerging diseases prevention interventions to include full-cost accounting of societal impacts of disease (including the cost of unintended consequences of interventions) so as to optimize investments and reduce trade-offs. Ensure ongoing and well-resourced preparedness and response mechanisms.

5. **MONITORING AND REGULATION:** Develop effective means of monitoring and regulating practices associated with zoonotic disease, including food systems from farm to fork (particularly for removing structural drivers of emergence) and improving sanitary measures, taking into account the nutritional, cultural and socio-economic benefits of these food systems.

6. **INCENTIVES:** Include health considerations in incentives for (sustainable) food systems, including wildlife source foods. Augment and incentivize management practices to control unsustainable agricultural practice, wildlife consumption and trade (including illegal activities). Develop alternatives for food security and livelihoods that do not rely on the destruction and unsustainable exploitation of habitats and biodiversity.

7. **BIOSECURITY AND CONTROL:** Identify key drivers of emerging diseases in animal husbandry, both in industrialized agriculture (intensive husbandry systems) and smallholder production. Include proper accounting of biosecurity measures in production-driven animal husbandry/livestock production to the overall cost of One Health. Incentivize proven and under-used animal husbandry management, biosecurity and zoonotic disease control measures for industrial and disadvantaged smallholder farmers and herders (e.g. through the removal of subsidies and perverse incentives of industrialized agriculture), and develop practices that strengthen the health, opportunity and sustainability of diverse smallholder systems.

8. **AGRICULTURE AND WILDLIFE HABITATS:** Support integrated management of landscapes and seascapes that enhance sustainable co-existence of agriculture and wildlife, including through investment in agro-ecological methods of food production that mitigate waste and pollution while reducing risk of zoonotic disease transmission. Reduce further destruction and fragmentation of wildlife habitat by strengthening the implementation of existing commitments on habitat conservation and restoration, the maintenance of ecological connectivity, reduction of habitat loss, and incorporating biodiversity values in governmental and private sector decision-making and planning processes.

9. **CAPACITY BUILDING:** Strengthen existing and build new capacities among health stakeholders in all countries to improve outcomes and to help them understand the human, animal and environment health dimensions of zoonotic and other diseases.

10. **OPERATIONALIZING THE ONE HEALTH APPROACH:** Adequately mainstream and implement the One Health approach in land-use and sustainable development planning, implementation and monitoring, among other fields.

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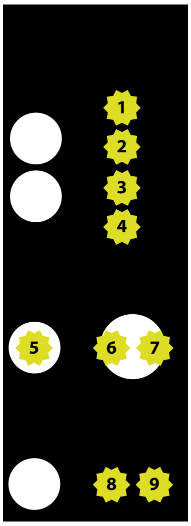

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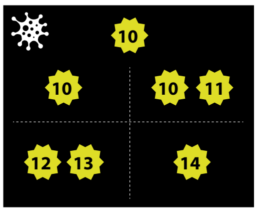

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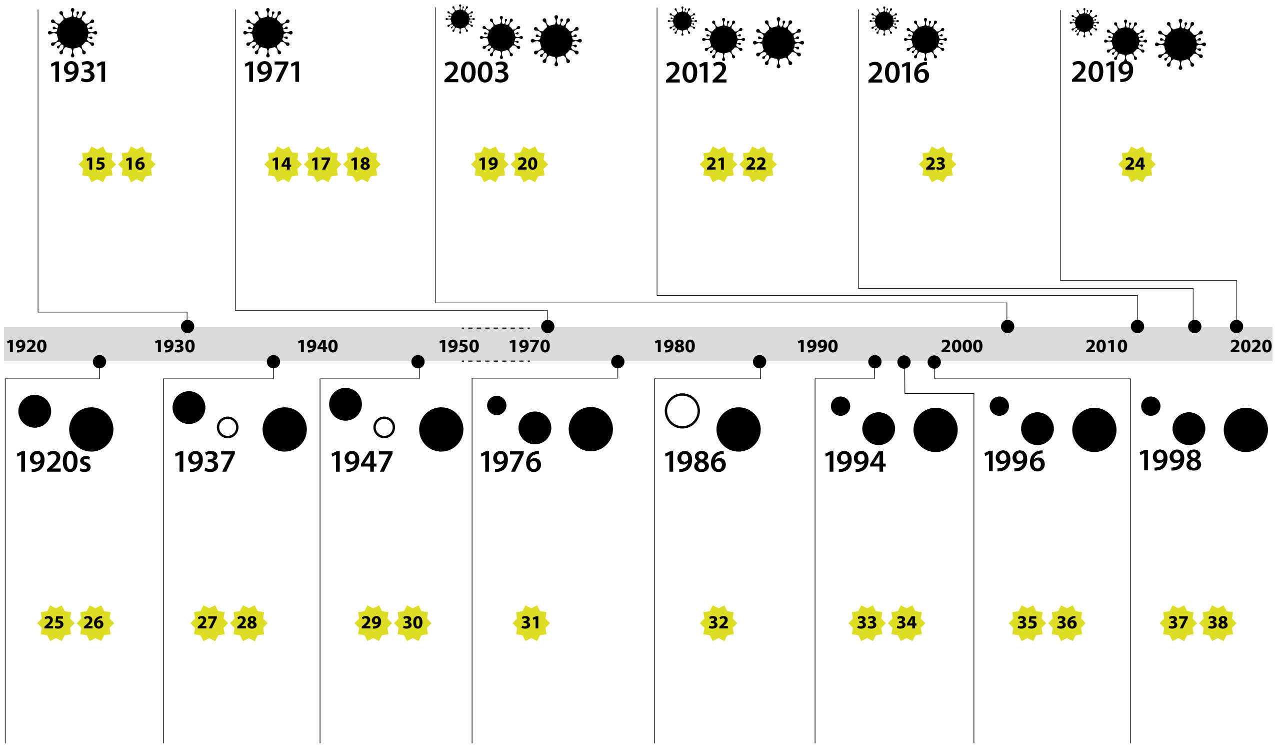

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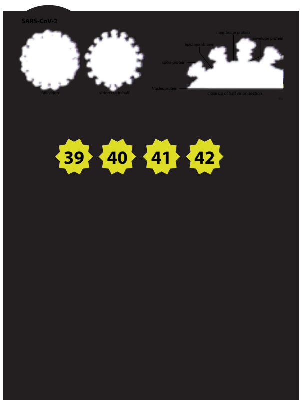

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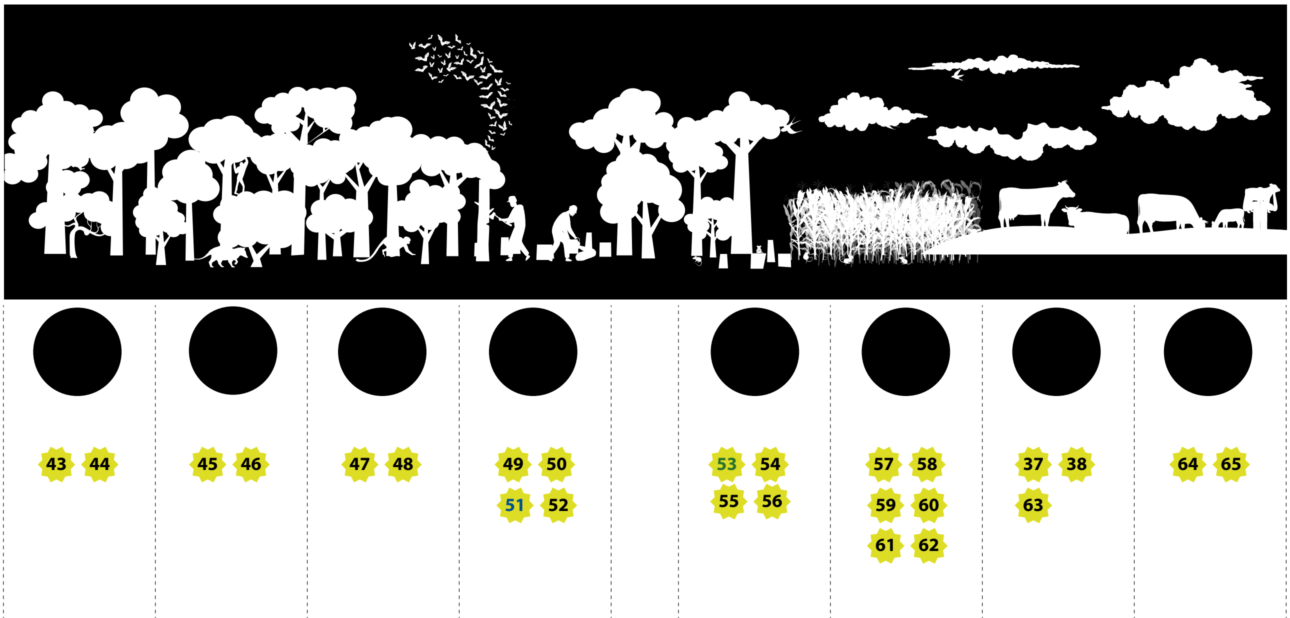

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Glossary

Aerosol transmission: One of two airborne means of infectious disease spreading. In aerosol form, viral particles are suspended in the air by physical and chemical forces for hours or more. In droplet form, in contrast, viral particles remain airborne for a few seconds after someone sneezes or coughs and are able to travel only a short distance before gravitational forces pull them down. STAT News

African trypanosomosis (also spelled 'trypanosomiasis'): A disease of livestock ('African animal trypanosomosis') and humans ('sleeping sickness'). These diseases are caused by single-celled trypanosome parasites (*Trypanosoma brucei gambiense*, *Trypanosoma rhodesiense* and *Trypanosoma brucei brucei*) that are transmitted to their animal and human hosts by the bite of trypanosome-infected tsetse flies (genus *Glossina*), which are found only in Africa. US CDC

Agricultural intensification: An increase in agricultural production per unit of inputs (e.g. labour, land, time, fertilizer, seed, feed, cash). This intensification has been a prerequisite to human civilization. Increased production is critical for expanding food supply; intensification that makes efficient use of inputs is critical for maintaining the health of agricultural environments. FAO

Anthrax: An ancient zoonotic disease that continues to cause serious illness in livestock, where it is a particular threat to cattle and small ruminants like sheep and goats. It can affect all warm-blooded animals, including humans. Treatment is possible with early diagnosis but often there are no symptoms and infected animals die swiftly. Humans generally acquire the disease directly or indirectly from infected animals or occupational exposure to infected or contaminated animal products. Although many countries have confirmed cases, this is not, in the main, a disease of wealthy countries. Incidences of both animal and human anthrax are frequently associated with conflict. FAO

Anthropogenic: Caused by humans or their activities. Cambridge Dictionary

Arthropod: An invertebrate animal having an exoskeleton, a segmented body and paired jointed appendages. Arthropods include insects, arachnids (such as ticks and spiders), myriapods and crustaceans. Biologydictionary.net

Asymptomatic carriers, also known as 'passive' or 'healthy' disease carriers: Individuals that, while infected with a pathogen, neither report nor appear to have any symptoms or signs of illness. US CDC

Avian influenza: A severe, often fatal, type of influenza that affects birds, especially poultry, and that can also be transmitted to humans. Known informally as *avian flu* or *bird flu*, the type with the greatest risk is *highly pathogenic avian influenza* (HPAI). Of three types of influenza viruses (A, B and C), influenza A virus is a zoonotic infection with a natural reservoir almost entirely in birds. Avian influenza, for most purposes, refers to the influenza A virus. Though influenza A is adapted to birds, it can also stably adapt and sustain person-to-person transmission. WHO

Behavioural nudging: In behavioural sciences, it is proposed that positive reinforcement and indirect suggestions can influence the behaviour and decision-making of groups or individuals. Nudging contrasts with other ways to achieve compliance, such as education, legislation or enforcement. UK ESRC and Wikipedia

Biodiversity: The variability among living organisms from all sources, including terrestrial, marine and other aquatic ecosystems, as well as the ecological complexes of which they are part. Biodiversity includes diversity within species, between species and of ecosystems. CBD

Biosecurity: A series of measures aimed at preventing the introduction and/or spread of harmful organisms in order to manage the risk to people, animals, plants and the environment. Biosecurity covers issues such as the introduction of plant pests, animal pests and diseases, and zoonoses, the introduction and release of genetically modified organisms and their products, and the introduction and management of invasive alien species and genotypes. The COVID-19 pandemic is a recent example of a threat that requires biosecurity policies and regulatory measures in all relevant sectors. FAO

Biotechnology: Any technique that encompasses a mix of scientific and practical disciplines and employs living organisms, or parts of such organisms, to make or modify products, to improve plants or animals or to develop microorganisms for specific uses. Biotechnological methods range from the traditional (beer- and bread-making) to the most advanced (genetically modified plants and animals, cell therapies and nanotechnology). World Bank

Bovine spongiform encephalopathy (BSE): Commonly known as 'mad cow disease', BSE is a progressive, fatal disease of the nervous system of cattle caused by the accumulation of an abnormal protein called 'prion' in nervous tissue. First detected in 1986, the implementation of appropriate control measures resulted in the decline of classical BSE cases worldwide. BSE is considered zoonotic due to its assumed link with the emergence of variant Creutzfeldt-Jakob disease in humans. OIE

Bovine tuberculosis: Zoonotic tuberculosis is a form of tuberculosis in people caused by Mycobacterium bovis, which belongs to the M. tuberculosis complex. It often affects sites other than the lungs, but in many cases is clinically indistinguishable from TB caused by M. tuberculosis. Within animal populations, M. bovis is the causative agent of bovine TB. It mainly affects cattle, which are the most important animal reservoir, and can become established in wildlife. The disease results in important economic losses and trade barriers with a major impact on the livelihoods of poor and marginalized communities. WHO-OIE-FAO

Brucellosis: A bacterial infection that spreads from animals to people. Most commonly, people are infected by eating raw or unpasteurized dairy products. Sometimes, the bacteria that cause brucellosis can spread through the air or through direct contact with infected animals. The infection can usually be treated with antibiotics but treatment takes several weeks to months, and the infection can recur. Brucellosis affects hundreds of thousands of people and animals worldwide. Mayo Clinic

***Campylobacter* bacteria**: One of four key global causes of diarrhoeal diseases and considered the most common bacterial cause of human gastroenteritis in the world. Campylobacter are mainly spiral-shaped, 'S'-shaped or curved, rod-shaped bacteria. Campylobacter infections are generally mild but can be fatal among very young children and elderly and immunosuppressed individuals. In developing countries, Campylobacter infections in children under the age of 2 years are especially frequent, sometimes resulting in death. Campylobacter species can be killed by heat and thoroughly cooking food. WHO

Chagas disease, also known as American trypanosomiasis: A potentially life-threatening neglected tropical disease caused by the protozoan parasite Trypanosoma cruzi. Found mainly in Latin American countries, where it is mostly vector-borne, often by a 'kissing bug', an estimated 8 million people are infected worldwide, mostly in Latin America. Chagas disease is clinically curable if treatment is initiated at an early stage. The disease has spread to other continents over the last century mainly because of greater travel. It is estimated that over 10,000 people die every year from clinical manifestations of Chagas disease and more than 25 million people risk acquiring the disease. WHO

Co-morbidities: More than one disease/condition present in an individual at the same time. Other names to describe co-morbid conditions are 'co-existing' or 'co-occurring' conditions and 'multimorbidity' or 'multiple chronic conditions'. US CDC

Coronavirus disease 2019: Illness caused by a novel coronavirus, 'severe acute respiratory syndrome coronavirus 2' (SARS-CoV-2), which was first identified amid an outbreak of respiratory illness cases in East Asia. The outbreak was first reported to WHO on 31 December 2019. On 30 January 2020, WHO declared the COVID-19 outbreak a global health emergency and the following March a global pandemic, WHO's first such designation since declaring H1N1 influenza a pandemic in 2009. Medscape

Coronavirus OC43: Human coronaviruses (named for the crown-like spikes on their surface) were first identified in the mid-1960s. Seven coronaviruses can infect people. Four of these are common human coronaviruses, 229E, NL63, OC43 and HKU1, which usually cause mild to moderate upper-respiratory tract illnesses like the common cold. But three of the seven coronaviruses—MERS-Cov, SARS-CoV and SARS-CoV-2—are novel and lethal coronaviruses that originated in animals and evolved in ways that, in humans, can cause serious illness and death. US CDC

Crimean Congo haemorrhagic fever (CCHF): A viral haemorrhagic fever usually transmitted by ticks. It can also be contracted through contact with animal tissue where the virus has entered the bloodstream during and immediately post-slaughter of animals. Outbreaks of the disease can lead to epidemics, have a high case fatality ratio (10–40 per cent) and are difficult to prevent and treat. First described in the Crimea in 1944, the disease is endemic in all of Africa, the Balkans, the Middle East and in Asia. WHO

Cysticercosis: A parasitic tissue infection caused by larval cysts of the tapeworm Taenia solium. These larval cysts infect brain, muscle or other tissue and are a major cause of adult onset seizures in most low-income countries. A person gets cysticercosis by swallowing eggs found in the faeces of a person who has an intestinal tapeworm. People do not get cysticercosis by eating undercooked pork, which can result in intestinal tapeworm if the pork contains larval cysts. Pigs become infected by eating tapeworm eggs in the faeces of a human infected with a tapeworm. Both the tapeworm infection, also known as taeniasis, and cysticercosis occur globally. The highest rates of infection are found in areas of Latin America, Asia and Africa that have poor sanitation and free-ranging pigs that have access to human feces. US CDC

DNA virus: A virus containing DNA as its genetic material and using a DNA–dependent DNA polymerase during replication. Most of these viruses must enter the host nucleus before they can replicate because they need the host cell's DNA polymerases when replicating their viral genome. Biology Online

Droplet transmission: Respiratory infections can be transmitted through droplets of different sizes when a person is in in close contact with someone who is coughing or sneezing and is therefore at risk of having his/her mouth and nose or eyes exposed to potentially infective respiratory droplets. According to current evidence, COVID-19 virus is primarily transmitted between people through respiratory droplets and contact routes. In an analysis of 75,465 COVID-19 cases in East Asia, airborne transmission was not reported. WHO

Early warning systems: Complex tools and processes aiming to reduce the impact of natural hazards by providing timely and relevant information in a systematic way. UNDP

Eastern equine encephalitis virus (EEE virus) is spread by mosquitoes and is a rare cause of brain infections (encephalitis). It can infect horses, causing fever, behavioural changes, and other symptoms of encephalitis, and infection is often deadly for the horse. Only a few human cases are reported in the United States each year, most in eastern or Gulf Coast states. Approximately 30 per cent of people with eastern equine encephalitis die and many survivors have ongoing neurologic problems. US CDC

Ebola virus disease (EVD): A rare and deadly disease in people and nonhuman primates. The viruses that cause Ebola are located mainly in sub-Saharan Africa. People can get Ebola through direct contact with an infected animal (bat or nonhuman primate) or a sick or dead person infected with Ebolavirus. US CDC

Echinococcosis: A parasitic disease that occurs in two main forms in humans: cystic echinococcosis (also known as hydatidosis or hydatid disease) and alveolar echinococcosis, caused by the tapeworms. Dogs, foxes and other carnivores harbour the adult worms in their intestine and evacuate the parasite eggs in their faeces. If the eggs are ingested by humans, they develop into larvae in several organs, mainly the liver and lungs. Both cystic and alveolar echinococcosis are characterized by asymptomatic incubation periods that can last many years until the parasite larvae evolve and trigger clinical signs. Both diseases can cause serious morbidity and death. Treatment is often difficult. The disease occurs in most areas of the world and currently affects about one million people. Prevention of cystic disease is by treating dogs that may carry the disease and vaccination of sheep. WHO

EcoHealth: An emerging field that examines the complex relationships among humans, animals and the environment, and how these relationships affect the health of each of these domains. One Health deals with biomedical questions, with an emphasis on zoonoses, and is historically more health science-driven. In contrast, the EcoHealth concept is defined as an ecosystem approach to health, tending to focus on environmental and socio-economic issues and initially designed by disease ecologists working in the field of biodiversity conservation. Roger *et al.* 2016; Lisitza and Wolbring 2018

Ecosystem: A dynamic complex of vegetable, animal and microorganism communities and their nonliving environment that interact as a functional unit. Ecosystems may be small and simple, like an isolated pond, or large and complex, like a specific tropical rainforest or a coral reef in tropical seas. IUCN

Ecosystem degradation: A long-term reduction in an ecosystem's structure, functionality, or capacity to provide benefits to people. IPBES

El Niño: The term refers to the large-scale ocean-atmosphere climate interaction linked to a periodic warming in sea surface temperatures across the central and east-central Equatorial Pacific. El Niño and La Niña are opposite phases of what is known as the El Niño-Southern Oscillation (ENSO) cycle. The ENSO cycle is a scientific term that describes the fluctuations in temperature between the ocean and atmosphere in the east-central Equatorial Pacific (approximately between the International Date Line and 120 degrees West). El Niño is sometimes referred to as the warm phase of ENSO, and La Niña as the cold phase of ENSO. These deviations from normal surface temperatures can have large-scale impacts not only on ocean processes, but also on global weather and climate. US NOAA

Emerging infectious disease: Infections that have recently appeared within a population or those whose incidence or geographic range is rapidly increasing or threatens to increase in the near future. Baylor College of Medicine

Endemic disease: The constant presence and/or usual prevalence of a disease or infectious agent in a population within a geographic area. US CDC

Endemic zoonoses are found throughout the developing world, wherever people live in close proximity to their animals, affecting not only the health of poor people but often also their livelihoods through the health of their livestock. Unlike newly emerging zoonoses that attract the attention of the developed world, these endemic zoonoses are by comparison neglected. This is, in part, a consequence of under-reporting, resulting in underestimation of their global burden, which in turn artificially downgrades their importance in the eyes of administrators and funding agencies. Maudlin *et al.* 2009

[The] environment: The natural world, as a whole or in a particular geographical area, especially as affected by human activity. Oxford Dictionary

Environment health vs environmental health: 'Environment health' refers to the health of the environment and is used in this report to distinguish it from the term 'environmental health', which is the branch of public health concerned with all aspects of the natural and built environment affecting human health. (Authors of this report)

Epidemic: The occurrence in a community or region of cases of an illness, specific health-related behaviour, or other health-related events clearly in excess of normal expectancy. The community or region and the period in which the cases occur are specified precisely. WHO

False negative: A test result that wrongly indicates that a particular condition or attribute is absent. Oxford Dictionary

False positive: A test result which wrongly indicates that a particular condition or attribute is present. Oxford Dictionary

FAO, OIE, WHO Tripartite Alliance: A collaboration between the Food and Agriculture Organization (FAO), the World Organisation for Animal Health (OIE) and the World Health Organization (WHO) to address risks from zoonoses and other public health threats existing and emerging at the human-animal-ecosystems interface and provide guidance on how to reduce these risks. These three organisations have worked together for many years to prevent, detect, control and eliminate health threats to humans, originating—directly or indirectly—from animals. Putting the 'One Health' vision into practice has been facilitated by a formal alliance the three organisations established in 2010, acknowledging their respective responsibilities in combating diseases which have a severe impact on health and the economy, particularly zoonoses. FAO; OIE; WHO

Fomite transmission refers to the transmission of infectious diseases by objects. It occurs when an inanimate object contaminated with or exposed to infectious agents (such as pathogenic bacteria, viruses or fungi) serve as a mechanism for transfer to a new host. Verywell Health

Food value chains comprise all the stakeholders who participate in the coordinated production and value-adding activities that are needed to make food products. FAO

Great apes: The great apes have traditionally comprised six species—chimpanzee, bonobo, Sumatran orangutan, Bornean orangutan, eastern gorilla and western lowland gorilla. In 2017 scientists identified a third orangutan species: the Tapanuli orangutan (Pongo tapanuliensis), which is restricted to South Tapanuli, on the island of Sumatra, in Indonesia, and is on the critically endangered species list. Great Apes Survival Partnership; Nater *et al.* 2017

Great ape range states: The 21 countries in Equatorial Africa and in 2 countries in Southeast Asia where the great apes—chimpanzees, bonobos, gorillas and orangutans—dwell, forage, reproduce and migrate. WWF

Guano: The excrement of seabirds and bats, used as fertilizer. Oxford Dictionary

Habitat: The natural home or environment of an animal, plant or other organism. Oxford Dictionary

Habitat fragmentation: A general term describing the set of processes by which habitat loss results in the division of continuous habitats into a greater number of smaller patches of lesser total and isolated from each other by a matrix of dissimilar habitats. Habitat fragmentation may occur through natural processes (e.g., forest and grassland fires, flooding) and through human activities (forestry, agriculture, urbanization). Habitat loss and fragmentation have long been considered the primary cause for biodiversity loss and ecosystem degradation worldwide. Habitat fragmentation often refers to the reduction of continuous tracts of habitat to smaller, spatially distinct remnant patches. Although some habitats are naturally patchy in terms of abiotic and biotic conditions, human actions have profoundly fragmented landscapes across the word, altering the quality and connectivity of habitats. IPBES; Wilson *et al.* 2015

Highly pathogenic avian influenza (HPAI): A highly contagious disease caused by viruses that occur mainly in birds and that can be deadly, especially in domestic poultry. Since 2003, an Asian HPAI H5N1 virus has resulted in high mortality in poultry and wild birds in Asia, the Middle East, Europe and Africa and has become endemic in some countries. US CDC

Host: An organism infected with or fed upon by a parasitic or pathogenic organism (for example, a virus, nematode, fungus). An animal or plant that nourishes and supports a parasite; the host does not benefit and is often harmed by the association. Biology Online

Host plasticity: The ability of a virus to infect a diverse range of hosts, such as bats, rodents, and primates. UC Davis One Health Institute

Human T-cell lymphotropic virus (HTLV): HTLV is a type of retrovirus that infects a type of white blood cell called a T-lymphocyte. HTLV can cause cancer. Simian T-cell leukemia viruses (STLVs) that infect Old World monkeys are the simian counterparts of HTLV, and these viruses are collectively called primate T-cell leukemia viruses (PTLVs). The close relationship between HTLV type 1 and STLV type 1 suggests a simian origin for HTLV type 1 as a result of multiple interspecies transmissions between primates and humans and also between different primate species. Courgnaud *et al*. 2004

Infectivity: In epidemiology, infectivity is the ability of a pathogen to enter, survive and multiply in the host and ultimately establish an infection. A pathogen's infectivity is subtly but importantly different from its transmissibility, which refers to a pathogen's capacity to spread from one organism to another. UCLA Fielding School of Public Health; Wikipedia

Inflammatory bowel disease (IBD): An umbrella term for two disorders that involve chronic inflammation of the digestive tract—Crohn's disease and ulcerative colitis, which are characterized by chronic inflammation of the gastrointestinal tract, which is damaged by prolonged inflammation. US CDC

Japanese encephalitis virus (JEV): A flavivirus related to dengue, yellow fever, and West Nile viruses and spread by mosquitoes. It is found principally in Asia and the Western Pacific and is the main cause of viral encephalitis in many countries of Asia, with an estimated 68,000 clinical cases every year. There is no cure for the disease. WHO

La Niña: La Niña episodes represent periods of below-average sea surface temperatures across the east-central Equatorial Pacific. During a La Niña year, winter temperatures are warmer than normal in the Southeast and cooler than normal in the Northwest Pacific. Global climate La Niña impacts tend to be opposite those of El Niño impacts. See also El Niño. US NOAA

Leishmaniasis: A disease caused by the protozoan Leishmania parasites which are transmitted by the bite of infected sandflies. There are three main forms of leishmaniases—visceral (also known as kala-azar, which is usually fatal if untreated), cutaneous (the most common) and mucocutaneous. The disease affects some of the poorest people on earth and is associated with malnutrition, population displacement, poor housing and a weak immune system. Leishmaniasis is linked to environmental changes such as deforestation, building of dams, irrigation schemes and urbanization. An estimated 700,000 to 1 million new cases occur annually. WHO

Leptospirosis: A bacterial disease affecting humans and animals caused by bacteria of the genus Leptospira. In humans, it can cause a wide range of symptoms such as fever, headache, diarrhoea, muscle ache. Without treatment, Leptospirosis can lead to kidney damage, meningitis (inflammation of the membrane around the brain and spinal cord), liver failure, respiratory distress, and even death. The bacteria that cause leptospirosis are spread through the urine of infected animals, which can get into water or soil and can survive there for weeks to months. Many different kinds of wild and domestic animals carry the bacterium. US CDC

Listeriosis: Foodborne listeriosis, caused by the bacteria Listeria monocytogenes, is one of the most serious and severe foodborne diseases. It is a relatively rare disease but the high rate of death associated with this infection makes it a significant public health concern. Listeria monocytogenes are widely distributed in nature. They can be found in soil, water, vegetation and the faeces of some animals and can contaminate foods. Vegetables may be contaminated through soil or the use of manure as fertilizer. Ready-to-eat food can also become contaminated during processing and the bacteria can multiply to dangerous levels during distribution and storage. Unlike many other common foodborne diseases causing bacteria, L. monocytogenes can survive and multiply at low temperatures usually found in refrigerators. WHO

Lockdown: A state of isolation or restricted access instituted as a security measure. Oxford Dictionary

Middle East respiratory syndrome (MERS): A viral respiratory disease caused by a novel coronavirus (Middle East respiratory syndrome coronavirus, or MERS-CoV) that was first identified in Saudi Arabia in 2012. Typical MERS symptoms include fever, cough and shortness of breath.

Approximately 35 per cent of reported patients with MERS have died. The virus does not seem to pass easily from person to person and most human cases of MERS have been attributed to human-to-human infections in health care settings. The largest outbreaks have occurred in Saudi Arabia, United Arab Emirates and the Republic of Korea. Current scientific evidence suggests that dromedary camels are a major reservoir host for MERS-CoV and an animal source of MERS infection in humans. WHO

Middle East respiratory syndrome coronavirus (MERS-CoV): A coronavirus causing Middle East respiratory syndrome (MERS). WHO

Molecular epidemiology: A discipline that uses molecular or genetic markers to trace the development of a disease in a population and to understand transmission as well as the population structure and evolution of bacterial pathogens. ScienceDirect

Multidisciplinary: Combining or involving several academic disciplines or professional specializations in an approach to a topic or problem. Oxford Dictionary

Natural environment: All living and non-living things that occur naturally on a particular region where human impact is kept under a certain limited level. Biology Online

Neglected zoonotic diseases include anthrax, brucellosis, foodborne trematodiases, human African trypanosomosis, leishmaniasis, leptospirosis, non-malarial febrile illnesses, schistosomiasis, rabies and taeniasis/cysticercosis. These neglected zoonoses are found in communities in low-resource settings across the world, where they impose a dual burden on people's health and that of the livestock they depend upon. Their management requires collaborative, cross-sectoral efforts of human and animal health systems and a multidisciplinary approach that considers the complexities of the ecosystems where humans and animals coexist. Where feasible, preventing and mitigating their occurrence in humans requires their elimination in their animal reservoirs. National governments are increasingly implementing control programmes to address these burdens. These initiatives have been strongly endorsed by the Food and Agriculture Organization of the United Nations, the World Organisation for Animal Health and World Health Organization Tripartite and financially supported the international community, including the Bill & Melinda Gates Foundation, the UK Department for International Development, the European Union, the International Development Research Centre and CGIAR. WHO

Non-random and random sampling: In random data collection, every individual observation has equal probability to be selected into a sample and there should be no pattern when drawing a sample. Although random sampling is generally the preferred survey method, few people doing surveys use it because of prohibitive costs. The method requires numbering each member of the survey population, whereas nonrandom sampling involves taking every nth member. Findings indicate that as long as the attribute being sampled is randomly distributed among the population, the two methods give essentially the same results. If the attribute is not randomly distributed, the two methods give radically different results. In some instances the nonrandom methods yield much better inferences about the population; in other instances, its inferences are much worse. Rand Corporation; Statistics Solutions

One Health: A collaborative, multisectoral, and trans-disciplinary approach—working at local, regional, national and global levels—to achieve optimal health and well-being outcomes recognizing the interconnections between people, animals, plants and their shared environments. One Health Commission

Pandemic: The worldwide spread of a new disease. An influenza pandemic occurs when a new influenza virus emerges and spreads around the world and most people do not have immunity. WHO

Pathogen: Any microorganism able to cause disease in a host organism. British Society for Immunology

Pathogenicity: The absolute ability of an infectious agent to cause disease/damage in a host—an infectious agent is either pathogenic or not. ScienceDirect

Peridomestic: Pertaining to living in and around human habitations. The rat is a peridomestic animal. WordSense Dictionary

Permafrost: A thick subsurface layer of soil that remains frozen throughout the year, occurring chiefly in polar regions. Oxford Dictionary

Phylogenetic analysis: Phylogeny is the relationship between all the organisms on Earth that have descended from a common ancestor, whether they are extinct or extant. Phylogenetics is the science of studying the evolutionary relatedness among biological groups and a phylogenetic tree is used to graphically represent this evolutionary relation related to the species of interest. ScienceDirect

Planetary health is defined as "the achievement of the highest attainable standard of health, wellbeing, and equity worldwide through judicious attention to the human systems—political, economic, and social—that shape the future of humanity and the Earth's natural systems that define the safe environmental limits within which humanity can flourish. Put simply, planetary health is the health of human civilization and the state of the natural systems on which it depends". In 2014 the Rockefeller Foundation and The Lancet jointly formed the Commission on Planetary Health to review the scientific basis for linking human health to the underlying integrity of Earth's natural system. The Rockefeller Foundation–Lancet Commission on Planetary Health

Porcine epidemic diarrhoea (PED): A non-zoonotic viral disease of pigs caused by a coronavirus and characterized by watery diarrhoea and weight loss. First identified and reported in 1971, it affects pigs of all ages, but most severely neonatal piglets, reaching a morbidity and mortality of up to 100 per cent, with mortality decreasing as age increases. It is a contagious disease transmissible mainly by the faecal-oral route. The prevention and management control are focused on strict biosecurity and early detection. There is no specific treatment for the disease. WHO

Pristine areas: Pristine means still in its original condition, such as a forest that hasn't been logged or damaged by humans. YourDictionary

Q fever: A disease caused by bacteria of the species Coxiella burnetii. This bacterium naturally infects some animals, such as goats, sheep and cattle. These bacteria are found in the birth products (i.e. placenta, amniotic fluid), urine, faeces and milk of infected animals. People can get infected by breathing in dust that has been contaminated by infected animal faeces, urine, milk and birth products or by eating contaminated unpasteurized dairy products. Some people never get sick; those who do usually develop flu-like symptoms. In a small percentage of people, the infection can resurface years later. This more deadly form of Q fever can damage the heart, liver, brain and lungs. US CDC

R_0 is the basic reproduction number (also called the 'basic reproduction ratio' or 'rate' or the 'basic reproductive rate'). It refers to the expected number of secondary infections arising from a single individual during his or her entire infectious period, in a population of susceptible individuals. This concept is fundamental to the study of epidemiology and within-host pathogen dynamics. Most importantly, R_0 often serves as a threshold parameter that predicts whether an infection will spread. Heffernan *et al*. 2005

Rabies: A vaccine-preventable, zoonotic, viral disease. Once clinical symptoms appear, rabies is virtually 100 per cent fatal. It can spread to people and pets if they are bitten or scratched by a rabid animal. In up to 99 per cent of cases, domestic dogs are responsible for rabies virus transmission to humans but it can affect both domestic and wild animals. The virus can cause disease in the brain, ultimately resulting in death. Rabies is present on all continents, except Antarctica, with over 95 per cent of human deaths occurring in the Asia and Africa regions. Rabies is one of the 'neglected tropical diseases that predominantly affects poor and vulnerable populations who live in remote rural locations. Although effective human vaccines and immunoglobulins exist for rabies, they are not readily available or accessible to those in need. WHO

Recombinant DNA: The joining together of DNA molecules from different organisms and inserting it into a host organism to produce new genetic combinations that are of value to science, medicine, agriculture and industry. The DNA sequences used in the construction of recombinant DNA molecules can originate from any species. For example, plant DNA may be joined to bacterial DNA, or human DNA may be joined with fungal DNA. In addition, DNA sequences that do not occur anywhere in nature may be created by the chemical synthesis of DNA and incorporated into recombinant molecules. Using recombinant DNA technology and synthetic DNA, any DNA sequence may be created and introduced into any of a very wide range of living organisms. Encyclopedia Britannica; Biology Online; Wikipedia

Reservoir: The habitat in which the agent normally lives, grows, and multiplies. Reservoirs include humans, animals, and the environment. The reservoir may or may not be the source from which an agent is transferred to a host. US CDC

Reservoir host: A primary host that harbours a pathogen but shows no ill effects and serves as a source of infection. Once discovered, natural reservoirs elucidate the complete life cycle of infectious diseases, providing effective prevention and control. Biology Online

Rift Valley fever (RVF): A mosquito-borne viral zoonotic disease that affects sheep, goats, cattle and camels, causing devastating losses, especially among pastoral communities that rely on livestock for their livelihoods. The disease occurs in explosive outbreaks following periods of above-normal and persistent rainfall. People can become infected with Rift Valley fever after being bitten by an infected mosquito or through close contact with acutely infected animals or their tissues. In people, the disease manifests itself as a mild influenza-like syndrome in over 80 per cent of cases or a severe disease with haemorrhagic fever, encephalitis or retinitis in a few cases. Because of its episodic occurrence and predilection for remote pastoral areas, the impact of the disease is often exacerbated by delays in the deployment of prevention and control measures. Livestock vaccination is regarded as the most reliable method for controlling the disease. ILRI

RNA viruses are those containing RNA as its genetic material. The RNA may be single stranded or double stranded. Examples of RNA viruses include Reoviruses, Picornaviruses, Togaviruses, Orthomyxoviruses, Rhabdoviruses, etc. A virus containing RNA as its genetic material. The RNA may be single stranded or double stranded. Examples of RNA viruses include Reoviruses, Picornaviruses, Togaviruses, Orthomyxoviruses and Rhabdoviruses. Most RNA viruses replicate in the cytoplasm of the host cells. Examples of human diseases caused by RNA viruses are SARS, influenza and hepatitis C. Biology Online

***Salmonella* bacteria** cause foodborne illness, commonly called food poisoning, with symptoms of diarrhoea, fever and stomach cramps. It is estimated that Salmonella causes one million foodborne illnesses every year in the United States. In the past few years, outbreaks of Salmonella illness have been linked to contaminated cucumbers, pre-cut melon, chicken, eggs, pistachios, raw tuna, sprouts, and many other foods. US CDC

Severe acute respiratory syndrome (SARS): A viral respiratory illness caused by a coronavirus, SARS-associated coronavirus (SARS-CoV). First reported in Asia in 2003, the illness spread to more than two dozen countries in North America, South America, Europe and Asia before the SARS global outbreak of 2003 was contained. Since 2004, no known cases of SARS have reported anywhere in the world. US CDC

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2): A novel coronavirus causing the 2019–2020 coronavirus 2019 (COVID-19) pandemic. On 11 February 2020, WHO named the new virus SARS-CoV-2 because the virus is genetically related to the coronavirus responsible for the SARS outbreak of 2003. While related, the two viruses are different. WHO announced 'COVID-19' as the name of this new disease on the same day, following guidelines previously developed with the World Organisation for Animal Health (OIE) and the Food and Agriculture Organization of the United Nations (FAO). WHO

Social distancing, also called 'physical distancing', means keeping six feet (two meters) of space between yourself and other people outside of your home, not gathering in groups, staying out of crowded places and avoiding mass gatherings. US CDC

Simian: Relating to, resembling, or affecting apes or monkeys. Oxford Dictionary

Sooty mangabey: Also known as the white-crowned or white-collared mangabey (*Cercocebus atys*), the sooty mangabey is a mostly terrestrial Old World monkey. Its distribution once ranged from the Casamance River in Senegal to the Sassandra/Nzo River system. Today, the species' conservation status is 'near-threatened', with its range now restricted to the west coast of Africa in Sierra Leone, Liberia and the western part of Ivory Coast, where these foraging monkeys can be found walking along the forest floor gathering fruits and seeds. Sooty mangabeys are considered to be mostly extinct in their former habitats in Senegal, Guinea-Bissau and parts of Guinea. New England Primate Conservancy

Sustainable agricultural intensification: A concept that challenges global agriculture (crops, livestock, forests, fisheries) to achieve a doubling in world food production while sustaining the environment in which we live. Food production efficiency needs to double in order to feed a growing global population using only currently available land while protecting our living environment and conserving natural and agricultural biodiversity. Sustainable agricultural intensification provides the means to do this with limited available resources. This ambition is highlighted in the Sustainable Development Goals. The resources to achieve this increase in food production will not increase, so the efficiency with which they are used will have to be enhanced to ensure ecosystems services are maintained. Sustainability also requires ensuring social equity in the productive and environmental benefits from sustainable agricultural intensification, otherwise the poorer sections of the farming population and women farmers risk being left behind or displaced by the promotion of intensification. NRI

Vector: An organism or vehicle that transmits the causative agent or disease-causing organism from the reservoir to the host. Often thought of as a biting insect or tick but can be an animal or inanimate object. Many living vectors are bloodsucking insects and ticks, which ingest disease-producing microorganisms during a blood meal from an infected host (human or animal) and later transmit it into a new host, after the pathogen has replicated. Often, once a vector becomes infectious, they are capable of transmitting the pathogen for the rest of their life during each subsequent bite/blood meal. Biology Online; WHO

Vector-borne diseases: Human illnesses caused by parasites, viruses and bacteria that are transmitted by vectors. Vector-borne diseases account for more than 17 per cent of all infectious diseases, causing more than 700,000 deaths annually. WHO

Vermin: Wild animals that are believed to be harmful to crops, farm animals, or game, or that carry disease, e.g., rodents. Oxford Dictionary

Virion: An entire virus particle, consisting of an outer protein shell, called a capsid, and an inner core of nucleic acid, either RNA or DNA. The core confers infectivity and the capsid provides specificity to the virus. Encyclopaedia Britannica

Virulence: the degree by which a pathogenic organism can cause disease in a host. Virulence is the measurement of pathogenicity—the ability of a pathogen to cause disease. Highly virulent pathogens are more likely to cause disease in a host. The virulence of a pathogen is often correlated with the so-called virulence factors that enables an organism to invade a host and cause disease. Biology Online; LibreTexts

Virus: An infectious agent of small size and simple composition that can multiply only in living cells of animals, plants or bacteria. The name is from a Latin word meaning "slimy liquid" or "poison." Encyclopaedia Britannica

West Nile virus (WNV): A member of the Flavivirus genus that belongs to the Japanese encephalitis antigenic complex of the family Flaviviridae. Commonly found in Africa, Europe, the Middle East, North America and West Asia, the virus is maintained in nature in a cycle involving transmission between birds and mosquitoes. Horses and other mammals can be infected along with humans, in whom it causes neurological disease and death. WHO

Wet market, also called public, informal and traditional market. The term 'wet market' is considered a pejorative by some, so this report uses the term 'informal market'. All these terms refer to a marketplace selling fresh meat, fish, produce and other perishable goods as distinguished from 'dry markets' that sell durable goods such as fabric and electronics. Not all wet markets sell live animals, but the term is sometimes used to signify a live animal market in which vendors slaughter animals upon customer purchase. Wet markets are common in many parts of the world and include a wide variety of markets, such as farmers' markets, fish markets and wildlife markets. They often play critical roles in urban food security due to factors of pricing, freshness of food, social interaction, and local cultures. Most wet markets do not trade in wild or exotic animals, but have been linked to outbreaks of zoonotic disease. One such market was believed to have played a role in the COVID-19 pandemic, although investigations into whether the virus originated from non-market sources are ongoing as of April 2020. BBC; Wikipedia

Wild meat, more commonly called 'bushmeat' (in this report, we prefer to use the term 'wild meat'). Wildlife makes an essential contribution to food security for many people worldwide. Estimated bushmeat consumption in the Congo Basin alone is over 4 million tonnes per year. For many, wild meat may be the main type of meat available, an important component of food diversity or a food that contributes to cultural identity. Wild meat is a natural healthy food, although (as with domestic stock) its use may carry health risks related to zoonoses—diseases transmitted to humans through the handling or consumption of animals. Declines in wildlife due to over-hunting or other causes, whether direct (e.g. habitat degradation) or indirect (e.g. weak governance or climate change) could significantly affect many people´s food security and nutritional health. Furthermore, an increasing number of vertebrate species are being hunted to dangerously low levels as a result of increased commercial demand for meat and medicines, with many now in danger of extinction. FAO

Zika virus: A mosquito-borne flavivirus first identified in Uganda in 1947 in monkeys. Zika virus disease is caused by a virus transmitted primarily by Aedes mosquitoes, which bite during the day. Most people infected with the Zika virus do not develop symptoms, and those that do suffer mild symptoms (fever, rash, conjunctivitis, muscle and joint pain, malaise or headache) for 2–7 days. Zika virus infection during pregnancy can cause infants to be born with microcephaly and other congenital malformations, known as congenital Zika syndrome, and is associated with other complications of pregnancy, including preterm birth and miscarriage. Outbreaks of Zika virus disease have been reported in Africa, Asia and the Americas. WHO

Zoonoses: Diseases that can spread between animals and people, moving from wild and domesticated animals to humans and from humans to animals. Every year, nearly 60,000 people die from rabies, and other zoonotic diseases such as avian influenza, Ebola and Rift Valley fever constitute additional threats. These diseases affect not only human health but also animal health and welfare by causing lowered productivity (e.g. in terms of milk or egg quality and safety) or death, with significant harm to farmer livelihoods and national economies. The current COVID-19 pandemic is a zoonotic disease. FAO; WHO

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