

Section Three

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



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).

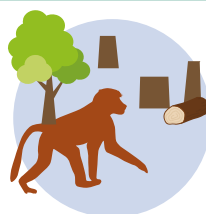
With wild vertebrates being reservoirs of a large repertoire of zoonotic pathogens, wild meat harvesting and trade in live animals enhances several pathways of zoonotic pathogen spillover. Hunters in many forested regions risk disease if injured by an animal during its capture, when carrying their prey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

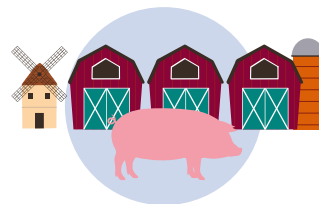
It is noteworthy that Ebola in Central Africa was spread among hunters opportunistically harvesting and handling infected gorilla and chimpanzee cadavers for meat consumption.¹¹⁹ While there is a risk in consuming wild



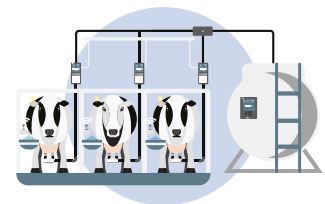
Rodents are associated with more than 80 zoonotic diseases. They are highly adaptable to habitat disturbances. A meta-analysis of 58 case studies from eight countries suggests that land use change is more favourable to rodent species that harbour zoonotic pathogens. Reservoir rodents were found to be 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

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 similarities¹³⁰, 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.

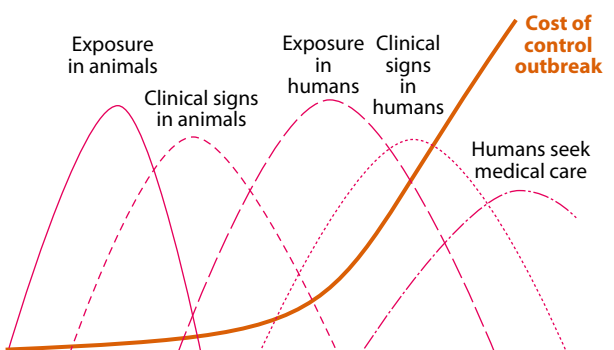
Like all viruses, over time, coronaviruses mutate into new strains possessing different degrees of pathogenicity (the ability to invade and cause disease within the host), virulence (severity of the disease in infected hosts) and infectiousness (capability of being transmitted). Coronaviruses have a 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



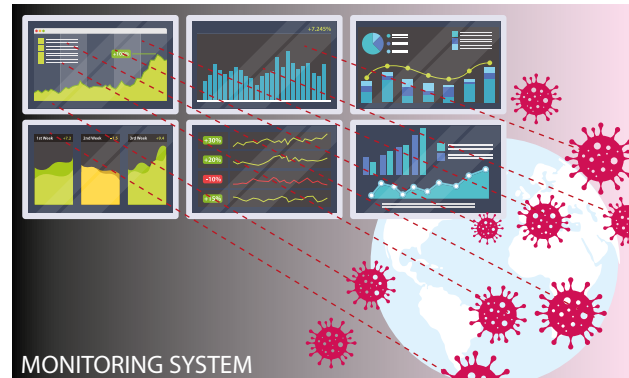
Effective control of zoonotic diseases requires early detection and accurate diagnosis at the animal source. Disease surveillance in animals is critical for preventing the spread of disease between animal populations, and minimizing the risk of transmission to human populations. The cost of disease control 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>

© OIE/Video



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.

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.



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



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.

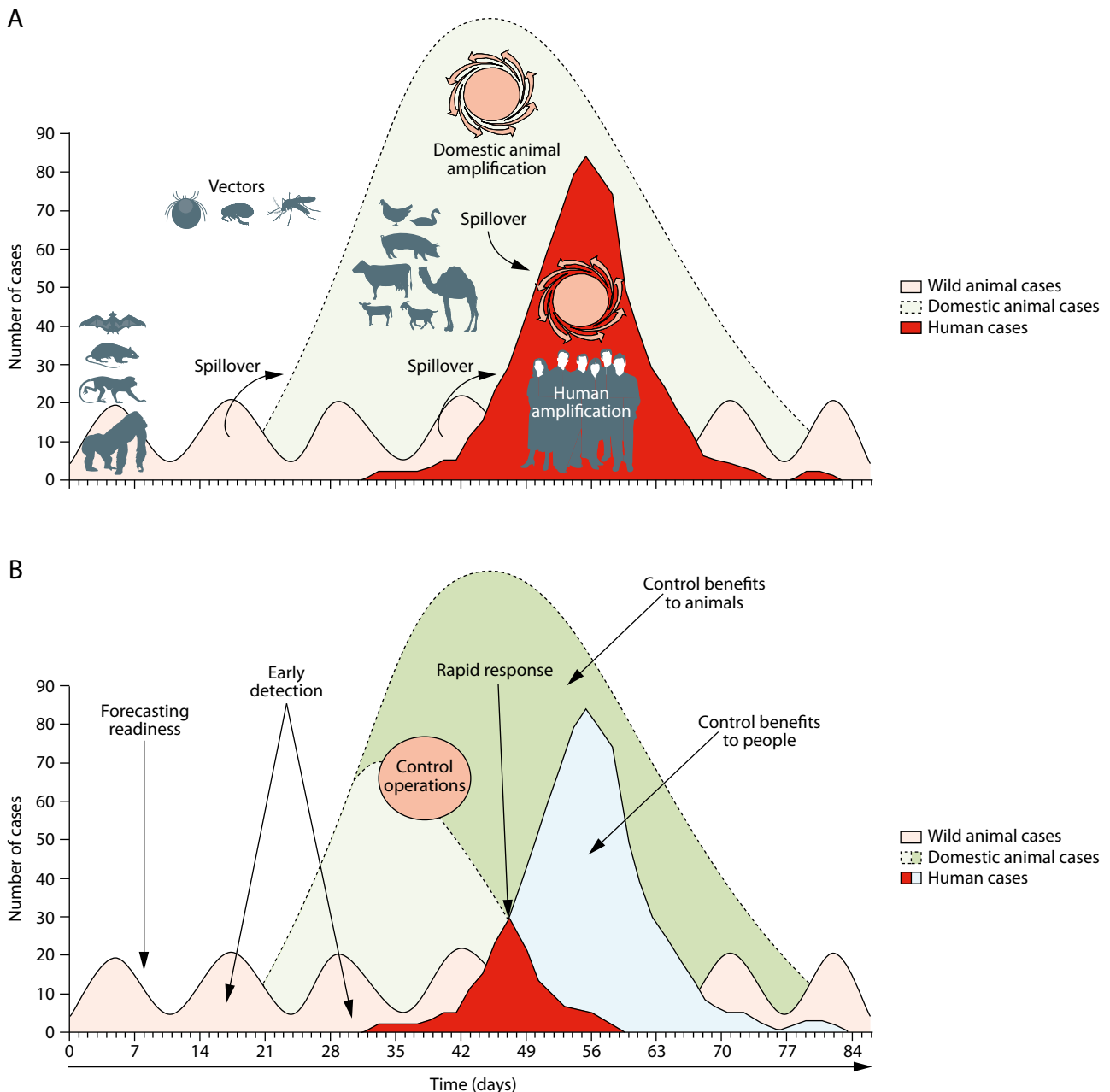
Effective policy responses to mitigate threats from zoonotic diseases require concerted policy action to stem the multiple drivers of their emergence, which include habitat loss and degradation, overexploitation of wildlife, and land-use changes, among other factors. This will be particularly important 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.

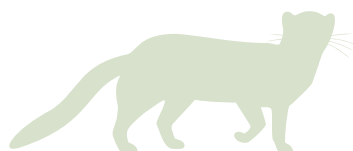
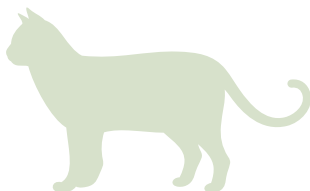
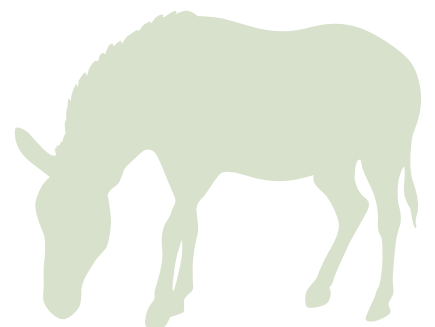
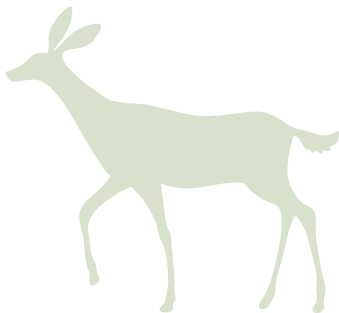
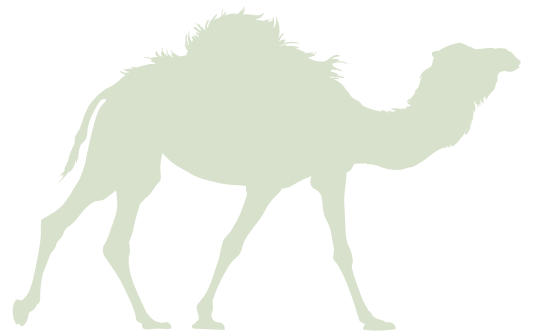
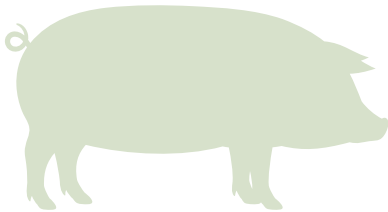
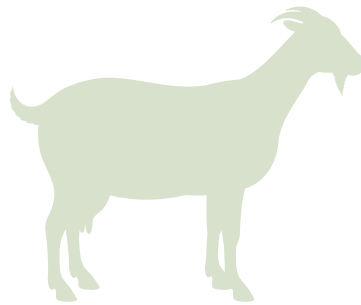
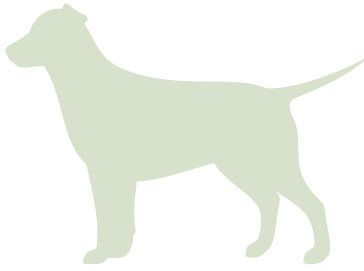
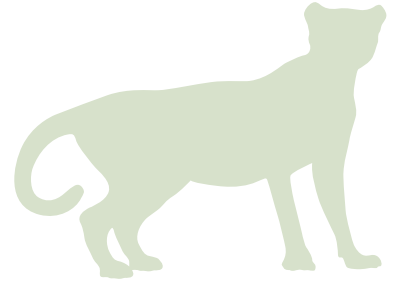
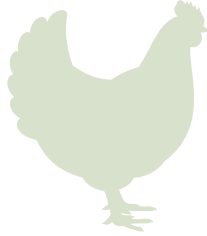
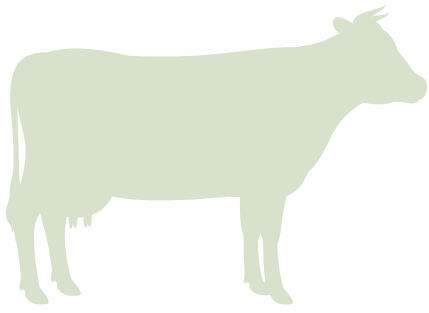
Greater efforts must be made to raise awareness among politicians, particularly with regards to the importance of investing in interdisciplinary surveillance, detection and preventive measures. The current crisis clearly demonstrates the much greater cost of not investing in detection, prevention and 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.



References

- United Nations (2020). *A UN framework for the immediate socio-economic response to COVID-19*. United Nations: New York. <https://unsdg.un.org/sites/default/files/2020-04/UN-framework-for-the-immediate-socio-economic-response-to-COVID-19.pdf>
- World Health Organization [WHO] and Secretariat of the Convention on Biological Diversity [CBD] (2015). *Connecting global priorities: Biodiversity and human health – A state of knowledge review*. WHO and CBD: Geneva and Montreal. <https://www.who.int/publications-detail/connecting-global-priorities-biodiversity-and-human-health>
- Convention on Biological Diversity [CBD] (2017). *Guidance on integrating biodiversity consideration into One Health approaches*. CBD/SBSTTA/21/9. <https://www.cbd.int/doc/c/8e34/8c61/a535d23833e68906c8c7551a/sbstta-21-09-en.pdf>
- Woolhouse, M.E.J. and Gowtage-Sequeria, S. (2005). Host range and emerging and reemerging pathogens. *Emerging Infectious Diseases*, 11, 1842–1847. <https://doi.org/10.3201/eid1112.050997>
- Taylor, L.H., Latham, S.M. and Woolhouse, M.E.J. (2001). Risk factors for human disease emergence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 356(1411), 983–989. <https://doi.org/10.1098/rstb.2001.0888>
- Kock, R. (2014). Drivers of disease emergence and spread: Is wildlife to blame? *Onderstepoort Journal of Veterinary Research*, 81(2). <http://dx.doi.org/10.4102/ojvr.v8i2.739>
- Grace, D. (2019). Infectious Diseases and Agriculture. *Encyclopedia of Food Security and Sustainability*, 3, 439–447. <https://doi.org/10.1016/B978-0-08-100596-5.21570-9>
- Johnson, C.K., Hitchens, P.L., Pandit, P. S., Rushmore, J., Evans, T.S., Young, Cristin C.W. and Doyle, M.M. (2020). Global shifts in mammalian population trends reveal key predictors of virus spillover risk. *Proceedings of the Royal Society B: Biological Sciences*, 287(1924), 20192736. <https://doi.org/10.1098/rspb.2019.2736>
- Cleaveland, S., Laurenson, M.K. and Taylor, L.H. (2001). Diseases of humans and their domestic mammals: Pathogen characteristics, host range and the risk of emergence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 256(1411), 991–999. <https://doi.org/10.1098/rstb.2001.0889>
- World Bank (2012). *People, pathogens and our planet: The economics of one health*. Washington DC: The World Bank. <http://hdl.handle.net/10986/11892>
- Cleaveland, S., Sharp, J., Abela-Ridder, B., Allan, K. J., Buza, J., Crump, J.A. et al. (2017). One health contributions towards more effective and equitable approaches to health in low- and middle-income countries. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372, 20160168. <https://doi.org/10.1098/rstb.2016.0168>
- Grace, D., Lindahl, J., Wanyoike, F., Bett, B., Randolph, T. and Rich, K.M. (2017). Poor livestock keepers: ecosystem–poverty–health interactions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372:20160166. <http://dx.doi.org/10.1098/rstb.2016.0166>
- Havelaar, A. H., Kirk, M. D., Torgerson, P. R., Gibb, H. J., Hald, T., Lake, R. J. et al. (2015). World Health Organization global estimates and regional comparisons of the burden of foodborne disease in 2010. *PLoS Medicine*, 12(12), e1001923. <https://doi.org/10.1371/journal.pmed.1001923>
- South Africa, National Institute for Communicable Diseases [NICD] (2019). An update on the outbreak of *Listeria monocytogenes*. *NICD*, South Africa. <http://www.nicd.ac.za/wp-content/uploads/2018/08/An-update-on-the-outbreak-of-Listeria-monocytogenes-South-Africa.pdf>
- Kock, R.A., Alders, R. and Wallace, R. (2012). Wildlife, wild food, food security and human society. In: *Animal Health and Biodiversity - Preparing for the Future. Illustrating Contributions to Public Health*, 71–79. Compendium of the OIE Global Conference on Wildlife, 23–25 February 2011, Paris, France. <https://www.oie.int/doc/ged/d12062.pdf>
- Wolfe, N.D., Dunavan, C. P. and Diamond, J. (2012). Origins of major human infectious diseases. *Improving Food Safety Through a One Health Approach: Workshop Summary*. Washington DC: National Academies Press (US). <https://www.ncbi.nlm.nih.gov/books/NBK114494/>
- Nunn, N. and Qian, N. (2010). The Columbian exchange: A history of disease, food, and ideas. *Journal of Economic Perspectives*, 24(2), 163–88. <https://doi.org/10.1257/jep.24.2.163>
- Doran, P., Carson, J., Costello, E. and More, S. J. (2009). An outbreak of tuberculosis affecting cattle and people on an Irish dairy farm, following the consumption of raw milk. *Irish Veterinary Journal*, 62(390). <https://doi.org/10.1186/2046-0481-62-6-390>
- Headrick, D.R. (2014). Sleeping Sickness Epidemics and Colonial Responses in East and Central Africa, 1900–1940. *PLoS Neglected Tropical Diseases*, 8(4), e2772. <https://doi.org/10.1371/journal.pntd.0002772>
- Jones, K.E., Patel, N.G., Levy, M.A., Storeygard, A., Balk, D., Gittleman, J. L. and Daszak, P. (2008). Global trends in emerging infectious diseases. *Nature*, 451(7181), 990–993. <https://doi.org/10.1038/nature06536>
- Grace, D., Mutua, F., Ochungo, P., Kruska, R., Jones, K., Brierley, L. et al. (2012). Mapping of poverty and likely zoonoses hotspots. Zoonoses Project 4. Report to the UK Department for International Development. Nairobi, Kenya: ILRI. <https://hdl.handle.net/10568/21161>
- Wallace, R.G., Gilbert, M., Wallace, R., Pittiglio, C., Mattioli, R. and Kock, R. (2016). Did Ebola emerge in West Africa by a policy-driven phase change in agroecology? In *Neoliberal Ebola*, Wallace, R. and Wallace, R. (eds). Springer, Cham. https://doi.org/10.1007/978-3-319-40940-5_1
- Allen, T., Murray, K.A., Zambrana-Torrel, C., Morse, S.S., Rondinini, C., Di Marco, M., Breit, N., Olival, K.J. and Daszak, P. (2017). Global hotspots and correlates of emerging zoonotic diseases. *Nature Communications*, 8, 1124. <https://doi.org/10.1038/s41467-017-00923-8>
- Perry, B.D., Grace, D. and Sones, K. (2011). Livestock and global change special feature: Current drivers and future directions of global livestock disease dynamics. *Proceedings of the National Academy of Sciences*, 110(52), 20871–20877. <https://doi.org/10.1073/pnas.1012953108>
- Jones, B.A., Grace, D., Kock, R., Alonso, S., Rushton, J. and Said, M.Y. (2013). Zoonosis emergence linked to agricultural intensification and environmental change. *Proceedings of the National Academy of Sciences of the United States of America*, 110(21), 8399–8404. <https://doi.org/10.1073/pnas.1208059110>
- Hassell, J.M., Begon, M., Ward, M.J. and Fèvre, E.M. (2017). Urbanization and disease emergence: Dynamics at the wildlife–livestock–human interface. *Trends in Ecology and Evolution*, 32(1), 55–67. <https://doi.org/10.1016/j.tree.2016.09.012>
- Schmidt, C.W. (2009). Swine CAFOs & novel H1N1 flu: Separating facts from fears. *Environmental Health Perspectives*, News, 1 September 2009. <https://doi.org/10.1289/ehp.117-a394>
- Rohr, J.R., Barrett, C. B., Civitello, D. J., Craft, M. E., Delius, B., DeLeo, G. et al. (2019). Emerging human infectious diseases and the links to global food production. *Nature Sustainability*, 2, 445–456. <https://doi.org/10.1038/s41893-019-0293-3>
- Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B. et al. (2014). Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science*, 344, 1118–1123. <https://doi.org/10.1126/science.1248525>
- Cronin, D.T., Woloszynek, S., Morra, W.A., Honarvar, S., Linder, J. M., Gonder, M.K., O'Connor, M.P. and Hearn, G.W. (2015). Long-term urban market dynamics reveal increased bushmeat carcass volume despite economic growth and proactive environmental legislation on Bioko Island, Equatorial Guinea. *PLoS ONE*, 10(7), e0134464. <https://doi.org/10.1371/journal.pone.0134464>
- Tensen, L. (2016). Under what circumstances can wildlife farming benefit species conservation? *Global Ecology and Conservation*, 6, 286–298. <https://doi.org/10.1016/j.gecco.2016.03.007>



32. Allan, B.F., Keesing, F. and Ostfeld, R.S. (2003). Effect of Forest Fragmentation on Lyme Disease Risk. *Conservation Biology*, 17(1), 267–272. <https://doi.org/10.1046/j.1523-1739.2003.01260.x>
33. Grace, D. and Roesel, K. (2014). *Food Safety and Informal Markets: Animal products in sub-Saharan Africa*. London: Routledge. <https://hdl.handle.net/10568/42438>
34. Grace, D. (2015). Food safety in low and middle income countries. *International Journal of Environmental Research and Public Health*, 12, 10490–10507. <https://doi.org/10.3390/ijerph120910490>
35. Chan, K.H., Peiris, J.S., Lam, S.Y., Poon, L.L., Yuen, K.Y. and Seto, W.H. (2011). The Effects of Temperature and Relative Humidity on the Viability of the SARS Coronavirus. *Advances in Virology*, 2011, 734690. <https://doi.org/10.1155/2011/734690>
36. Khan, N., Fahad, S., Naushad, M. and Muhammad, A. (2020). Climate Impact on Corona Virus in the World (March 25, 2020). SSRN. <http://dx.doi.org/10.2139/ssrn.3561155>
37. Naicker, P.R. (2011). The impact of climate change and other factors on zoonotic diseases. *Archives of Clinical Microbiology*, 2(2:4). <https://www.acmicrob.com/microbiology/the-impact-of-climate-change-and-other-factors-on-zoonotic-diseases.pdf>
38. Wells, K. and Clark, N. J. (2019). Host Specificity in Variable Environments. *Trends in Parasitology*, 35(6), 452–465. <https://doi.org/10.1016/j.pt.2019.04.001>
39. Nava, A., Shimabukuro, J.S., Chmura, A. A. and Luz, S.L.B. (2017). The Impact of Global Environmental Changes on Infectious Disease Emergence with a Focus on Risks for Brazil. *ILAR Journal*, 58(3), 393–400. <https://doi.org/10.1093/ilar/ilx034>
40. Huber, I., Potapova, K., Ammosova, E., Beyer, W., Blagodatskiy, S., Desyatkin, R. et al. (2020). Symposium report: emerging threats for human health—impact of socioeconomic and climate change on zoonanthroposis in the Republic of Sakha (Yakutia), Russia. *International Journal of Circumpolar Health*, 79(1). <https://doi.org/10.1080/022423982.2020.1715698>
41. Barré-Sinoussi, F., Chermann, J.C., Rey, F., Nugeyre, M.T., Chamaret, S., Gruest, J. et al. (1983). Isolation of a T-lymphotropic retrovirus from a patient at risk for acquired immune deficiency syndrome (AIDS). *Science*, 220(4599), 868–871. <https://doi.org/10.1126/science.6189183>
42. Clavel, F., Guyader, M., Guétard, D., Sallé, M., Montagnier, L. and Alizon, M. (1986). Molecular cloning and polymorphism of the human immune deficiency virus type 2. *Nature*, 324(6098), 691–695. <https://doi.org/10.1038/324691a0>
43. Sharp, P. M. and Hahn, B. H. (2010). The evolution of HIV-1 and the origin of AIDS. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365: 2487–2494. <https://doi.org/10.1098/rstb.2010.0031>
44. Hirsch, V.M., Olmsted, R.A., Murphey-Corb, M., Purcell, R.H. and Johnson, P.R. (1989). An African primate lentivirus (SIV sm) closely related to HIV-2. *Nature*, 339(6223), 389–392. <https://doi.org/10.1038/339389a0>
45. Chen, Z., Luckay, A., Sodora, D. L., Telfer, P., Reed, P., Gettie, A. et al. (1997). Human immunodeficiency virus type 2 (HIV-2) seroprevalence and characterization of a distinct HIV-2 genetic subtype from the natural range of simian immunodeficiency virus-infected sooty mangabeys. *Journal of Virology*, 71(5), 3953–3960. <https://doi.org/10.1128/jvi.71.5.3953-3960.1997>
46. Marx, P.A., Li, Y., Lerche, N.W., Sutjipto, S., Gettie, A., Yee, J.A. et al. (1991). Isolation of a simian immunodeficiency virus related to human immunodeficiency virus type 2 from a west African pet sooty mangabey. *Journal of virology*, 65(8), 4480–4485. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC248889/>
47. Hahn, B.H., Shaw, G.M., De Cock, K.M. and Sharp, P.M. (2000). AIDS as a zoonosis: Scientific and public health implications. *Science*, 287(5453), 607–614. <https://doi.org/10.1126/science.287.5453.607>
48. Peeters, M. and Courgnaud, V. (2002) 'Overview of primate lentiviruses and their evolution in non-human primates in Africa. In: HIV Sequence Compendium 2002 (Ed by Kuiken C, Foley B, Freed E, Hahn B, Korber B, Marx PA, McCutchan F, Mellors, JW, and Wolinsky S.), pp. 2–23. Theoretical Biology and Biophysics Group, Los Alamos National Laboratory, Los Alamos, NM. LA-UR 03-3564.'
49. Peeters, M., Courgnaud, V., Abela, B., Auzel, P., Pourrut, X., Bibollet-Ruche, et al. (2002). Risk to human health from a plethora of Simian immunodeficiency viruses in primate bushmeat. *Emerging Infectious Diseases*, 8(5), 451–457. <https://doi.org/10.3201/eid0805.010522>
50. Keele, B.F., Jones, J.H., Terio, K. A., Estes, J.D., Rudicell, R.S., Wilson, M.L. et al. (2009). Increased mortality and AIDS-like immunopathology in wild chimpanzees infected with SIVcpz. *Nature*, 460, 515–519. <https://doi.org/10.1038/nature08200>
51. Worobey, M., Telfer, P., Souquière, S., Hunter, M., Coleman, C. A., Metzger, M. J. et al. (2010). Island biogeography reveals the deep history of SIV. *Science*, 329(5998), 1487. <https://doi.org/10.1126/science.1193550>
52. Cook, J.K.A., Jackwood, M. and Jones, R.C. (2012). The long view: 40 years of infectious bronchitis research. *Avian Pathology*, 41(3), 239–250. <https://doi.org/10.1080/03079457.2012.680432>
53. Chen, F., Knutson, T.P., Rossow, S., Saif, L.J. and Marthaler, D.G. (2019). Decline of transmissible gastroenteritis virus and its complex evolutionary relationship with porcine respiratory coronavirus in the United States. *Scientific Reports*, 9, 3953. <https://doi.org/10.1038/s41598-019-40564-z>
54. Lee, C. (2015). Porcine epidemic diarrhea virus: An emerging and re-emerging epizootic swine virus. *Virology Journal*. <https://doi.org/10.1186/s12985-015-0421-2>
55. Hilgenfeld, R. and Peiris, M. (2013). From SARS to MERS: 10 years of research on highly pathogenic human coronaviruses. *Antiviral Research*, 100(1), 286–295. <https://doi.org/10.1016/j.antiviral.2013.08.015>
56. Ramadan, N. and Shaib, H. (2019). Middle east respiratory syndrome coronavirus (MERS-COV): A review. *GERMS*. <https://doi.org/10.18683/germs.2019.1155>
57. Lau, S.K., Luk, H.K., Wong, A.C., Li, K.S., Zhu, L., He, Z. et al. (2020). Possible bat origin of severe acute respiratory syndrome coronavirus 2. *Emerging Infectious Diseases*, 26(7). In press for July 2020. <https://doi.org/10.3201/eid2607.200092>
58. Zhou, P., Yang, X. Lou, Wang, X. G., Hu, B., Zhang, L., Zhang, W., et al. (2020). A pneumonia outbreak associated with a new coronavirus of probable bat origin. *Nature*, 579(7798), 270–273. <https://doi.org/10.1038/s41586-020-2012-7>
59. Vijaykrishna, D., Smith, G. J. D., Zhang, J. X., Peiris, J. S. M., Chen, H. and Guan, Y. (2007). Evolutionary Insights into the Ecology of Coronaviruses. *Journal of Virology*. <https://doi.org/10.1128/jvi.02605-06>
60. Luis, A.D., Hayman, D.T.S., O'Shea, T.J., Cryan, P.M., Gilbert, A.T., Pulliam, J.R. et al. (2013). A comparison of bats and rodents as reservoirs of zoonotic viruses: Are bats special?. *Proceedings of the Royal Society B: Biological Sciences*, 280(1756). <https://doi.org/10.1098/rspb.2012.2753>
61. Kunz, T.H., de Torre, E.B., Bauer, D., Lobova, T. and Fleming, T.H. (2011). Ecosystem services provided by bats. *Annals of the New York Academy of Sciences*, 1223(1), 1–38. <https://doi.org/10.1111/j.1749-6632.2011.06004.x>
62. Wang, W., Yang, L., Wronski, T., Chen, S., Hu, Y. and Huang, S. (2019). Captive breeding of wildlife resources—China's revised supply-side approach to conservation. *Wildlife Society Bulletin*, 43(3), 425–435. <https://doi.org/10.1002/wsb.988>
63. Shairp, R., Verissimo, D., Fraser, I., Challender, D. and Macmillan, D. (2016). Understanding urban demand for wild meat in Vietnam: Implications for conservation actions. *PLoS ONE*, 11(1), e0134787. <https://doi.org/10.1371/journal.pone.0134787>
64. Farag, E., Sikkema, R. S., Vinks, T., Islam, M. M., Nour, M., Al-Romaihi, H. et al. (2018). Drivers of MERS-CoV Emergence in Qatar. *Viruses*, 11(22). <https://doi.org/10.3390/v11010022>
65. Hu, B., Zeng, L. P., Yang, X. Lou, Ge, X. Y., Zhang, W. et al. (2017). Discovery of a rich gene pool of bat SARS-related coronaviruses provides new insights into the origin of SARS coronavirus. *PLoS Pathogens*, 13(11), e1006698. <https://doi.org/10.1371/journal.ppat.1006698>
66. Huang, C., Wang, Y., Li, X., Ren, L., Zhao, J., Hu, Y. et al. (2020). Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. *The Lancet*, 395, 497–506. [https://doi.org/10.1016/S0140-6736\(20\)30183-5](https://doi.org/10.1016/S0140-6736(20)30183-5)
67. Webster, R.G. (2004). Wet markets - A continuing source of severe acute respiratory syndrome and influenza? *The Lancet*, 363(9404), 234–236. [https://doi.org/10.1016/S0140-6736\(03\)15329-9](https://doi.org/10.1016/S0140-6736(03)15329-9)

68. Kock, R.A., Karesh, W.B., Veas, F., Velavan, T. P., Simons, D., Mboera, L.E.G. *et al.* (2020). 2019-nCoV in context: lessons learned? *The Lancet Planetary Health*, 4(3), e87–e88. [https://doi.org/10.1016/S2542-5196\(20\)30035-8](https://doi.org/10.1016/S2542-5196(20)30035-8)
69. Ribeiro, J., Bingre, P., Strubbe, D. and Reino, L. (2020). Coronavirus: why a permanent ban on wildlife trade might not work in China. *Nature, Correspondence*, 11 February 2020. <https://doi.org/10.1038/d41586-020-00377-x>
70. Food and Agriculture Organization of the United Nations (2020). *Global Forest Resources Assessment 2020*. Rome: FAO. <https://doi.org/10.4060/ca8753en>
71. Wilcox, B.A. and Ellis, B. (2006). Forests and emerging infectious diseases of humans. *Unasylva*, 224(57), 11–19. <http://www.fao.org/tempref/docrep/fao/009/a0789e/a0789e03.pdf>
72. Steiger, D.B., Ritchie, S. A. and Laurance, S. G. W. (2016) Mosquito communities and disease risk influenced by land use change and seasonality in the Australian tropics. *Parasites and Vectors*, 9(1), 387. <https://doi.org/10.1186/s13071-016-1675-2>.
73. Mills, J.N. (2006). Biodiversity loss and emerging infectious disease: An example from the rodent-borne hemorrhagic fevers. *Biodiversity*, 7(1), 9–17. <https://doi.org/10.1080/14888386.2006.9712789>
74. Friggens, M.M. and Beier, P. (2010). Anthropogenic disturbance and the risk of flea-borne disease transmission. *Oecologia*, 164(3), 809–820. <https://doi.org/10.1007/s00442-010-1747-5>
75. Zimmer, K. (2019). Deforestation is leading to more infectious diseases in humans, 22 November 2019. <https://www.nationalgeographic.com/science/2019/11/deforestation-leading-to-more-infectious-diseases-in-humans/>
76. Ostfeld, R.S. (2009). Biodiversity loss and the rise of zoonotic pathogens. *Clinical Microbiology and Infection*, 15, Suppl 1:40–3. <https://doi.org/10.1111/j.1469-0691.2008.02691.x>
77. Faust, C.L., Dobson, A.P., Gottdenker, N., Bloomfield, L.S.P., McCallum, H.I., Gillespie, T.R. *et al.* (2017). Null expectations for disease dynamics in shrinking habitat: Dilution or amplification? *Philosophical Transactions of the Royal Society B: Biological Sciences*, 372, 20160173. <https://doi.org/10.1098/rstb.2016.0173>
78. Olival, K. J., Hosseini, P. R., Zambrana-Torrel, C., Ross, N., Bogich, T. L. and Daszak, P. (2017). Host and viral traits predict zoonotic spillover from mammals. *Nature*, 546, 646–650. <https://doi.org/10.1038/nature22975>
79. Köndgen, S., Kühl, H., N'Goran, P.K., Walsh, P.D., Schenk, S., Ernst, N. *et al.* (2008). Pandemic human viruses cause decline of endangered great apes. *Current Biology*, 18, 260–264. <https://doi.org/10.1016/j.cub.2008.01.012>
80. Patrono, L.V., Samuni, L., Corman, V. M., Nourifar, L., Röthemer, C., Wittig, *et al.* (2018). Human coronavirus OC43 outbreak in wild chimpanzees, Côte d'Ivoire, 2016. *Emerging Microbes & Infections*. Nature Publishing Group, 7(1), 1–4. <https://doi.org/10.1038/s41426-018-0121-2>
81. Gillespie, T.R., Ahoua, S., Acrenaz, M., Bergl, R. Calvignac-Spencer, S., Couacy-Hymann, E., Deschner, T., Dux, A., Fuh-Neba, T., Gogarten, J.F., Herlinger, I., Kalema-Zikusoka, G., Kone, I., Lonsdorf, E.V., Lumbu Banza, C.-P., Makoutoutou Nzassi, P., Raphael, J., Mjungu, D.C., Patrono, L.V., Refisch, J., Robbins, M., Rwego, I.B., Surbeck, M., Wich, S., Wittig, R., Travis, D., Leendertz, F. (2020). COVID-19: protect great apes during human pandemics. Supplementary information (The Great Ape Health Consortium). *Nature correspondence* (579):497. <https://doi.org/10.1038/d41586-020-00859-y> <https://doi.org/10.1038/d41586-020-00859-y>
82. Gilardi, K.V., Gillespie, T.R., Leendertz, F.H., Macfie, E.J., Travis, D.A., Whittier, *et al.* (2015). *Best Practice Guidelines for Health Monitoring and Disease Control in Great Ape Populations*. IUCN SSC Primate Specialist Group, Gland, Switzerland. <https://portals.iucn.org/library/sites/library/files/documents/SSC-OP-056.pdf>
83. Macfie, E.J. and Williamson, E.A. (2010). *Best practice guidelines for great ape tourism*. Gland, Switzerland: IUCN/SSC Primate Specialist Group. <https://portals.iucn.org/library/sites/library/files/documents/SSC-OP-038.pdf>
84. Olivero, J., Fa, J. E., Real, R., Márquez, A. L., Farfán, M. A., Vargas, *et al.* (2017). Recent loss of closed forests is associated with Ebola virus disease outbreaks. *Scientific Reports*, 7, 14291. <https://doi.org/10.1038/s41598-017-14727-9>
85. Rulli, M.C., Santini, M., Hayman, D.T.S. and D'Odorico, P. (2017). The nexus between forest fragmentation in Africa and Ebola virus disease outbreaks. *Scientific Reports*, 7, 41613. <https://doi.org/10.1038/srep41613>
86. Leroy, E.M., Rouquet, P., Formenty, P., Souquière, S., Kilbourne, A., Froment, J.-M. *et al.* (2004). Multiple Ebola Virus Transmission Events and Rapid Decline of Central African Wildlife. *Science*, 303(5656), 387–390. <https://doi.org/10.1126/science.1092528>
87. Walsh, P.D., Abernethy, K.A., Bermejo, M., Beyers, R., De Wachter, P., Akou, M.E. *et al.* (2003). Catastrophic ape decline in western equatorial Africa. *Nature*, 422, 611–614. <https://doi.org/10.1038/nature01566>
88. Zohdy, S., Schwartz, T.S. and Oaks, J.R. (2019). The Coevolution Effect as a Driver of Spillover. *Trends in Parasitology*, 35(6), 399–408. <https://doi.org/10.1016/j.pt.2019.03.010>
89. Keesing, F., Belden, L.K., Daszak, P., Dobson, A., Harvell, C. D., Holt, R.D. *et al.* (2010). Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature*, 468, 647–652. <https://doi.org/10.1038/nature09575>
90. Albery, G.F., Eskew, E.A., Ross, N. and Olival, K.J. (2020). Predicting the global mammalian viral sharing network using phylogeography. *Nature Communications*, 11, 2260. <https://doi.org/10.1038/s41467-020-16153-4>
91. Karesh, W.B., Cook, R. A., Bennett, E. L. and Newcomb, J. (2005). Wildlife trade and global disease emergence. *Emerging Infectious Diseases*, 11(7), 1000–1002. <https://doi.org/10.3201/eid1107.050194>
92. Coad, L., Fa, J.E., Van Vliet, N., Abernethy, K., Santamaria, C., Wilkie, D., Cawthorn, D.-M. and Nasi, R. (2019). *Towards a sustainable, participatory and inclusive wild meat sector*. Bogor, Indonesia: CIFOR. <https://doi.org/10.17528/cifor/007046>
93. Nasi, R., Taber, A. and Van Vliet, N. (2011). Empty forests, empty stomachs? Bushmeat and livelihoods in the Congo and Amazon Basins. *International Forestry Review*, 13(3), 355–368. <https://doi.org/10.1505/146554811798293872>
94. Fa, J.E., Currie, D. and Meeuwij, J. (2003). Bushmeat and food security in the Congo Basin: Linkages between wildlife and people's future. *Environmental Conservation*. <https://doi.org/10.1017/S0376892903000067>
95. Nielsen, M. R., Meilby, H., Smith-Hall, C., Pouliot, M. and Treue, T. (2018). The Importance of Wild Meat in the Global South. *Ecological Economics*, 146, 696–705. <https://doi.org/10.1016/j.ecolecon.2017.12.018>
96. Convention on the Conservation of Migratory Species of Wild Animals [CMS] (2017). *Aquatic Wild Meat (Prepared by the Aquatic Mammals Working Group of the Scientific Council and the Secretariat)*. UNEP/CMS/COP12/Doc.24.2.3/Rev.1. https://www.cms.int/sites/default/files/document/cms_cop12_doc.24.2.3_rev1_aquatic-wild-meat_e.pdf
97. Altizer, S., Bartel, R. and Han, B.A. (2011). Animal migration and infectious disease risk. *Science*, 331(6015), 296–302. <https://doi.org/10.1126/science.1194694>
98. Hall, R.J., Altizer, S. and Bartel, R.A. (2014). Greater migratory propensity in hosts lowers pathogen transmission and impacts. *Journal of Animal Ecology*, 83, 1068–1077. <https://doi.org/10.1111/1365-2656.12204>
99. McKay, F. A. and Hoyer, B. J. (2016). Are Migratory Animals Superspreaders of Infection? *Integrative and Comparative Biology*, 260–267. <https://doi.org/10.1093/icb/icw054>
100. Convention on the Conservation of Migratory Species of Wild Animals [CMS] (2020). *Review of the Conservation Status of Migratory Species (Prepared for the Secretariat, in consultation with the Scientific Council)*. UNEP/CMS/COP13/Doc.24/Rev.1. https://www.cms.int/sites/default/files/document/cms_cop13_doc.24_rev.1_review-conservation-status-migratory-species_e.pdf
101. Wilkinson, D.A., Marshall, J.C., French, N.P. and Hayman, D.T. (2018). Habitat fragmentation, biodiversity loss and the risk of novel infectious disease emergence. *Journal of the Royal Society Interface*, 15, 20180403. <https://doi.org/10.1098/rsif.2018.0403>
102. Convention on Biological Diversity (2018). Recommendation adopted by the subsidiary body on scientific, technical and technological advice: XXI/2. Sustainable wildlife management: guidance for a sustainable wild meat sector. CBD/SBSTTA/REC/XXI/2, 14 December 2017. <https://www.cbd.int/doc/decisions/cop-14/cop-14-dec-07-en.pdf>

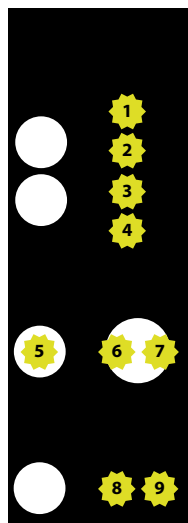


103. World Bank. (2017). *World Bank Annual Report 2017*. Washington DC: The World Bank. <https://doi.org/10.1596/1978-1-4648-1119-7>
104. Wicander, S. and Coad, L. (2018). Can the Provision of Alternative Livelihoods Reduce the Impact of Wild Meat Hunting in West and Central Africa? *Conservation and Society*, 16(4), 441–458. https://doi.org/10.4103/cs.cs_17_56
105. De Merode, E., Homewood, K. and Cowlshaw, G. (2004). The value of bushmeat and other wild foods to rural households living in extreme poverty in Democratic Republic of Congo. *Biological Conservation*, 118(5), 573–581. <https://doi.org/10.1016/j.biocon.2003.10.005>
106. Mbete, R.A., Banga-Mboko, H., Racey, P., Mfoukou-Ntsakala, A., Nganga, I., Vermeulen, C. et al. (2011). Household bushmeat consumption in Brazzaville, the republic of the Congo. *Tropical Conservation Science*, 4(2), 187–202. <https://doi.org/10.1177/194008291100400207>
107. South Africa, Department of Environmental Affairs (2019). *Biodiversity Economy-Game Meat*. Brochure. Department of Environmental Affairs, Government of South Africa. Pretoria, South Africa. https://www.environment.gov.za/sites/default/files/docs/publications/biodiversityeconomy_gamemeat.pdf
108. International Institute for Environment and Development (1995). *The Hidden Harvest – The value of wild resources in agricultural systems: a project summary*. London. <https://pubs.iied.org/pdfs/6135IIED.pdf>
109. Hoffman, L.C. and Cawthorn, D-M. (2012). What is the role and contribution of meat from wildlife in providing high quality protein for consumption? *Animal Frontiers*, 2(4), 40–53. <https://doi.org/10.2527/af.2012-0061>
110. Lindsey, P. (2011). An analysis of game meat production and wildlife-based land uses on freehold land in Namibia: Links with food security. *TRAFFIC East/Southern Africa*, Harare, Zimbabwe. <https://www.traffic.org/publications/reports/an-analysis-of-game-meat-production-and-wildlife-based-land-uses-on-freehold-land-in-namibia-links-with-food-security/>
111. White, P.A. and Belant, J.L. (2015). Provisioning of game meat to rural communities as a benefit of sport hunting in Zambia. *PLoS ONE*, 10(2): e0117237. <https://doi.org/10.1371/journal.pone.0117237>
112. TRAFFIC (2020). Wildlife Trade, COVID 19, and zoonotic disease risks. Cambridge, UK. <https://www.traffic.org/site/assets/files/12764/covid-19-briefing-vfinal.pdf>
113. Johnson, C.K., Hitchens, P.L., Evans, T.S., Goldstein, T., Thomas, K., Clements, A. et al. (2015). Spillover and pandemic properties of zoonotic viruses with high host plasticity. *Scientific Reports*, 5, 14830. <https://doi.org/10.1038/srep14830>
114. Subramanian, M. (2012). Zoonotic disease risk and the bushmeat trade: Assessing awareness among hunters and traders in Sierra Leone. *EcoHealth*, 9, 471–482. <https://doi.org/10.1007/s10393-012-0807-1>
115. LeBreton, M., Prosser, A. T., Tamoufe, U., Sateren, W., Mpoudi-Ngole, E., Diffo, J.L. et al. (2006) Patterns of bushmeat hunting and perceptions of disease risk among central African communities. *Animal Conservation*. <https://doi.org/10.1111/j.1469-1795.2006.00030.x>
116. Wolfe, N.D., Heneine, W., Carr, J.K., Garcia, A.D., Shanmugam, V., Tamoufe, U. et al. (2005). Emergence of unique primate T-lymphotropic viruses among central African bushmeat hunters. *Proceedings of the National Academy of Sciences of the United States of America*, 102(22), 7994–7999. <https://doi.org/10.1073/pnas.0501734102>
117. Wolfe, N.D., Switzer, W.M., Carr, J.K., Bhullar, V.B., Shanmugam, V., Tamoufe, U. et al. (2004). Naturally acquired simian retrovirus infections in central African hunters. *The Lancet*, 363(9413), 932–937. [https://doi.org/10.1016/S0140-6736\(04\)15787-5](https://doi.org/10.1016/S0140-6736(04)15787-5)
118. Aghokeng, A.F., Ayoub, A., Mpoudi-Ngole, E., Loul, S., Liegeois, F., Delaporte, E. and Peeters, M. (2010). Extensive survey on the prevalence and genetic diversity of SIVs in primate bushmeat provides insights into risks for potential new cross-species transmissions. *Infection, Genetics and Evolution*, 10(3), 386–396. <https://doi.org/10.1016/j.meegid.2009.04.014>
119. Leendertz, S.A.J., Gogarten, J.F., Düx, A., Calvignac-Spencer, S. and Leendertz, F.H. (2016). Assessing the evidence supporting fruit bats as the primary reservoirs for ebola viruses. *EcoHealth*, 13(1), 18–25. <https://doi.org/10.1007/s10393-015-1053-0>
120. Can, Ö.E., D'Cruze, N. and Macdonald, D.W. (2019). Dealing in deadly pathogens: Taking stock of the legal trade in live wildlife and potential risks to human health. *Global Ecology and Conservation*, 17, e00515. <https://doi.org/10.1016/j.gecco.2018.e00515>
121. Katani, R., Schilling, M.A., Lyimo, B., Tonui, T., Cattadori, I.M., Eblate, E. et al. (2019). Microbial diversity in bushmeat samples recovered from the Serengeti ecosystem in Tanzania. *Scientific Reports*, 9(1), 18086. <https://doi.org/10.1038/s41598-019-53969-7>
122. Greatorex, Z. F., Olson, S. H., Singhalath, S., Silithammavong, S., Khammavong, K., Fine, A.E. et al. (2016). Wildlife trade and human health in Lao PDR: An assessment of the zoonotic disease risk in markets. *PLoS ONE*, 11(3): e0150666. <https://doi.org/10.1371/journal.pone.0150666>
123. Pavlin, B.I., Schloegel, L.M. and Daszak, P. (2009). Risk of importing zoonotic diseases through wildlife trade, United States. *Emerging Infectious Diseases*, 15(11), 1721–1726. <https://dx.doi.org/10.3201/eid1511.090467>
124. Bernard, S.M. and Anderson, S.A. (2006). Qualitative assessment of risk for monkeypox associated with domestic trade in certain animal species, United States. *Emerging Infectious Diseases*, 12(12), 1827–1833. <https://doi.org/10.3201/eid1212.060454>
125. United States of America, Centers for Disease Control and Prevention (2018). Multistate Outbreak of *Salmonella* Agbeni Infections Linked to Pet Turtles, 2017. Accessed 18 May 2020. <https://www.cdc.gov/salmonella/agbeni-08-17/index.html>
126. PREDICT (2016). *UC Davis School of Veterinary Medicine*. Yellow Fever In Bolivian Howler Monkeys. [online] Available at: <<https://ccah.vetmed.ucdavis.edu/areas-study/genetics/information-impacts>> [Accessed 19 May 2020].
127. Grace, D. (2014). The business case for one health. *Onderstepoort Journal of Veterinary Research*, 81(2). <https://doi.org/10.4102/ojvr.v81i2.725>
128. Harrison, S., Kivuti-Bitok, L., Macmillan, A. and Priest, P. (2019). EcoHealth and One Health: A theory-focused review in response to calls for convergence. *Environment International*, 132, 105058. <https://doi.org/10.1016/j.envint.2019.105058>
129. Lerner, H. and Berg, C.A. (2017). Comparison of Three Holistic Approaches to Health: One Health, EcoHealth, and Planetary Health. *Frontiers in Veterinary Science*, 4, 163. <https://doi.org/10.3389/fvets.2017.00163>
130. Zinsstag, J. (2012). Convergence of ecohealth and one health. *EcoHealth*, 9, 371–373. <https://doi.org/10.1007/s10393-013-0812-z>
131. World Organization for Animal Health. (2008). A Strategic Framework for Reducing Risks of Infectious Diseases at the Animal–Human–Ecosystems Interface. OIE, Paris. <https://www.oie.int/doc/ged/D5720.PDF>
132. FAO-OIE-WHO Collaboration (2010). *Sharing Responsibilities and Coordinating global activities to address health risks at the animal-human-ecosystems interfaces: A Tripartite Concept Note*. World Health Organisation. https://www.who.int/influenza/resources/documents/tripartite_concept_note_hanoi/en/
133. Convention on Biological Diversity (2018). Decision adopted by the Conference of the Parties to the Convention on Biological Diversity: 14/4. Health and biodiversity. CBD/COP/DEC/14/4, 30 November 2018. <https://www.cbd.int/doc/decisions/cop-14/cop-14-dec-04-en.pdf>
134. Musoke, D., Ndejjo, R., Atusingwize, E. and Halage, A. A. (2016). The role of environmental health in One Health: A Uganda perspective. *One Health*, 2, 157–160. <https://doi.org/10.1016/j.onehlt.2016.10.003>
135. Cork, S., Hall, D. and Liljebljelke, K. (2016) *One Health case studies: Addressing complex problems in a changing world*. Sheffield: 5M Publishing Ltd. <https://doi.org/10.1111/avj.12699>
136. Alexander, K.A., Sanderson, C.E., Marathe, M., Lewis, B.L., Rivers, C.M., Shaman, J. et al. (2015). What factors might have led to the emergence of ebola in West Africa? *PLoS Neglected Tropical Diseases*, e0003652. <https://doi.org/10.1371/journal.pntd.0003652>
137. Grace, D. (2020). Animal disease research: Key issues. *Engineering*, 6(1), 8–9. <https://doi.org/10.1016/j.eng.2019.11.005>
138. Amuguni, H.J., Mazan, M. and Kibuuka, R. (2017). Producing Interdisciplinary competent professionals: Integrating One Health core competencies into the veterinary curriculum at the University of Rwanda. *Journal of Veterinary Medical Education*, 44(4), 649–659. <https://doi.org/10.3138/jvme.0815-133R>

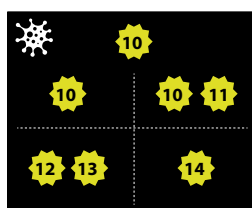
139. Friedson-Ridenour, S., Dutcher, T.V., Calderon, C., Brown, L.D. and Olsen, C.W. (2019). Gender Analysis for One Health: Theoretical Perspectives and Recommendations for Practice. *EcoHealth*, 16(2), 306–316. <https://doi.org/10.1007/s10393-019-01410-w>
140. Baum, S.E., Machalaba, C., Daszak, P., Salerno, R.H. and Karesh, W.B. (2017). Evaluating one health: Are we demonstrating effectiveness? *One Health*, 3, 5–10. <https://doi.org/10.1016/j.onehlt.2016.10.004>
141. Grace, D. and McDermott, J. (2011). Livestock epidemics. In *Routledge Handbook of Hazards and Disaster Risk Reduction*. Wisner, B., Gaillard, J., and Kelman, I. (eds). London: Routledge. Chapter 31, 372–383.
142. Kavle, J. A., El-Zanaty, F., Landry, M. and Galloway, R. (2015). The rise in stunting in relation to avian influenza and food consumption patterns in Lower Egypt in comparison to Upper Egypt: Results from 2005 and 2008 Demographic and Health Surveys. *BMC Public Health*, 15(1), 285. <https://doi.org/10.1186/s12889-015-1627-3>
143. Weber, D.S., Mandler, T., Dyck, M., De Groot, P.J.V.C., Lee, D.S. *et al.* (2015). Unexpected and undesired conservation outcomes of wildlife trade bans—An emerging problem for stakeholders?. *Global Ecology and Conservation*, 3, 389–400. <https://doi.org/10.1016/j.gecco.2015.01.006>
144. Falzon, L.C., Alumasa, L., Amany, F., Kangethe, E.K., Kariuki, S., Momanyi, K. *et al.* (2019). One Health in action: Operational aspects of an integrated surveillance system for zoonoses in western Kenya. *Frontiers in Veterinary Science*, 6, 252. <https://doi.org/10.3389/fvets.2019.00252>
145. Anderson, T., Capua, I., Dauphin, G., Donis, R., Fouchier, R., Mumford, E. *et al.* (2010). FAO-OIE-WHO Joint Technical Consultation on Avian Influenza at the Human-Animal Interface. *Influenza and Other Respiratory Viruses*, 4(Suppl 1), 1–29. <https://doi.org/10.1111/j.1750-2659.2009.00114.x>
146. Wilcox, B.A. and Gubler, D.J. (2005). Disease ecology and the global emergence of zoonotic pathogens. *Environmental Health and Preventive Medicine*, 10(5), 263–272. <https://doi.org/10.1007/BF02897701>
147. Bett, B. 2019. Co-infection with Rift Valley fever virus, *Brucella* spp. and *Coxiella burnetii* in humans and animals in Kenya: Disease burden and ecological factors. Presented at the inaugural workshop of a bio-surveillance project on Rift Valley fever, brucellosis and Q fever, Nairobi, Kenya, 3 September 2019. Nairobi, Kenya: ILRI. <https://www.ilri.org/research/projects/co-infection-rift-valley-fever-virus-brucella-spp-and-coxiella-burnetii-humans-and>
148. HLPE (2016). *Sustainable agricultural development for food security and nutrition: what roles for livestock?* A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security. Rome. <http://www.fao.org/3/a-i5795e.pdf>
149. Kluser, S. and Peduzzi, P. (2007). Global pollinator decline: A Literature Review. *UNEP/GRID-Europe*. https://unepgrid.ch/storage/app/media/legacy/37/Global_pollinator_decline_literature_review_2007.pdf
150. The Great Apes Survival Partnership [GRASP] (2016). *Ebola and Great Apes*. United Nations Educational, Scientific & Cultural Organization and United Nations Environment Programme: Paris and Nairobi. <https://www.un-grasp.org/wp-content/uploads/2018/07/GRASPEbolaGreatApes-eng-min.pdf>
151. Rimi, N. A., Sultana, R., Ishtiaq-Ahmed, K., Rahman, M. Z., Hasin, M., Islam, M.S. *et al.* (2016). Understanding the failure of a behavior change intervention to reduce risk behaviors for avian influenza transmission among backyard poultry raisers in rural Bangladesh: A focused ethnography. *BMC Public Health*, 16(1), 858 <https://doi.org/10.1186/s12889-016-3543-6>
152. Mutua, E.N., Bukachi, S.A., Bett, B.K., Estambale, B.A. and Nyamongo, I.K. (2017). “We do not bury dead livestock like human beings”: Community behaviors and risk of Rift Valley Fever virus infection in Baringo County, Kenya. *PLOS Neglected Tropical Diseases*, 11(5), e0005582. <https://doi.org/10.1371/journal.pntd.0005582>
153. Ouma, E., Dione, M., Birungi, R., Lule, P., Mayega, L. and Dizyee, K. (2018). African swine fever control and market integration in Ugandan peri-urban smallholder pig value chains: an ex-ante impact assessment of interventions and their interaction. *Preventive Veterinary Medicine*, 151, 29–39. <https://doi.org/10.1016/j.prevetmed.2017.12.010>
154. Furmanski, M. (2014). *Threatened pandemics and laboratory escapes: Self-fulfilling prophecies*. Bulletin of the Atomic Scientists, 31 March 2014. <https://thebulletin.org/2014/03/threatened-pandemics-and-laboratory-escapes-self-fulfilling-prophecies/#>
155. Siengsan-Lamont, J. and Blacksell, S.D. (2018). A Review of Laboratory-Acquired Infections in the Asia-Pacific: Understanding Risk and the Need for Improved Biosafety for Veterinary and Zoonotic Diseases. *Tropical Medicine and Infectious Disease*, 3(2), 36. <https://doi.org/10.3390/tropicalmed3020036>
156. Welburn, S.C., Beange, I., Ducrotoy, M.J. and Okello, A.L. (2015). The neglected zoonoses—the case for integrated control and advocacy. *Clinical Microbiology and Infection*, 21(5), 433–443. <https://doi.org/10.1016/j.cmi.2015.04.011>
157. Bett, B., Lindahl, J. and Delia, G. (2019). Climate change and infectious livestock diseases: The case of Rift Valley fever and tick-borne diseases. In *The Climate-Smart Agriculture Papers*, Rosenstock T., Nowak A., Girvetz E. (eds). Springer, Cham. 29–37. https://doi.org/10.1007/978-3-319-92798-5_3
158. Pike, B.L., Saylor, K.E., Fair, J.N., LeBreton, M., Tamoufe, U. *et al.* (2010). The origin and prevention of pandemics. *Clinical Infectious Diseases*, 50(12), 1636–1640. <https://doi.org/10.1086/652860>
159. World Health Organisation [WHO] (2016). The International Health Regulations (2005) Third edition. International Organizations Law Review. Geneva, Switzerland: WHO Press. <https://www.who.int/ihr/publications/9789241580496/en/>
160. Liverani, M., Waage, J., Barnett, T., Pfeiffer, D.U., Rushton, J., Rudge, J.W. *et al.* (2013). Understanding and managing zoonotic risk in the new livestock industries. *Environmental Health Perspectives*, 121(8), 873–877. <https://doi.org/10.1289/ehp.1206001>
161. Wicander, S. and Coad, L. (2015). *Learning our lessons: a review of alternative livelihood projects in Central Africa*. Gland: IUCN. <https://doi.org/10.13140/2.1.2993.7287>
162. Wright, J.H., Hill, N.A., Roe, D., Rowcliffe, J.M., Kumpel, N.F., Day, M. *et al.* (2016). Reframing the concept of alternative livelihoods. *Conservation Biology*, 30(1), 7–13. <https://doi.org/10.1111/cobi.12607>
163. Zinsstag, J., Schelling, E., Roth, F., Bonhof, B., De Savigny, D. and Tanner, M. (2007). Human benefits of animal interventions for zoonosis control. *Emerging Infectious Diseases*, 13(4), 527. <https://doi.org/10.3201%2Feid1304.060381>
164. Meyer, A., Holt, H.R., Selby, R. and Guitian, J. (2016). Past and ongoing tsetse and animal trypanosomiasis control operations in five African countries: a systematic review. *PLoS Neglected Tropical Diseases*, 10(12), e0005247. <https://doi.org/10.1371/journal.pntd.0005247>
165. Molyneux, D., Hallaj, Z., Keusch, G.T., McManus, D.P., Ngowi, H., Cleaveland, S. *et al.* (2011). Zoonoses and marginalised infectious diseases of poverty: where do we stand? *Parasites & Vectors*, 4(1), 106. <https://doi.org/10.1186/1756-3305-4-106>
166. Berthe, F.C.J., Bouley, T., Karesh, W.B., Legall, F.G., Machalaba, C.C., Plante, C.A. and Seifman, R.M. (2018). *Operational framework for strengthening human, animal and environmental public health systems at their interfaces*. Washington DC: World Bank Group. <http://documents.worldbank.org/curated/en/703711517234402168/Operational-framework-for-strengthening-human-animal-and-environmental-public-health-systems-at-their-interface>
167. Karesh, W.B., Dobson, A., Lloyd-Smith, J.O., Lubroth, J., Dixon, M.A., Bennett, M. *et al.* (2012). Ecology of zoonoses: natural and unnatural histories. *The Lancet*, 380(9857), 1936–1945. [https://doi.org/10.1016/S0140-6736\(12\)61678-X](https://doi.org/10.1016/S0140-6736(12)61678-X)



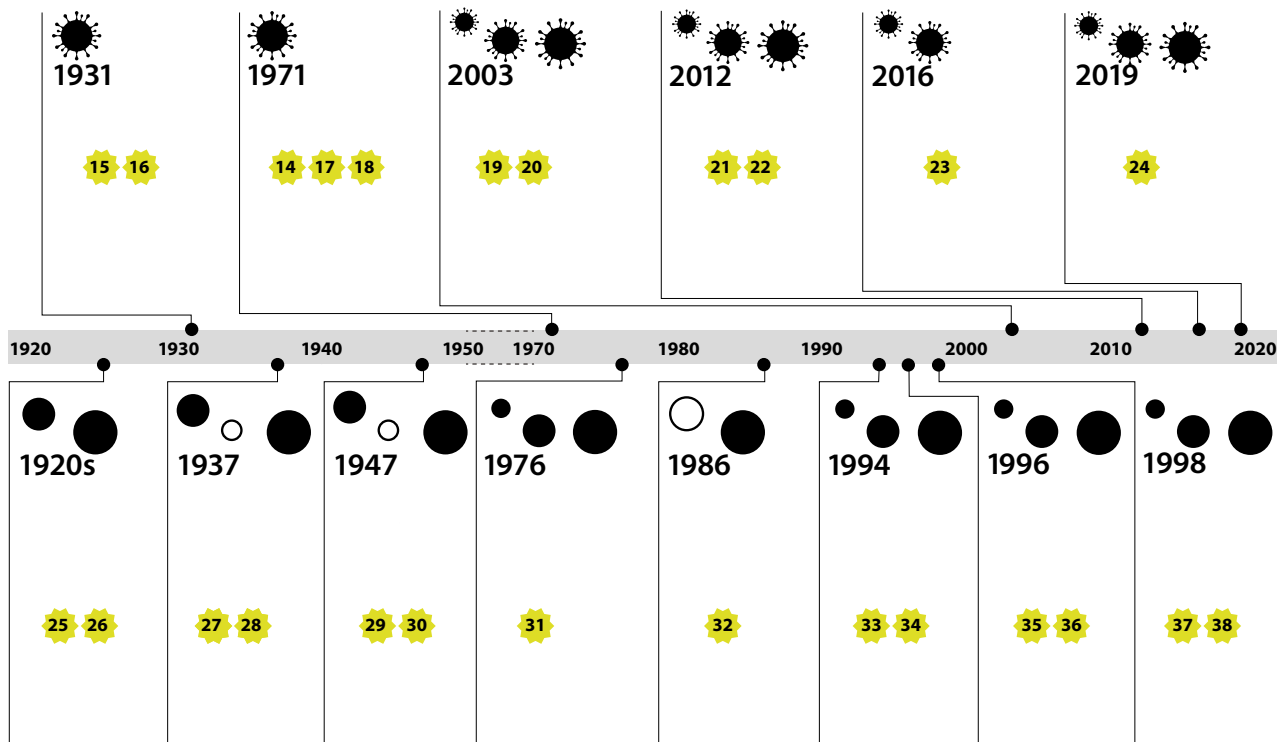
Graphic References



1. Van Bortel, T., Basnayake, A., Wurie, F., Jambai, M., Koroma, A.S., Muana, A.T. *et al.* (2016). Psychosocial effects of an Ebola outbreak at individual, community and international levels. *Bulletin of the World Health Organization*, 94(3), 210. <https://doi.org/10.2471/BLT.15.158543>
2. The World Bank (2016). *2014-2015 West Africa Ebola crisis: Impact update*. The World Bank, Washington DC. <http://pubdocs.worldbank.org/en/297531463677588074/Ebola-Economic-Impact-and-Lessons-Paper-short-version.pdf>
3. Rice, M.E., Galang, R.R., Roth, N.M., Ellington, S.R., Moore, C.A., Valencia-Prado, M. *et al.* (2018). Vital Signs: Zika-Associated Birth Defects and Neurodevelopmental Abnormalities Possibly Associated with Congenital Zika Virus Infection — U.S. Territories and Freely Associated States, 2018. *Morbidity and Mortality Weekly Report*, 67(31), 858-867. <http://dx.doi.org/10.15585/mmwr.mm6731e1>
4. United Nations Development Programme (2017). *A Socio-economic Impact Assessment of the Zika Virus in Latin America and the Caribbean: with a focus on Brazil, Colombia and Suriname*. UNDP, New York. <https://www.ifrc.org/Global/Photos/Secretariat/201702/UNDP-Zika-04-03-2017-English-WEB.pdf>
5. Anyamba, A., Chretien, J., Britch, S.C., Soebiyanto, R.P., Small, J.L., Jepsen, R. *et al.* (2019). Global Disease Outbreaks Associated with the 2015–2016 El Niño Event. *Scientific Report*, 9(1930). <https://doi.org/10.1038/s41598-018-38034-z>
6. Hueffer, K., Drown, D., Romanovsky, V. and Hennessy, T. (2020). Factors contributing to anthrax outbreaks in the Circumpolar North. *EcoHealth*, 17, 174–180. <https://doi.org/10.1007/s10393-020-01474-z>
7. Walsh, M.G., de Smalen, A.D. and Mor, S.M. (2018). Climatic influence on anthrax suitability in warming northern latitudes. *Scientific Reports*, 8, 9269. <https://doi.org/10.1038/s41598-018-27604-w>
8. World Health Organization (2017). 10 facts about neurocysticercosis. April 2017. Accessed 3 June 2020. <https://www.who.int/features/factfiles/neurocysticercosis/en/>
9. World Health Organization (2020). Neglected tropical diseases. Accessed 3 June 2020. https://www.who.int/neglected_diseases/diseases/zoonoses_figures/en/



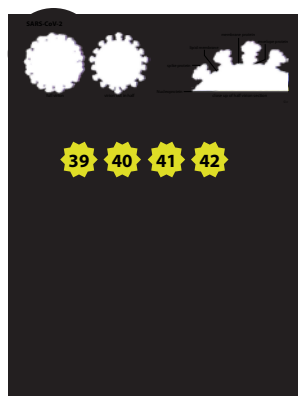
10. Cui, J., Li, F. and Shi, Z.L. (2019). Origin and evolution of pathogenic coronaviruses. *Nature Reviews Microbiology*, 17(3), 181-192. <https://doi.org/10.1038/s41579-018-0118-9>
11. Hu, B., Ge, X., Wang, L. and Shi, Z. (2015). Bat origin of human coronaviruses. *Virology Journal*, 12, 221. <https://doi.org/10.1186/s12985-015-0422-1>
12. Woo, P.C., Lau, S.K., Lam, C.S., Tsang, A.K., Hui, S-W., Fan, R.Y. *et al.* (2013). Discovery of a Novel Bottlenose Dolphin Coronavirus Reveals a Distinct Species of Marine Mammal Coronavirus in Gammacoronavirus. *Journal of Virology*, 88(2), 1318-1331. <https://doi.org/10.1128/JVI.02351-13>
13. Franzo, G., Massi, P., Tucciarone, C.M., Barbieri, I., Tosi, G., Fiorentini, L. *et al.* (2017). Think globally, act locally: Phylodynamic reconstruction of infectious bronchitis virus (IBV) QX genotype (GI-19 lineage) reveals different population dynamics and spreading patterns when evaluated on different epidemiological scales. *PLoS ONE*, 12(9): e0184401. <https://doi.org/10.1371/journal.pone.0184401>
14. Wang, Q., Vlasova, A.N., Kenney, S.P. and Saif, L.J. (2019). Emerging and re-emerging coronaviruses in pigs. *Current Opinion in Virology*, 34, 39–49. <https://doi.org/10.1016/j.coviro.2018.12.001>



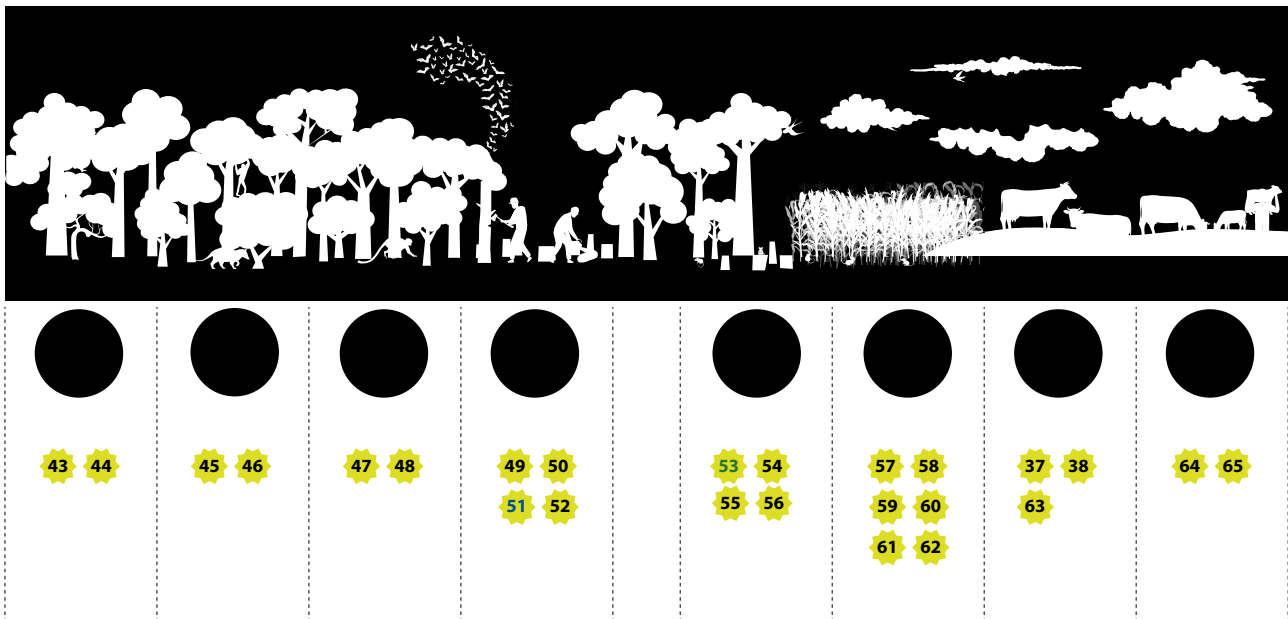
15. Cook, J.K.A., Jackwood, M. and Jones, R.C. (2012). The long view: 40 years of infectious bronchitis research. *Avian Pathology*, 41(3), 239-250. <https://doi.org/10.1080/03079457.2012.680432>
16. Jackwood, M.W. (2012). Review of infectious bronchitis virus around the world. *Avian Diseases*, 56(4), 634-641. <https://doi.org/10.1637/10227-043012-Review.1>
17. World Organisation for Animal Health (2014). Infection with porcine epidemic diarrhoea virus. OIE Technical Factsheet, September 2014. https://www.oie.int/fileadmin/Home/fr/Media_Center/docs/pdf/factsheet_PEDV.pdf
18. Lee, C. (2015). Porcine epidemic diarrhea virus: An emerging and re-emerging epizootic swine virus. *Virology Journal*, 12, 193. <https://doi.org/10.1186/s12985-015-0421-2>
19. Lau, S.K., Woo, P.C., Li, K.S., Huang, Y., Tsoi, H.W., Wong, B.H. et al. (2005). Severe acute respiratory syndrome coronavirus-like virus in Chinese horseshoe bats. *Proceedings of the National Academy of Sciences*, 102, 14040-14045. <https://doi.org/10.1073/pnas.0506735102>
20. Li, W., Shi, Z., Yu, M., Ren, W., Smith, C., Epstein, J.H. et al. (2005). Bats are natural reservoirs of SARS-like coronaviruses. *Science*, 310, 676-679. <https://doi.org/10.1126/science.1118391>
21. El-Kafrawy, S.A., Corman, V.M., Tolah, A.M., Al Masaudi, S.B., Hassan, A.M., Müller, M.A. et al. (2019). Enzootic patterns of Middle East respiratory syndrome coronavirus in imported African and local Arabian dromedary camels: a prospective genomic study. *The Lancet*, 3(12), E521-E528. [https://doi.org/10.1016/S2542-5196\(19\)30243-8](https://doi.org/10.1016/S2542-5196(19)30243-8)
22. Reusken, C.B., Raj, V.S., Koopmans, M.P. and Haagmans, B.L. (2016). Cross host transmission in the emergence of MERS coronavirus. *Current Opinion in Virology*, 16, 55-62. <http://dx.doi.org/10.1016/j.coviro.2016.01.004>
23. Zhou, P., Fan, H., Lan, T., Yang, X-L., Shi, W-F., Zhang, W. et al. (2018). Fatal swine acute diarrhoea syndrome caused by an HKU2-related coronavirus of bat origin. *Nature*, 556, 255-258. <https://doi.org/10.1038/s41586-018-0010-9>
24. Zhou, P., Yang, X. Lou, Wang, X. G., Hu, B., Zhang, L., Zhang, W. et al. (2020). A pneumonia outbreak associated with a new coronavirus of probable bat origin. *Nature*, 579(7798), 270-273. <https://doi.org/10.1038/s41586-020-2012-7>
25. Sharp, P. M. and Hahn, B. H. (2010). The evolution of HIV-1 and the origin of AIDS. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365: 2487-2494. <https://doi.org/10.1098/rstb.2010.0031>
26. Faria, N.R., Rambaut, A., Suchard, M.A., Baele, G., Bedford, T., Ward, M.J. et al. (2014). HIV epidemiology. The early spread and epidemic ignition of HIV-1 in human populations. *Science*, 346(6205), 56-61. <https://doi.org/doi:10.1126/science.1256739>
27. McLean, R.G., Ubico, S.R., Docherty, D.E., Hansen, W.R., Sileo, L. and McNamara, T.S. (2001). West Nile virus transmission and ecology in birds. *Annals of the New York Academy of Sciences*, 951(1), 54-57. <https://doi.org/10.1111/j.1749-6632.2001.tb02684.x>
28. Colpitts, T.M., Conway, M.J., Montgomery, R.R. and Fikrig, E. (2012). West Nile virus: Biology, transmission, and human infection. *Clinical Microbiology Reviews*, 25(4), 635-648. <https://doi.org/10.1128/CMR.00045-12>
29. Gubler, D.J., Vasilakis, N. and Musso, D. (2017). History and emergence of Zika virus. *The Journal of Infectious Diseases*, 216(Suppl 10), S860-S867. <https://doi.org/10.1093/infdis/jix451>



- 30. World Health Organization (2020). The history of Zika virus. Accessed 3 June 2020. <https://www.who.int/emergencies/zika-virus/timeline/en/>
- 31. World Health Organization (2020). Ebola virus disease. Accessed 3 June 2020. <https://www.who.int/news-room/fact-sheets/detail/ebola-virus-disease>
- 32. World Organisation for Animal Health (2018). Bovine spongiform encephalopathy (BSE). Accessed 3 June 2020. <https://www.oie.int/en/animal-health-in-the-world/animal-diseases/Bovine-spongiform-encephalopathy/>
- 33. Walsh, M.G., Wiethoelter, A. and Haseeb, M.A. (2017). The impact of human population pressure on flying fox niches and the potential consequences for Hendra virus spillover. *Scientific Reports*, 7, 8226. <https://doi.org/10.1038/s41598-017-08065-z>
- 34. Boardman, W.S., Baker, M.L., Boyd, V., Crameri, G., Peck, G.R., Reardon, T. *et al.* (2020) Seroprevalence of three paramyxoviruses; Hendra virus, Tioman virus, Cedar virus and a rhabdovirus, Australian bat lyssavirus, in a range expanding fruit bat, the Grey-headed flying fox (*Pteropus poliocephalus*). *PLoS ONE*, 15(5), e0232339. <https://doi.org/10.1371/journal.pone.0232339>
- 35. Webster, R.G., Peiris, M., Chen, H. and Guan, Y. (2006). H5N1 Outbreaks and Enzootic Influenza. *Emerging Infectious Diseases*, 12(1), 3–8. <https://doi.org/10.3201/eid1201.051024>
- 36. Sonnberg, S., Webby, R.J. and Webster, R.G. (2013). Natural History of Highly Pathogenic Avian Influenza H5N1. *Virus Research*, 178(1), 63–77. <https://doi.org/10.1016/j.virusres.2013.05.009>
- 37. Daszak, P., Plowright, R., Epstein, J.H., Pulliam, J., Abdul Rahman, S., Field, H.E. *et al.* (2006). The emergence of Nipah and Hendra virus: pathogen dynamics across a wildlife-livestock-human continuum. In *Disease ecology: community structure and pathogen dynamics*, Collinge, S. and Ray, S. (eds), 186–201. Oxford (UK): Oxford University Press. <https://doi.org/10.1093/acprof:oso/9780198567080.001.0001>
- 38. Epstein, J.H., Field, H.E., Luby, S., Pulliam, J.R. and Daszak, P. (2006). Nipah virus: Impact, origins, and causes of emergence. *Current Infectious Disease Reports*, 8(1), 59–65. <https://doi.org/10.1007/s11908-006-0036-2>



- 39. Cyranoski, D. (2020). Profile of a killer: the complex biology powering the coronavirus pandemic, 4 May. <https://www.nature.com/articles/d41586-020-01315-7>
- 40. Hoffmann, M., Kleine-Weber, H., Schroeder, S., Krüger, N., Herrler, T. and Erichsen, S. *et al.* (2020). SARS-CoV-2 Cell Entry Depends on ACE2 and TMPRSS2 and Is Blocked by a Clinically Proven Protease Inhibitor. *Cell*, 181(2), 271–280.e8. <https://doi.org/10.1016/j.cell.2020.02.052>
- 41. UK Research and Innovation (2020). Getting to know the new coronavirus. Accessed 3 June 2020. <https://coronavirusexplained.ukri.org/en/article/cad0010/>
- 42. Zimmer, K. (2020). Why Some COVID-19 Cases Are Worse than Others, 24 February. <https://www.the-scientist.com/news-opinion/why-some-covid-19-cases-are-worse-than-others-67160>
- 43. Olivero, J., Fa, J. E., Real, R., Márquez, A. L., Farfán, M. A., Vargas, J.M. *et al.* (2017). Recent loss of closed forests is associated with Ebola virus disease outbreaks. *Scientific Reports*, 7, 14291. <https://doi.org/10.1038/s41598-017-14727-9>
- 44. Rulli, M.C., Santini, M., Hayman, D.T.S. and D'Odorico, P. (2017). The nexus between forest fragmentation in Africa and Ebola virus disease outbreaks. *Scientific Reports*, 7, 41613. <https://doi.org/10.1038/srep41613>
- 45. Vaz, V.C., D'Andrea, P.S. and Jansen, A.M. (2007). Effects of habitat fragmentation on wild mammal infection by *Trypanosoma cruzi*. *Parasitology*, 134(12), 1785–1793. <https://doi.org/10.1017/S003118200700323X>
- 46. Xavier, S.C.dC., Roque, A.L., Lima, V.dS., Monteiro, K.J., Otaviano, J.C. *et al.* (2012). Lower richness of small wild mammal species and Chagas disease risk. *PLOS Neglected Tropical Diseases*, 6(5), e1647. <https://doi.org/10.1371/journal.pntd.0001647>
- 47. Goldberg TL, Gillespie TR, Rwego IB, Estoff EL, Chapman CA (2008). Forest fragmentation as cause of bacterial transmission among nonhuman primates, humans, and livestock, Uganda. *Emerging Infectious Diseases*, 14(9), 1375–1382. <https://doi.org/10.3201/eid1409.071196>
- 48. Rwego, I.B., Isabirye-Basuta, G., Gillespie, T.R. and Ggoldberg, T.L. (2008). Gastrointestinal bacterial transmission among humans, mountain gorillas, and livestock in Bwindi Impenetrable National Park, Uganda. *Conservation Biology*, 22(6), 1600–1607. <https://doi.org/10.1111/j.1523-1739.2008.01018.x>
- 49. Field, H.E. (2009). Bats and Emerging Zoonoses: Henipaviruses and SARS. *Zoonoses and Public Health*, 56(6–7), 278–284. <https://doi.org/10.1111/j.1863-2378.2008.01218.x>



50. Pongsiri, M.J., Roman, J., Ezenwa, V.O., Goldberg, T.L., Koren, H.S., Newbold, S.C. *et al.* (2009). Biodiversity loss affects global disease ecology. *BioScience*, 59(11), 945–954. <https://doi.org/10.1525/bio.2009.59.11.6>
51. McFarlane, R.A., Sleight, A.C. and McMichael, A.J. (2013). Land-use change and emerging infectious disease on an island continent. *International Journal of Environmental Research and Public Health*, 10(7), 2699–2719. <https://doi.org/10.3390/ijerph10072699>
52. Walsh, M.G., Wiethoelter, A. and Haseeb, M.A. (2017). The impact of human population pressure on flying fox niches and the potential consequences for Hendra virus spillover. *Scientific Reports*, 7(8226). <https://doi.org/10.1038/s41598-017-08065-z>
53. Young, H.S., Dirzo, R., Helgen, K.M., McCauley, D.J., Billeterd, S.A., Kosoy, M.Y. *et al.* (2014). Declines in large wildlife increase landscape-level prevalence of rodent-borne disease in Africa. *Proceedings of the National Academy of Sciences*, 111(19), 7036–7041. <https://doi.org/10.1073/pnas.1404958111>
54. Young, H.S., Dirzo, R., Helgen, K.M., McCauley, D.J., Nunn, C.L., Snyder, P. *et al.* (2016). Large wildlife removal drives immune defence increases in rodents. *Functional Ecology*, 30, 799–807. <https://doi.org/10.1111/1365-2435.12542>
55. Titcomb, G., Allan, B.F., Ainsworth, T., Henson, L., Hedlund, T., Pringle, R.M. *et al.* (2017). Interacting effects of wildlife loss and climate on ticks and tick-borne disease. *Proceedings of the Royal Society B: Biological Sciences*, 284, 20170475. <http://dx.doi.org/10.1098/rspb.2017.0475>
56. Mendoza, H., Rubio, A.V., García-Peña, G.E., Suzán, G. and Simonetti, J.A. (2020). Does land-use change increase the abundance of zoonotic reservoirs? Rodents say yes. *European Journal of Wildlife Research*, 66(6). <https://doi.org/10.1007/s10344-019-1344-9>
57. LaDeau, S., Kilpatrick, A. and Marra, P. (2007). West Nile virus emergence and large-scale declines of North American bird populations. *Nature*, 447, 710–713. <https://doi.org/10.1038/nature05829>
58. Allan, B.F., Langerhans, R.B., Ryberg, W.A., Landesman, W.J., Griffin, N.W., Katz, R.S. *et al.* (2009). Ecological correlates of risk and incidence of West Nile virus in the United States. *Oecologia*, 158, 699–708. <https://doi.org/10.1007/s00442-008-1169-9>
59. Keesing, F., Belden, L.K., Daszak, P., Dobson, A., Harvell, C.D., Holt, R.D. *et al.* (2010). Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature*, 468, 647–652. <https://doi.org/10.1038/nature09575>
60. George, R.L., Harrigan, R.J., LaManna, J.A., DeSante, D.F., Saracco, J.F. and Smith, T.B. (2015). Persistent impacts of West Nile virus on North American bird populations. *Proceedings of the National Academy of Sciences*, 112 (46), 14290–14294. <https://doi.org/10.1073/pnas.1507747112>
61. Kilpatrick, A.M. and Wheeler, S.S. (2019). Impact of West Nile virus on bird populations: Limited lasting effects, evidence for recovery, and gaps in our understanding of impacts on ecosystems. *Journal of Medical Entomology*, 56(6), 1491–1497. <https://doi.org/10.1093/jme/tjz149>
62. Byas, A.D. and Ebel, G.D. (2020). Comparative pathology of West Nile virus in humans and non-human animals. *Pathogens*, 9(48). <https://doi.org/10.3390/pathogens9010048>
63. Loh, E.H., Murray, K.A., Nava, A., Aguirre, A.A. and Daszak, P. (2016). Evaluating the links between biodiversity, land-use change, and infectious disease emergence in tropical fragmented landscapes. In *Tropical Conservation: Perspectives on Local and Global Priorities*. Aguirre, A.A. and Sukumar, R. (eds.). Oxford University Press, New York City.
64. Grace, D. (2015). Food safety in low and middle income countries. *International Journal of Environmental Research and Public Health*, 12, 10490–10507. <https://doi.org/10.3390/ijerph120910490>
65. Rohr, J.R., Barrett, C. B., Civitello, D. J., Craft, M. E., Delius, B., DeLeo, G. *et al.* (2019). Emerging human infectious diseases and the links to global food production. *Nature Sustainability*, 2, 445–456. <https://doi.org/10.1038/s41893-019-0293-3>



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 trypanosomiasis (also spelled 'trypanosomiasis'): A disease of livestock ('African animal trypanosomiasis') 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 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 leishmaniasis—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 trematodiasis, human African trypanosomiasis, 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 *n*th 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 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](#)

