# The COVID-19 pandemic is intricately linked to biodiversity loss and ecosystem health

*Odette K Lawler, Hannah L Allan, Peter W J Baxter, Romi Castagnino, Marina Corella Tor, Leah E Dann, Joshua Hungerford, Dibesh Karmacharya, Thomas J Lloyd, María José López-Jara, Gloeta N Massie, Junior Novera, Andrew M Rogers, Salit Kark*

**The ongoing COVID-19 pandemic, caused by zoonotic SARS-CoV-2, has important links to biodiversity loss and ecosystem health. These links range from anthropogenic activities driving zoonotic disease emergence and extend to the pandemic affecting biodiversity conservation, environmental policy, ecosystem services, and multiple conservation facets. Crucially, such effects can exacerbate the initial drivers, resulting in feedback loops that are likely to promote future zoonotic disease outbreaks. We explore these feedback loops and relationships, highlighting known and potential zoonotic disease emergence drivers (eg, land-use change, intensive livestock production, wildlife trade, and climate change), and discuss direct and indirect effects of the ongoing pandemic on biodiversity loss and ecosystem health. We stress that responses to COVID-19 must include actions aimed at safeguarding biodiversity and ecosystems, in order to avoid future emergence of zoonoses and prevent their wide-ranging effects on human health, economies, and society. Such responses would benefit from adopting a One Health approach, enhancing cross-sector, transboundary communication, as well as from collaboration among multiple actors, promoting planetary and human health.**

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**The Biodiversity Research Group, School of Biological Sciences, Centre for Biodiversity and Conservation Science** (O K Lawler MConsBiol, H L Allan BSc (Hons), P W J Baxter PhD, R Castagnino MConsSci, M Corella Tor MSci, L E Dann MSc, J Hungerford MConsSci, D Karmacharya PhD, T J Lloyd MConsSci, M J López-Jara MSc, G N Massie MSc, J Novera MSc, A M Rogers PhD, Prof Salit Kark PhD)**, and School of Earth and Environmental Sciences** (T J Lloyd, M J López-Jara)**, The University of Queensland, Brisbane, QLD, Australia; Center for Molecular Dynamics Nepal, Kathmandu, Nepal** (D Karmacharya)

Correspondence to: Prof Salit Kark, The Biodiversity Research Group, School of Biological Sciences, Centre for Biodiversity and Conservation Science, The University of Queensland, Brisbane 4072, QLD, Australia
**s.kark@uq.edu.au**

## Biodiversity loss and ecosystem health are strongly linked to human health

The emergence of a zoonotic pathogen in humans, such as SARS-CoV-2, was not unpredicted.[1–3] Of the novel or re-emerging infectious diseases affecting humans in the 21st century, most (75%) have been zoonotic in origin,[4,5] with their natural reservoirs being other vertebrates.[6] The majority (over 70%) of these diseases with zoonotic origin have originated from wildlife,[7] such as HIV/AIDS, the Ebola virus, and severe acute respiratory syndrome (SARS).[4] Globally, known events of zoonotic disease emerging from wildlife have significantly increased over the past 80 years,[7,8] raising public health, economic, societal and environmental concerns, as exemplified by the COVID-19 pandemic.[9–12] The current weight of evidence suggests that SARS-CoV-2, or its progenitor,[13,14] probably emerged in humans from a zoonotic source in Wuhan, China, where it was first identified in 2019.[13–16] Although evidence on the origins of SARS-CoV-2 are inconclusive, bats have been suggested to be the most probable evolutionary source for the virus.[14,16–18] Alignment of the full-length genome sequence of SARS-CoV-2 showed the closest relationship (identity 96%) was with the bat SARS-like coronavirus strain BatCov RaTG13.[14,17,18] An unknown intermediate host might have played a role in the emergence of SARS-CoV-2 in humans.[16,17] Pangolins were initially cited as the potential intermediate hosts,[19] yet evidence has since challenged their potential role,[15,16,20,21] and identified a range of potential animal hosts (including mink, rabbits, raccoon dogs, civets, ferret badgers, snakes, and domesticated cats).[14,16] Direct spillover of SARS-CoV-2 or its progenitor to humans from a bat host has also been proposed as a possibility (appendix pp 1–2).[13,14,16] Further research is deemed necessary to determine the exact SARS-CoV-2 evolution and transmission pathways.[13,14,17,21,22]

See Online for appendix

Cross-species pathogen transmission events, or so-called spillover events, arise when pathogens exploit new niches, enabled by increased host exposure or acquisition of favourable variations. Spillover events are affected by biological, ecological, and evolutionary characteristics of both pathogens and hosts, and by environmental factors.[4,23,24] In the context of pathogen spillover to human populations, anthropogenic activities related to social, cultural, and economic human behaviour promote the human–animal interface, a suite of complex interactions between humans and other animals that frequently

### Key messages

- Multiple anthropogenic drivers promote zoonotic pathogen spillover and disease emergence, such as land-use change, intensive livestock production, wildlife trade, and climate change
- Effects of the COVID-19 pandemic on biodiversity and ecosystem health can exacerbate drivers of zoonotic and infectious disease emergence, increasing the risk for future zoonotic pathogen spillover events and possible public health crises; these cyclic relationships create a positive feedback loop
- Biodiversity and ecosystem health effects of COVID-19 are diverse and interconnected, and include effects on conservation funding, tourism, environmental policy, Indigenous land managers, and human-wildlife contact
- Decision makers should consider how actions and strategies in response to COVID-19 could affect drivers of zoonotic disease, biodiversity, and ecosystem health, and urgently act to minimise their negative effects and feedback loops
- A One Health collaborative approach, decision science, and sustainable pandemic recovery strategies provide important tools for addressing both the COVID-19 pandemic recovery globally and future zoonotic spillover risk, while taking into account biodiversity and ecosystem health

provide the opportunity for pathogens to cross the interspecific boundary.[8,23,24]

**Anthropogenic drivers of zoonotic disease emergence**

Multiple human-mediated environmental changes and activities have been found to be key drivers of zoonotic disease emergence, promoting the conditions in which zoonoses can emerge.[4,5,25,26] Such drivers include, for example, land-use change, intensive livestock production, wildlife trade, and anthropogenic climate change,[5] all of which have been linked to multiple zoonotic disease outbreaks in humans (appendix pp 4–7).

## Land-use change

Land-use change often involves the encroachment of human activity into wildlife habitat resulting from urban expansion and infrastructure development, agriculture and livestock farming, hydrological alteration, natural resource extraction, and other practices. Land-use change can often result in environmental alterations, such as deforestation and habitat fragmentation.[27,28] Such anthropogenic disturbances can affect pathogen transmission dynamics by changing ecological community composition, population structure, vector ecology, host abundance, host behaviour, and immunity. This effect can alter host exposure, susceptibility, and transmission rates of pathogens.[29] Through these alterations, destruction and degradation of habitats often lead to an increased interface for wild host, vector, and human interactions, potentially facilitating zoonotic pathogen spillover to new hosts, including humans.[28–32] Land-use change can forge new pathways for direct human–wildlife interactions, for example, by facilitating access of poachers engaged in the wildlife trade to previously less accessible natural environments.[33,34] When land is converted for agriculture and other uses, boundary and edge areas between natural ecosystems and human-modified areas often increase.[35,36] This change provides additional opportunity for pathogen spillover and adaptation to new hosts,[35,37] and has been involved in the emergence pathway of several zoonotic diseases, such as rabies, yellow fever, and the Ebola virus.[35] A 2020 study in Uganda's Kibale National Park found that landscape fragmentation, including higher densities of edges and forest core loss due to deforestation, is associated with increased interactions between humans and non-human primates, enhancing opportunity for spillover of zoonotic pathogens.[38]

## Intensive livestock production

The intensification and expansion of agriculture, largely stimulated by the growing demand for animal protein and products globally, is a major factor shaping land-use change, which creates opportunities for livestock to facilitate zoonotic pathogen spillover events.[5] Encroachment of livestock production activities into natural and semi-natural habitats provides unintended avenues for pathogens to spread from the wild pathogen hosts to humans (through direct, indirect, or vector-facilitated pathways), via domestic animals, which have been identified to play a key role in cross-species transmission of zoonotic pathogens in the past.[32] For example, domestic pigs can act both as amplifying and intermediate hosts in the transmission of influenza,[39] Nipah virus,[40] and Japanese encephalitis.[41] In these cases, they maintain and multiply the virus within populations—potentially also enabling the evolution of novel strains through genetic reassortment—and subsequently can transmit these viruses to humans. As livestock production practices are increasingly intensified globally, livestock and poultry are kept in increasingly crowded conditions, and, in some cases, are bred with higher genetic homogeneity, enhancing their vulnerability to pathogens.[5,37] Movement of people between farms and urban areas also increases with agricultural intensification, including livestock production, which further increases the risk of transmission events.[37]

## Wildlife trade

Wildlife trade involves the harvest, transport, buying, selling, or other exchange of wild animals and their products.[42] In both its legal and illegal forms, wildlife trade brings animals into direct and indirect contact with humans, domestic animals and other species outside of their normal interactions in the wild.[43] This contact provides the context for new intra-specific and inter-specific pathogen transmission events, including spillover to humans, as hunters, traders, handlers, and consumers interact directly and indirectly with wild animals.[25,44] Humans could act as a so-called dead-end host, with no substantial human-to-human transmission occurring, or alternatively, pathogens can be transmitted and spread within human populations, leading to infectious disease outbreaks or epidemics.[23]

## Climate change

Anthropogenic climate change affects the incidence of zoonotic disease emergence in humans, as shifting climatic conditions drive alterations in both host and vector spatial distributions, population densities, pathogen load in individuals, and the prevalence of pathogens in potential animal reservoirs.[45] Climate change can also affect the interactions between reservoir hosts, intermediate hosts, vectors, and pathogens,[46,47] and drive the evolution of pathogens, and, where relevant, their hosts and vectors.[45,48] All of these factors can, individually or combined, affect the transmission dynamics between pathogen hosts and can influence the likelihood of the emergence of a zoonotic disease in human populations.[48] The effects of climate change are especially relevant for vector-borne zoonotic diseases, including many already established in the human population, such as mosquito-borne Rift Valley fever and West Nile fever.[45,46,49,50]

Considering the increasing trend of zoonosis emergence and the ongoing COVID-19 pandemic,[7,8] along with mounting evidence indicating that human-mediated factors drive spillover events,[4,28,31,45,51] it is paramount to examine how the drivers of zoonotic disease emergence are indirectly affected by the COVID-19 pandemic and its associated economic, social, and environmental fallout.

Land-use change, intensive livestock production, wildlife trade, and climate change are dynamic processes that vary in magnitude, extent, and attributes over space and time as they interact with and are altered by each other and external factors.[52] These complex interactions have implications for the various drivers and their impacts on zoonotic disease emergence (figure 1). Figure 2 illustrates the interconnectedness of the drivers with additional dimensions affected by the COVID-19 health crisis, all of which relate in some way to the state of biodiversity and ecosystems (appendix pp 11–21). Crucially, adverse effects exacerbate drivers of zoonosis emergence, thus increasing the risks for future zoonotic disease events (figure 1).

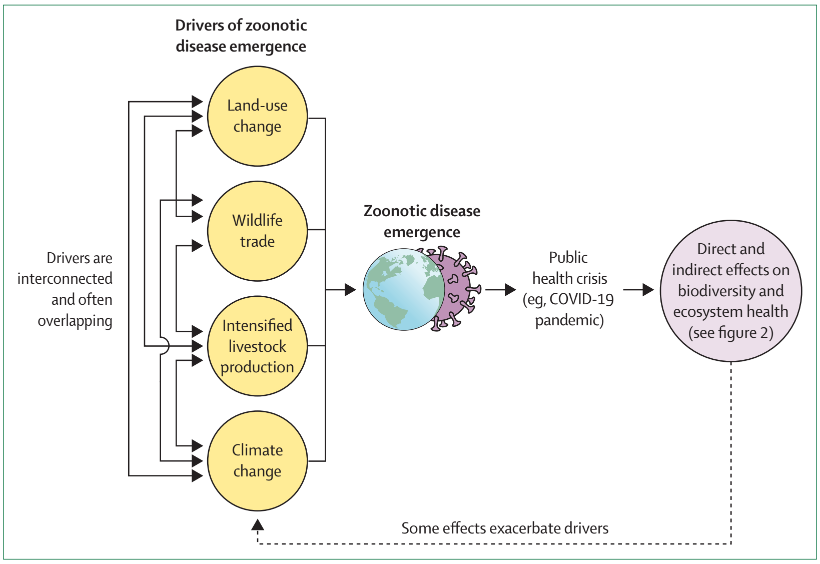


*Figure 1:* **Zoonotic disease emergence feedback loop**
Key anthropogenic drivers of zoonotic disease emergence (eg, including land-use change, wildlife trade, intensive livestock production, and climate change) increase the likelihood of zoonotic disease emergence, which could result in public health crises, such as the COVID-19 pandemic. Such crises could have negative effects on biodiversity and ecosystem health, as COVID-19 has had and could continue to have (appendix pp 11–21). These effects can consequently exacerbate the drivers, leading to further emergence of zoonosis and potential future health crises with their own suite of effects. The continuation of this cycle would reinforce a feedback loop with substantial implications for human health, economies, society, and the environment.

## Th effects of the COVID-19 pandemic on biodiversity loss and ecosystem health and drivers of zoonotic disease emergence

Human life across local, regional, and global scales has been greatly affected by the COVID-19 pandemic. As of Oct 25, 2021, more than 243 million confirmed COVID-19 cases and almost 5 million COVID-19-attributed deaths have been reported globally.[53] Despite rapid progress of vaccine development and delivery, many countries are still experiencing high transmission rates and repeated resurgences with new SARS-CoV-2 variants arising.[53] Since early 2020, in an attempt to reduce spread, countries worldwide have enforced varying degrees of travel restrictions, with approximately 75% of nations completely shutting down their borders at some point.[11,54] Governments globally have implemented a range of quarantine measures and many have reallocated funding to health-related services and industries.[11] Lockdowns, curfews, and restrictions of a range of economic activities deemed non-essential have been enacted. Many industries have required employees to work from home.[55] Simultaneously, governments have been striving to mitigate the inevitable economic, social, and political repercussions of these restrictions, delivering fiscal packages directed toward individuals, as well as public and private sectors.[56] This suite of COVID-19-related activity has broad direct and indirect effects on biodiversity loss and ecosystem health. Identifying the diverse repercussions of such effects is important for better understanding how they might feed back into the drivers of zoonosis emergence and re-emergence (appendix pp 11–21). Many of these effects could further promote the drivers of zoonotic spillover, hence, reinforcing a feedback loop further contributing to the rising trend of disease emergence.[7,8]

### Conservation funding

Among the key areas of impact is the reduced funding for conservation, which was already considerably under_ funded before COVID-19.[57,58] In many cases, conservation is largely funded via governmental and non-governmental organisations, charitable foundations, and other organisations.[59] During economic downturns, charitable donations and government funding for conservation typically decline, as people limit spending, and resources are funnelled towards goods and services deemed more essential. For example, following the 2008 recession, charitable foundation endowments in the USA declined by 25%,[59] and government investment for Spain's Ministry of Agriculture, Food, and Environment declined by 31%, affecting research and conservation programmes.[60] Pergams and colleagues[61] determined that gross domestic product and personal income can help predict conservation spending, including conservation-focused land purchases, national parks visitation, university programmes in the conservation field and membership in professional conservation organisations, suggesting that diminished gross domestic product and income can lead to reductions in these indicators.[61]

In a Wildlife and Countryside Link survey from March, 2020,[62] estimated losses due to COVID-19 for 23 responding organisations were already greater than US$100 million, not inclusive of future losses from decreased grant opportunities. Reduced funding for conservation has been substantial in many locations,[63] impeding effective global biodiversity conservation, including achieving UN Aichi biodiversity targets, and issues such as deforestation, wildlife poaching, and greenhouse gas emissions.[64] The $343 billion global wildlife tourism industry[65] has been substantially affected

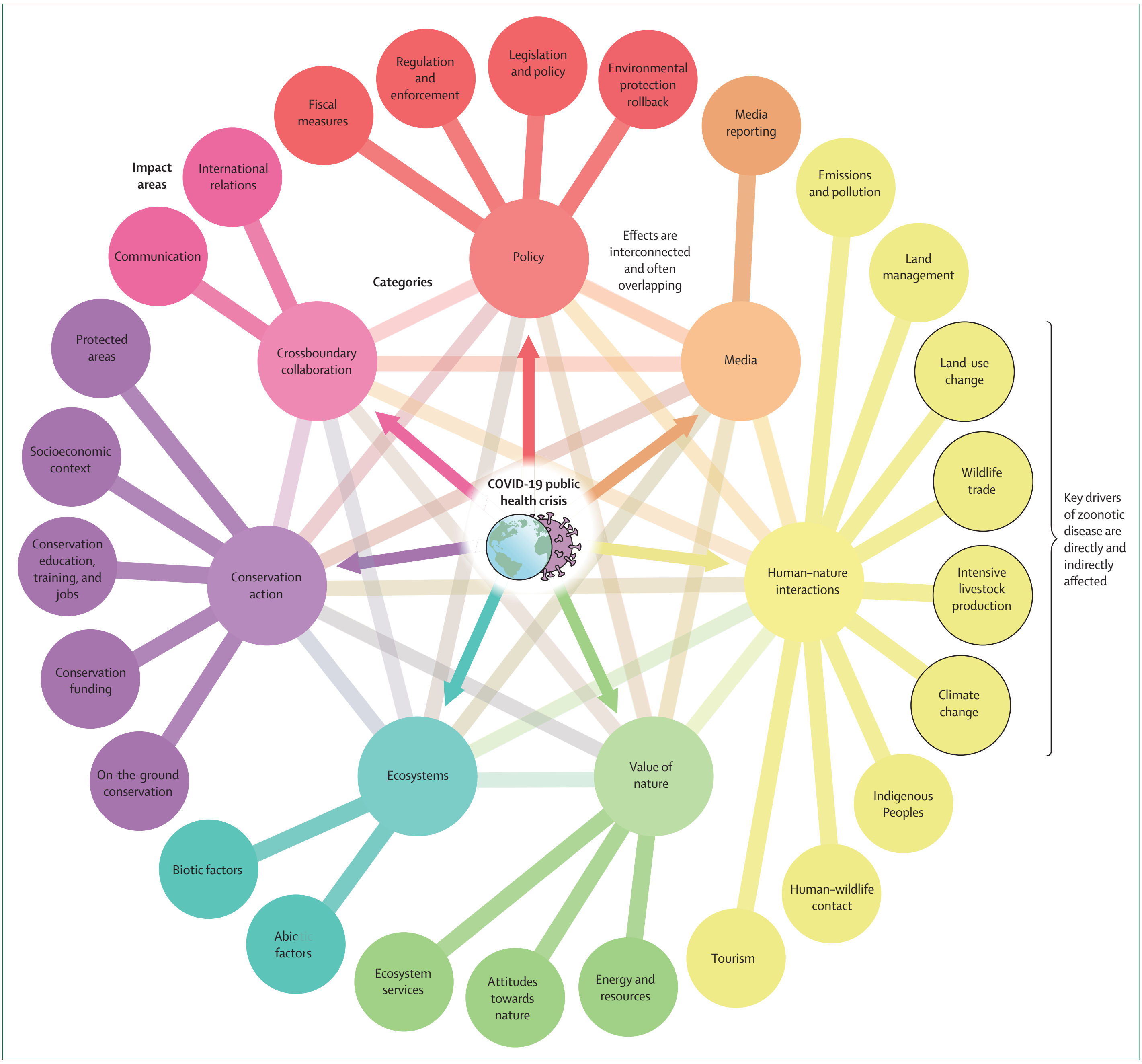


*Figure 2:* **Effects of the COVID-19 public health crisis related to biodiversity loss and ecosystem health**
The figure shows multiple interconnected areas related to biodiversity loss and ecosystem health, which have been or are likely to be affected by the COVID-19 pandemic. The impact areas (outer circle) were assembled into seven categories (inner circle; connected via corresponding colours to relevant impact areas) for ease of visualisation and interpretation. Impacts areas could, in reality, correspond to multiple categories. The human-nature interactions category includes the key drivers of zoonotic disease emergence—land-use change, intensive livestock production, wildlife trade, and climate change, as shown in figure 1. Semi-transparent lines between categories show that effects are interlinked, with many effects directly or indirectly affecting others, including the drivers of zoonotic disease emergence. See appendix (pp 11–21) for a selection of effects of the COVID-19 pandemic on biodiversity and ecosystem health, organised by impact categories and impact areas.

by the COVID-19 pandemic[66] with income shock affecting households throughout a range of countries and regions with high biodiversity,[66] and wildlife-related tourism activity entirely vanishing in some locations.[63] For example, in Kenya, tourism to Tsavo National Park generates a mainstream revenue for the Kenya Wildlife Service, whose operations are crucial to wildlife protection, protected area establishment, and anti-poaching enforcement.[67] Tsavo Trust reported a 50% reduction in their capacity to operate in March, 2020,[67] which could substantially disrupt conservation work for years to come. Such disruptions can lead to increased illegal resource extraction and wildlife poaching that feeds into the illegal trade, both as a result of diminished capacity to patrol protected areas, and severe reductions in income that wildlife tourism provides to millions worldwide.[57] Although data on the effects is still being collected for some of these cases, there have already been increased instances of poaching and illegal resource harvesting, although, these trends might not be universal.[57]

## Lockdown effects

Lockdowns and restrictions to human movement have had diverse effects, with consequences for biodiversity and ecosystems. On the one hand, they have reduced tourism pressure in many areas, but on the other hand, they have simultaneously disrupted important environmental conservation programmes.[68] For example, the Australian Antarctic Division experienced COVID-19-related project delays, reduced capacity to train and deploy expedition teams,[69] and scaled back their 2020–21 summer expedition, potentially undermining the realisation of research goals.[70] These changes came as Antarctica's 2019–20 summer temperatures were substantially above average,[71] concluding the Earth's hottest decade ever recorded.[72,73] This disruption and similar other interferences could compromise the accuracy and continuity of climate research that is required to both guide and measure progress on reducing greenhouse emissions, and impede mitigation of climate change's effects on disease emergence.[47] Although economic shutdowns initially led to some significant reductions in air pollution and $CO_2$ emissions around the world,[74,75] emissions declined less than expected by climate researchers and rose substantially again as 2020 progressed.[76] A continued surge of activity aimed at economic recovery as social lockdowns and economic shutdowns are relaxed could probably negate the benefits of a short pause in human activity unless managed correctly.[56]

## Rural and low-income populations

Also relevant to biodiversity loss and ecosystem health, and ultimately zoonotic disease drivers, are the effects of COVID-19 on the world's rural and low-income populations. Due to financial, cultural, and a host of other factors, people in some cases participate in activities promoting deforestation and wildlife trade to support their livelihoods. Research on the effects of the Global Financial Crisis in Cameroon, for example, showed multiple effects on livelihood and biodiversity indicators.[77] Although global demand for timber products decreased, workers laid-off from the logging industry turned to poaching and slash and burn agriculture.[77] As the economy recovered in 2010–11, biodiversity indicators improved more slowly than livelihood indicators, suggesting a lag in environmental recovery following the events.[77] Understanding previous examples can help forecast and prepare for the future trajectories of environmental health recovery from COVID-19 effects. Addressing issues specific to the world's low-income and rural populations is required to prevent adverse results for these groups, and flow-on effects for the environment, which ultimately could increase the risks for zoonosis emergence in the future.

## Indigenous Peoples and biodiversity

Indigenous Peoples own or are involved in the management of around 40% of the world's terrestrial protected areas.[78] Indigenous Peoples' engagement in biodiversity conservation corresponds with: (1) enhanced conservation outcomes for many of the world's most biodiverse regions; (2) more innovative and cost-effective conservation and management; (3) support of climate change abatement objectives; and (4) realisation of Indigenous Peoples' interests.[79] Inadequate efforts to protect Indigenous communities from COVID-19 and related issues are evident in regions such as the Brazilian Amazon[63,80] and in Canada, where conflicts between the interests of Indigenous Peoples and extractive industries have intensified during the pandemic.[81] Such inadequacies are not only damaging to the wellbeing of Indigenous People in many areas around the world, but can also feed back into the key drivers of zoonotic disease emergence. As a result, ecosystems managed by Indigenous Peoples could become more susceptible to land-use change from resource extraction and agriculture,[27,63] more accessible to those engaged in the wildlife trade,[33,63] and the Traditional Knowledge held about biodiversity stewardship and resilience to historic disease outbreaks could be threatened.[82]

## Policy responses to COVID-19

COVID-19 has triggered major changes to policy, legislation, and government interventions around the world.[83] Policy makers' responses to COVID-19 and the associated economic fallout are arguably the most crucial determinants of how biodiversity and ecosystem health have been and could be affected in the near future by the COVID-19 crisis. Policy actions, such as subsidising extractive, agricultural and development industries, can drive fast economic growth but can also exacerbate land-use changes, biodiversity loss, greenhouse gas emissions, and unsustainable agricultural intensification, all of which can drive and contribute to future emerging diseases. For example, deforestation in the Brazilian Amazon has surged during the current administration.[84,85] As of March, 2021, 57 pieces of legislation that weaken existing environmental policies have been signed.[86] The government's pro-development approach during the COVID-19 pandemic has opened native forests to extractive industries, such as agriculture and cattle ranching, with proposals promoting land grabs[87] and mining in Indigenous reserves[88,89] also in the pipeline. Reductions to the Ministry of Environment budget will further affect Brazil's oversight bodies that monitor illegal deforestation, pollution levels, pesticide contamination, illegal mining, and illegal wildlife trafficking.[90] The effects on these activities and their links to wildfires, biodiversity loss, and increased greenhouse gas emissions[86,91] can feed back into increased risk of zoonotic spillover events in Brazil and internationally.

As seen following the fiscal policy implemented around the 2008–09 Global Financial Crisis, governments increased agricultural, industry (eg, mining) and forestry subsidies to protect or boost economies, leading to further biodiversity deterioration.[92] A multitude of international meetings and negotiations relating to biodiversity, conservation, and climate change policy scheduled for 2020 were postponed due to the COVID-19 pandemic,[68] such as the International Union for Conservation of Nature World Conservation Congress 2020,[93] the COP26 UN climate change conference,[94] and the 10th Pacific Islands Conference on Nature Conservation and Protected Areas.[95] These postponements slow international momentum for addressing key issues such as climate change, and combined with rollbacks on existing environmental policy, could be detrimental to multiple areas of biodiversity and ecosystem functioning and conservation, and, in turn, lead to a feedback loop of increased risk of zoonotic disease emergence (figure 2).

### Responsible pandemic recovery action can limit future zoonotic disease risk

It is already evident from the COVID-19 pandemic and past zoonotic disease outbreaks (appendix pp 4–7) that human interactions with nature and wildlife are inextricably linked to human health. Efficient actions are urgently required to address the pandemic's direct and indirect threats to biodiversity and ecosystems to prevent the aggravation of the drivers of zoonotic disease, including land-use change, wildlife trade, intensive livestock production, and climate change (figure 2; appendix pp 11–21). These actions are essential to avoid feedback loops that can lead to future zoonotic disease emergence and possible resulting pandemics (figure 1). Efforts to address COVID-19's many effects on biodiversity and ecosystem health are insufficient (figure 2). This gap largely results from insufficient understanding of the interconnectedness of human and environmental health among policy makers, insufficient cross-boundary collaboration, and deficient resourcing for conservation and ecosystem health. We therefore outline below some key actions that should be taken to mitigate future occurrence.

### Sustainable socioeconomic recovery and conservation investment can minimise future zoonotic disease risk

Sustainable investment strategies, such as investment in conservation, can be utilised to mitigate the COVID-19 pandemic's economic effects while simultaneously addressing drivers of zoonotic disease emergence. The economic downturn associated with the COVID-19 pandemic has seen governments globally reacting with a range of fiscal responses to prevent or alleviate national and regional declines in economic activity and stability.[83] Investment in conservation is crucial for preventing biodiversity declines[64] and for addressing the key drivers of zoonotic disease. Many conservation practices can be directly linked to managing zoonotic disease risk, such as safeguarding remaining tropical forests[36] and protecting predators and scavengers.[96] Directing funding towards conservation actions and promotion of environmental sustainability can be utilised as a recovery mechanism during and following the pandemic, either alongside or as an alternative to other investment strategies, and can be targeted to prevent future zoonotic disease emergence and its potential for substantial global impact. For example, the state government of Western Australia announced in October, 2020, that their COVID-19 recovery plan will include investment of almost AU$67 million over 4 years to increase the state's existing network of protected areas and to fund their Parks and Wildlife Service infrastructure,[97] an action which can bolster the state's tourism sector while simultaneously supporting conservation. Similar fiscal policy approaches could reform existing subsidies for forestry, agriculture, mining, and energy production to better support biodiversity conservation and sustainability.[92]

Redirecting subsidies that do not promote sustainable socioeconomic recovery, and shifting the policies that they promote to fund conservation-centric activities, such as sustainable agriculture, natural capital projects, and new energy technologies, could safeguard industries and economic stability while promoting practices that address zoonotic disease drivers,[92] reducing the risks of future regional and global health crises. For example, global agricultural subsidies alone are estimated at over US$700 billion annually,[98] but commonly drive environmental degradation, unsustainable production, provide insufficient social benefits and do not promote, in some cases, environmental and social responsibility initiatives such as the UN Sustainable Development Goals.[99,100] There are multiple synergies available to explore in the achievement of sustainable development, zoonotic disease risk minimisation, and pandemic recovery, and these should be identified and integrated into national and global policy with urgency.[101] For example, new government subsidies aimed at economic recovery during and following the COVID-19 pandemic provide an opportunity to enable a better balance between swift recovery and long-term biodiversity and ecosystem health targets, which will also support the prevention of future pandemics. These subsidies can help promote job creation in areas such as sustainable agriculture, resource recovery and recycling, clean energy, sustainable urban planning, and ecosystem restoration, and replace some subsidies for activities that, while boosting economies, have trade-offs such as promoting deforestation, wildlife trafficking, livestock disease risk, and increased greenhouse emissions.[101,102]

Hepburn and colleagues[56] identified five fiscal recovery models that have high potential to adequately address both economic multiplier effects and climate effect criteria in the context of COVID-19 recovery. These include:

(1) natural capital and ecosystem service restoration and resilience; (2) clean energy infrastructure; (3) efficiency-retrofits for buildings; (4) clean technology research and development; and (5) education and training to address COVID-19-related unemployment and decarbonisation shifts. The COVID-19 crisis has forced many businesses to increase adaptability given rapidly changing circumstances.[103] Governments can use this momentum to steer economies towards more sustainable, environmental, and human health-promoting futures. In addition to subsidy redirection, governments can take this opportunity to introduce new or strengthen existing carbon-trading and other regulatory frameworks to encourage private sector support of biodiversity and ecosystem health. Such initiatives could allow aid budgets to be allocated to biodiversity conservation (where compatible with poverty alleviation and development), provision of landholder payments for preserving ecosystem services, and increased tax benefits for landholders facilitating conservation through land covenants or easement.[92]

### Biodiversity and ecosystem-supporting job creation

Addressing global COVID-19-related unemployment is an opportunity to provide novel jobs in the transition towards the UN's Sustainable Development Goals[99] with minimal additional economic disruption. Rather than reverting to the very policies and actions that promote zoonosis emergence, governments, financial institutions, and the private sector can better implement and adjust policies addressing unemployment to focus on Sustainable Development Goals such as Responsible Consumption and Production, Sustainable Cities and Communities, and Good Health and Wellbeing.[99] For example, in May, 2020, the New Zealand Government proposed a COVID-19 recovery fund, which earmarked at least NZ$887 million for nature-based jobs focused on habitat protection and restoration,[104] and the USA Government has announced a US$10 billion budget for a Civilian Climate Corps, which can help create jobs in conservation, land restoration, and other so-called green areas.[105] In Australia, a coalition of conservation and agricultural organisations have advocated for AU$4 billion in funding to similarly be directed to an employment-centred conservation and land-management programme.[106]

### Regulation and surveillance of the global wildlife trade

Reducing zoonotic disease emergence risks posed by the trade and consumption of wildlife is obviously a crucial element of any approach that seeks to limit opportunities for cross-species pathogen transmission and zoonoses outbreaks. SARS-CoV-2 has understandably highlighted the trade and consumption of wild animals and their products as a risk factor for future spillover events with pandemic potential.[107] Although scientists, international leaders, and others have called for blanket bans on wildlife trade, these could sometimes have unintended consequences of non-subsistence wildlife trade bans and mass shutdowns of wildlife markets, and debate around whether such actions would be effective.[63,108–110] Even though the banning of wildlife trade activities could address problems, including population declines in trafficked species, ecosystem disruption, and risks for zoonotic pathogen spillover events, the complexities of the trade must be considered. These complexities include the trade's existence in both legal and illegal forms, the multiple scales at which it occurs (from local to global), its sustainable and unsustainable elements, the multiple ways in which its actors depend on it (including for economic and food security),[110,111] and the disproportionate effects bans could have on low-income populations in regions such as Africa and Asia compared with high-income countries.[109,111] Historically, shutting down legal wildlife trade in response to zoonotic disease outbreaks has often driven increases in illegal trade,[109] as prices for illegal goods rise.[112] Such unintended outcomes have resulted in trade with less regulation and surveillance, not necessarily less trade activity, and a loss of community trust in both conservation and the outbreak response.[109]

One Health approaches to addressing wildlife trade could deliver more robust threat-alleviation results, with increased cost-effectiveness and better socioeconomic outcomes and health outcomes for people.[113] Approaches should include multiscale collaboration targeting both supply and demand, careful regulation, and a high level of surveillance, particularly around activity that is illegal or carries higher risks for zoonotic spillover and conservation.[108,114] Strategies by governments and international bodies to address the risks of wildlife trade, such as the Vietnamese Government's July 2020 directive mandating increased enforcement of wildlife protection legislation,[115] should without doubt be encouraged. However, it is crucial that such strategies be developed and implemented in a collaborative, diversified context, with the involvement of local communities and stakeholders in decision making.[111] Ensuring this can minimise the trade-offs and negative consequences often associated with strategies, such as loss of subsistence livelihood for people involved in the trade, which could feed into increased illegal trade and undermine intended aims. Wildlife Enforcement Networks approach enforcement of the wildlife trade on the basis of single-nation or single-agency approaches often being inadequate, due to the complex multiactor and cross-boundary nature of the trade. Networks such as the Association of Southeast Asian Nations' Wildlife Enforcement Network aim to enable stronger cooperation on wildlife law enforcement between countries, contributing to overcoming the geographical and economic barriers to approaches of single nations or entities.[116]

### Applying decision science to prevent emerging infectious diseases

Conservation science is a crisis discipline,[117] and in its short history has developed methods parallel to crisis

### Search strategy and selection criteria

The investigation for this Personal View began in March 31, 2020, when COVID-19 was declared a pandemic. Due to the rapidly changing dynamic context and insufficient primary research on COVID-19 in the early stages, we used a broad diversity of search terms derived from group discussions and from historical pandemic literature, and added sources as they became available during 2020–21. Our search terms included "zoonotic origins covid-19", "zoonotic disease outbreaks", "human-animal interface", "human wildlife interactions", "zoonotic spillover", "government response covid-19", "economic response covid-19", "driver zoonotic disease", "land use change zoonotic disease", "deforestation zoonotic disease", "wildlife trade zoonotic diseases", "climate change zoonotic disease", "livestock zoonotic disease", "agriculture zoonotic disease", and "environmental impacts covid-19". We searched across the "Impact Areas" terms used in figure 2. We also searched the names of the diseases and pathogens listed in appendix (pp 4–7; past zoonotic outbreaks) combined with the terms "origins", "zoonotic source", "animal", "land-use change", "deforestation", "wildlife trade", and "climate change". Interchangeably with "zoonotic disease", we used the terms "zoonoses", "pathogens", "cross-species disease", "pathogen transmission", and "zoonotic spillover". We used these terms to search Scopus, PubMed, Web of Science, Google Scholar, the *New England Journal of Medicine*, and *The Lancet* archives. Additionally, we contacted experts around the world in search of further information.

management in public health.[118] Both disciplines are confronted with the need for urgent action, evidence-based policy support, and emergency response, while often facing insufficient resources[119] (eg, responding to discovery of a pathogen or newly established invasive species for which swift control is imperative).[120] Similar to its initial wartime application, the regrettable necessity of triaging has also been recognised in conservation,[118] highlighting the need for careful prioritisation of actions. Decision science in conservation can provide transparent ways of identifying the optimal combination and timing of actions from data acquisition to direct intervention to maximise successful outcomes or minimise likely losses within fixed budgets,[121] or to optimise return on conservation investment.[122,123] The decision science requirement for clear definition of objectives adds to transparent decision-making processes, and methods can incorporate diverse, even divergent, objectives.[123,124] Acknowledging and incorporating the probability of programme success or failure[125] can further affect which management actions are considered optimal, and with the current realisation of dramatic sudden losses in budget, personnel and logistical agility, we foresee that inclusion of these concepts will increase in conservation management planning. As for reducing mortality and economic costs associated with pandemic events, it has been proposed that maintaining intact habitat, by reducing deforestation and regulating wildlife trade, would yield a high return on investment, supporting the adoption of preventive approaches targeting the drivers of emerging infectious diseases.[36] The parallels between management of conservation and public health crises can lead to future advances in decision theory relevant to, and essential for, both endeavours.

### Taking a One Health approach

The COVID-19 pandemic shows how zoonotic spillover events can quickly become a costly global problem and affect an immense breadth of health, social, economic, and environmental factors. Novel approaches to addressing drivers of zoonotic disease emergence through policy reform, regulation, fiscal measures, and more, will be enhanced by coordination, cooperation, and collaboration across international and regional borders, as well as disciplinary and sectoral boundaries.[114,126] To achieve this, there is a pressing need for more effective communication among all relevant actors across fields, including medical and public health scientists, practitioners and officials, Indigenous knowledge holders, conservation scientists and practitioners, veterinarians, zoologists, ecologists, social scientists, economists, policy makers, governmental authorities, non-governmental organisations, research bodies, and multiple other stakeholders and actors.[82,91,114,127,128] Considering the inter-related nature of biodiversity, environmental health, and human health, it is appropriate that strategies to prevent the exacerbation of zoonosis drivers take a One Health approach.[113,114] This integrative approach, which has been called for by many in light of the COVID-19 pandemic,[5,63,129] acknowledges the tight relationship between the health of our planet and the health of humans. It works to address complex challenges faced in the environmental and global health spheres to achieve mutually beneficial, sustainable outcomes.[113] Through this approach, major issues such as land-use change, wildlife trade, intensive livestock production, and climate change are addressed as public health and economic challenges, including environmental issues. Strategies to comprehensively address these issues involve transdisciplinary collaboration and actions.[27]

## Building a planetary health future

The devastating worldwide effects of the COVID-19 pandemic underline the necessity of minimising risks of future zoonotic disease emergence and re-emergence that could engender similar health, societal, and economic consequences. Doing so involves addressing the anthropogenic factors known to increase the risk of spillover events—land-use change, wildlife trade, intensive livestock production, and climate change—and, crucially, addressing COVID-19's effects on biodiversity loss and ecosystem health, which in turn, can exacerbate these drivers.

If global efforts to address these drivers are inadequate, humans could perpetuate a feedback loop that results in increased risk of zoonotic disease emergence. Therefore, the goals of leaders, the health community, and the conservation community globally should better align now, more than ever. To achieve common goals however, we need to take an integrative One Health approach, which focuses on appropriate fiscal recovery responses, policy, legislation, and regulatory actions that prioritise the safeguarding of biodiversity and ecosystems. Communication across international, regional, and interdisciplinary boundaries at all scales, including a willingness to collaborate, is necessary. Despite the adverse nature of the COVID-19 pandemic, the crisis presents some unique positive opportunities, which governments, decision makers, and citizens can leverage. Society must more readily accept the health of biodiversity and ecosystems as a high priority, not only for the preservation of biodiversity, but as a public health measure of global importance to human health and wellbeing. Without immediate and sufficient reform of our response to zoonotic disease emergence and high-impact events, such as the COVID-19 crisis—including efforts to return to business as usual—biodiversity, ecosystems, and human health will continue to suffer. As the links and feedback loops between biodiversity and ecosystem health, COVID-19 and emerging infectious diseases are becoming clearer, conservation actions and a One Health approach are urgently needed to manage zoonotic risk and avoid further feedback loops that can negatively impact human health, biodiversity and ecosystem health.

**Contributors**

OKL, HLA, PWJB, RC, MCT, LED, JH, TJL, GMM, JN, AMR, and SK took part in the study design. OKL and SK conceived the study. All authors contributed to the literature search. OKL and SK led the writing and revision of drafts, with contributions from HLA, PWJB, RC, MCT, LED, JH, DK, TJL, MJL-J, GMM, JN, and SK. OKL, RC, MCT, and SK created the figures with contributions from all authors. All authors provided critical feedback and editing of the manuscript and read and approved the final manuscript. SK supervised the project.

**Declaration of interests**

We declare no competing interests.

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