



Nature and COVID-19: The pandemic, the environment, and the way ahead

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Abstract The COVID-19 pandemic has brought profound social, political, economic, and environmental challenges to the world. The virus may have emerged from wildlife reservoirs linked to environmental disruption, was transmitted to humans via the wildlife trade, and its spread was facilitated by economic globalization. The pandemic arrived at a time when wildfires, high temperatures, floods, and storms amplified human suffering. These challenges call for a powerful response to COVID-19 that addresses social and economic development, climate change, and biodiversity together, offering an opportunity to bring transformational change to the structure and functioning of the global economy. This biodefense can include a “One Health” approach in all relevant sectors; a greener approach to agriculture that minimizes greenhouse gas emissions and leads to healthier diets; sustainable forms of energy; more effective international environmental agreements; post-COVID development that is equitable and sustainable; and nature-compatible international trade. Restoring and enhancing protected areas as part of devoting 50% of the planet’s land to environmentally sound management that conserves biodiversity would also support adaptation to climate change and limit human contact with zoonotic pathogens. The essential links between human health and well-being, biodiversity, and climate change could inspire a new generation of innovators to provide green solutions to enable humans to live in a healthy balance with nature leading to a long-term resilient future.

Keywords Biodefense · Biodiversity · Climate change · Health · Wildlife trade · Zoonotic diseases

INTRODUCTION

In the mid-fourteenth century the bubonic plague was carried by the flea-borne bacterium *Yersinia pestis* on great gerbils (*Rhombomys opimus*) that were flourishing in the grasslands of Central Asia during a high productivity rainy climatic period (Kausrud et al. 2010). The epidemic was spread by traders and black rats (*Rattus rattus*) along the Silk Road west to Europe and east to China. In the west, the Black Death killed over a third of the European population; in the east, over 25 million Chinese were fatally infected (Kohn 2007). What happened next: the end of feudalism in Europe, economic and social changes as scarce labor became more valuable, and a new flowering of European art and science that led to the Renaissance (Herlihy 1997); and China transitioned from the Mongol-controlled Yuan Dynasty to the Han-controlled Ming Dynasty, known for its expanded trade, new plants from abroad (potatoes, maize, and chili peppers), writing, porcelain, and innovative approaches to government (Swanson 2017; Smith and von Glahn 2020). The recovery from a disastrous pandemic inspired new social, cultural, and political arrangements that soon led to Eurasian countries dominating the entire world (Campbell 2016).

In late 2019 the novel coronavirus SARS-CoV-2 and the COVID-19 disease it causes in humans emerged from Wuhan, China, and attacked a world made vulnerable by globalization of trade and travel, social inequities, effects of climate change, resource over-exploitation, unsustainable production and consumption, biodiversity loss, and governance poorly prepared to respond. A year later, at least 50 million people were infected by the pandemic, over a million had died, and the global economy was devastated.

In both pandemics, the pathogen was hardly the only problem. Rather, it was a catalyst that helped to focus attention on the political, social, economic, and environmental problems that were making the mid-fourteenth century and perhaps the early twenty-first century times when change was overdue. And times of rapid change present opportunities for innovative approaches to rebuild societies in a more sustainable direction that can enhance resilience to the changing conditions. In the Middle Ages, Europe, the Middle East, and China moved toward more prosperous and innovative directions as impacts from the bubonic plague faded. Can the modern world respond likewise to COVID-19?

While not as disruptive or virulent as the bubonic plague pandemic, COVID-19 has generated draconian control measures that have dramatically affected many sectors of modern economies, including industries, airlines, farming, fisheries, sports, social events, education, and tourism, among others. The restrictions were effective in reducing transmission of the virus (Hsiang et al. 2020), but high unemployment, social disruption, and bankruptcies have been common side effects. The World Bank expects that at least 120 million people will be pushed toward deeper poverty, the global economy will shrink by over 5%, and global trade will decline up to 32% in 2020. Some national economies are falling even more, with second quarter GDP dropping 25.2% in India, 20.4% in the UK, 17.1% in Mexico, and 16.4% in South Africa (OECD 2020). The resulting global economic contraction could even be called “a pandemic depression” because the recession has spread more widely than at any time since the 1929–1933 Great Depression (Reinhart and Reinhart 2020).

The economic shocks that have accompanied COVID-19 indicate that some of the fundamentals of the global economy may not be sustainable on environmental, social, and economic grounds. Economic growth based on increasing consumption of natural resources has already had profound negative impacts on the global environment and biodiversity; global GDP grew from US\$ 3.4×10^{12} in 1970 to over US\$ 142×10^{12} in 2019, an increase in economic activity of 40 times at the same time that wild species populations were declining by 68% (Tienhaara 2010; WWF 2020). The World Economic Forum, a leading international business body, contends that business as usual has no future because over half of global GDP is potentially threatened by the loss of biodiversity and ecosystem services. But a greener form of development could generate 400 million jobs and US\$ 8×10^{12} in business value annually by 2030 (WEF 2020).

The world is unlikely to be returning to anything resembling its pre-pandemic resource-extracting prosperity any time soon, if ever. Domestic turbulence is to be expected when high unemployment leads to a recession

that will last for many months or even years, and the unprecedented debt burden at both household and government levels continues to create public tensions that may lead to inequitable forms of justice (Fukuyama 2020). How will the world respond?

This review will provide a perspective on the environmental conditions that prevailed when the new coronavirus arrived, highlight how COVID-19 has affected the environment, present some of the links between emerging infectious diseases and the environment, and conclude by drawing from lessons learned to suggest some policies to bring nature back into the mainstream of helping human societies adapt to emerging challenges. It will show that building environmental resilience is the key to a sustainable future, calling for social, economic, and environmental innovation.

SETTING THE ENVIRONMENTAL STAGE FOR COVID-19 AND THE RESPONSES TO IT

While the human health and economic impacts of the pandemic appropriately are receiving the most urgent attention (Morens and Fauci 2020), the complex environmental issues of biodiversity loss and climate change are at the very heart of the pandemic and affect responses to it. Emerging infectious diseases (EID) are driven by growing human populations increasingly disrupting natural ecosystems, globalization that can send an EID around the world even before its symptoms become apparent, and changing climates that are affecting drivers such as increasing demand for animal protein, unsustainable agricultural intensification, and destructive harvest of natural resources (UNEP/ILRI 2020).

Emerging infectious diseases always have environmental dimensions

COVID-19 was no surprise because new EIDs were clearly expected (Quammen 2012). A database on 335 EIDs starting in 1941 showed that they have been increasing significantly and have often been linked to environmental factors. Zoonoses, diseases originating in animals that can be passed to humans, were found to be 60.3% of EIDs; 71.8% of these originated in wildlife and 29.2% were from domestic species (Jones et al. 2008). Notable examples include the remarkably fatal Ebola hemorrhagic fever that emerged in West Africa in 1976 and had numerous outbreaks with mortality rates of up to 43%. A study of 40 Ebola outbreaks after 2004 found that they were significantly linked to the recent clearing of mature forest that led to more frequent contact between humans and infected animals (Olivero et al. 2017).

A major contributor to the 1997–1998 outbreak of the Nipah virus in Malaysia was the clearing of species-rich tropical rainforests to make room for commercial farming of vast expanses of oil palm (*Elaeis guineensis*) that replaced the tropical forest habitat of Malaysia's 17 species of fruit bats (Family Pteropodidae). The bats then turned to domestic fruit orchards planted near factory farms where domestic pigs fed on fallen fruit contaminated with excreta from the bats and became infected with Nipah virus which they then passed on to pig farmers who suffered a devastating 40% mortality rate (Cheng et al. 2018).

The conclusion is clear: when mature old-growth forests are cleared to create farms (as in West Africa), plantations (as in Malaysia), or pastures (as in Brazil), wild species move into new habitats and come into contact with species they do not normally encounter, which may then spread infectious diseases (Wolfe et al. 2005; Rohr et al. 2020). Some EIDs have much higher mortality rates than that of COVID-19 (currently averaging 3–4%, with much variation among countries), another good reason to treat future EID threats seriously, seek to stop their spread as soon as they emerge, and be prepared to respond effectively if they start to spread.

The COVID-19 pandemic arrived at a time of significant biodiversity loss

Biological diversity (biodiversity for short) is the variability among living organisms and the ecological complexes of which they are part, including diversity within species, between species and of ecosystems (CBD 1992). Biodiversity generates substantial economic benefits, especially through supporting ecosystem services (Ninan 2009; Kumar 2010), and diverse species at multiple trophic levels are required to deliver the full benefits of ecosystems (Soliveres et al. 2016). This variability of nature supports human health (Rohr et al. 2020), with about 75% of the new drugs to fight bacterial infections, viruses, and parasites developed since 1981 coming from natural products (WHO and SCBD 2015). More generally, biodiversity in natural ecosystems has helped to keep contagious pathogens from becoming pandemics through nature's systems of checks and balances (Everard et al. 2020).

Biodiversity supports the fulfillment of all of the United Nations Sustainable Development Goals (Sachs et al. 2019), and the Convention on Biological Diversity (CBD) agreed a Strategic Plan for Biodiversity 2011–2020 with an ambitious set of 20 targets (known as the Aichi Targets after the city in Japan where the plan was agreed) (SCBD 2010) (www.cbd.int/gbo). By 2020, six of the Aichi targets had been partially achieved and all of them had led to at least some conservation action by government agencies (SCBD 2020). While conservation has saved some

Endangered species from extinction, at least temporarily (Bolam et al. 2020), nature today is still declining at a rate unprecedented in human history and species extinction is accelerating. The direct anthropogenic drivers of nature's decline are well known: changes in land and sea use that leads to habitat loss; direct exploitation of species of plants and animals; climate change that drives ecosystem changes and extreme climatic events; pollution of soils, fresh and salt waters, and the atmosphere; and the spread of alien invasive species (IPBES 2019).

These drivers are closely linked to human health. More than 500 000 species lack sufficient habitat to ensure their survival (IPBES 2019), and habitat loss also creates the edge effects that have been implicated in promoting more human–wildlife contacts that can lead to the spread of zoonotic diseases. Some 30% of global species threats are due to international trade (Lenzen et al. 2012), with a wide variety of commodities being sent from tropical developing countries to industrial and individual consumers in North America, the European Union, China, Japan, and elsewhere, and setting the stage for pandemics.

The loss of biodiversity over the past century has been so grave that many biologists contend that the planet is now approaching “the Sixth Extinction”, coming 65 million years after the Fifth Extinction saw the disappearance of the dinosaurs following a devastating shower of meteorites that left a clearly visible layer in the geological record (Ceballos et al. 2020). In short, growing numbers of humans are consuming more of nature's resources, using new technologies that facilitate resource exploitation, reaching into new “untouched” areas, taking advantage of the globalized spread of resource consumption, avoiding payment of the environmental costs, and posing threats to a healthy environment.

Ecosystem degradation is driving COVID-19 and other pandemics

In terms of scale, ecosystems are the largest components of biodiversity, and pandemics can emerge from many of them. Here, the focus will be on two major types of ecosystems that are especially relevant to COVID-19: forests, because they support most biodiversity and are home to the wild species that carry the most zoonoses; and domesticated lands (farms and pastures) that are replacing many forests and provide a stage for contagious interactions between wild animals, domestic animals, and people.

Forests provide habitats for 80% of amphibians, 75 percent of birds, and 68% of mammals (FAO and UNEP 2020). Tropical forests alone contain about 60% of the planet's plant species. But forests are still being cleared at a rate of 100 000 km² per year, with old-growth tropical forests targeted for agricultural expansion (especially oil

palm, maize, and soya beans, and cattle ranching). From 1990 to 2020, the global forest area decreased by 1.78 million km² (FAO 2020). Small wonder that about 8000 of the world's estimated 60 000 tree species are considered globally Threatened and 1400 are Critically Endangered (IUCN 2020). This degradation of tropical forests is reducing their ability to deliver their former abundance of ecosystem services (Gibson et al. 2011).

The conversion of forest ecosystems from natural to human-dominated is often driven by fragmentation through transportation and other linear infrastructure, especially railroads, highways, canals, and fences that cut natural ecosystems into smaller parcels at a time when connectivity of natural landscapes is widely recognized as an important conservation objective (Hanski 2011; Fahrig 2017). Fragmentation reduces species richness in the remaining patches by up to 75%, alters nutrient cycles (Haddad et al. 2017), and brings people into closer contact with species that are hosts of potentially zoonotic pathogens like COVID-19.

Already, more than a third of the land and almost 75% of freshwater resources are being devoted to production of crops and supporting livestock, but 23% of the agricultural land has been so degraded that its productivity is declining and soil is being eroded far faster than it is being enriched (IPBES 2019). Agriculture is also the major polluter of land and water, as well as the source of about a quarter of the anthropogenic greenhouse gas emissions; livestock production alone generates 18% of greenhouse gases (O'Mara 2011).

Environmental problems exposed by COVID-19 include the destruction of species and ecosystems to support the human demand for animal protein, such as the clearing of biologically-rich Amazon forests and Cerrado tropical savanna in Brazil to make pastures for cattle. Meat demand is driving the large-scale ranching of cattle (global population: 987 million in 2020) and industrial raising of chickens and pigs at even higher densities (in 2019, 767 million domestic pigs and 23×10^9 domestic chickens worldwide). As people and their domestic animals move closer to the wild species that can carry viruses, bacteria, and other pathogens, they increase their likelihood of contracting zoonotic diseases such as swine flu, bird flu, and many others (Gibb et al. 2020).

The COVID-19 pandemic is threatening global food security made worse by climate change, bringing new attention to sustainable agriculture (Laborde et al. 2020). With over 820 million people now facing chronic hunger (people who go to bed hungry every night), the Executive Director of the World Food Program has warned of a looming global humanitarian catastrophe as a result of the pandemic (Beasley 2020). Famines can result from breakdowns of supply, and COVID-19 has encouraged

governments to keep more of their food at home, posing problems for the food-importing countries in Africa and the Middle East. In China, a new program to encourage mealtime thrift and avoid food waste is based at least partly on concerns about food supply as prices of vegetables and pork are increasing (Dou 2020). New approaches to feeding the planet's human population are emerging.

Global and local trade enabled the spread of COVID-19

COVID-19 arrived at a time when the global economy was based on international and domestic trade that accelerated habitat degradation in developing countries to provide food, timber, energy, wildlife, and minerals for consumers in distant lands who are far removed from the damage their consumption was causing (Diaz et al. 2019). The farming of wild species can also be a source of spreading COVID-19 (Fig. 1). Almost 5600 vertebrate species are traded (Scheffers et al. 2019), carrying with them a wide range of viruses, bacteria, fungi, ectoparasites, and other pathogens. Trade-related biodiversity loss reflects the entire production chain, from harvest in wild habitats to export markets in cities and demand from importing countries (Lenzen et al. 2012).

While many ecosystems are losing native species, they are also being invaded by alien non-native species that are carried freely around the world as an externality of global trade and cause serious harm by replacing native species that were adapted to their ecosystem; some may also serve as new vectors of zoonotic pathogens. As a dramatic example, the fungus *Batrachochytrium dendrobatidis* emerged from the Korean Peninsula in 2009 to cause a devastating panzootic disease that is threatening amphibians throughout the world (146 species already extinct and another 848 Endangered) (O'Hanlon et al. 2020). Addressing the threats from invasive alien species (IAS) requires managing the symptoms (loss of native species, transformation of ecosystems, and economic costs) (Wittenberg and Cock 2001) and dealing with the complex issues of global economics and trade that drive the invasions (Myerson and Mooney 2007).

Wild animal markets bring together species that would not be interacting in their natural habitats, thereby exposing both the captive wild species as well as merchants and shoppers to pathogens that they would not have encountered in nature (Fig. 2). Wild animals kept in small unsanitary cages in markets are stressed and often poorly nourished, which can weaken their immune systems and predispose them to infection from viruses carried by other animals. Controlling the spread of EIDs will require more effective regulation of the impacts of trade on biodiversity and human health.



Fig. 1 COVID-19 has spread between humans and farmed wild mink, causing hundreds of human infections. The USA, Sweden, Spain, Italy, Denmark, and the Netherlands have been affected, and the latter two have culled their total mink population and virtually closed the industry at substantial economic and social cost. Fur farms are now being banned in many countries, at least partly because of concerns about the spread of zoonotic diseases. Photo by Dzivnieku Briviba (Onyx AB 08 licensed under CC BY 2.0)



Fig. 2 Wuhan, the capital of China's Hubei Province, hosts the Huanan Seafood Wholesale Market that has been officially identified as a potential source or amplifier of the COVID-19 outbreak. Photo by Toehk ("Wuhan road" licensed under CC BY 2.0)

Climate change influenced the spread of COVID-19 and responses to it

The World Health Organization describes climate change as the greatest threat to human health in the twenty first century (WHO 2003), especially because of the health impacts from the ecological changes associated with increasing temperatures. The Intergovernmental Panel on

Climate Change (IPCC 2018) projects a global temperature increase by 1.5° C by 2040, which is expected to lead to significant sea level rise, population movements, and extreme climatic events (storms, droughts, floods, heat waves, and forest fires). Such changes present significant risks to health, livelihoods, food security, water supply, human security, and economies, with damage predicted to reach US\$ 54×10^{12} , though greater warming would yield a higher bill to deal with more damage.

But significant climate change has already arrived, judging from some of the extreme climatic events that occurred during the pandemic. For example, the Arctic is warming at three times the rate of the rest of the world (Landrum and Holland 2020). Siberian fires from the exposed tundra vegetation released over 59 million metric megatons of carbon emissions in June 2020 and 100 million metric megatons in July, thereby adding to the global warming that will support an even warmer Arctic (Civarella et al. 2020; Hugelius et al. 2020). This abrupt Arctic climate change indicates that global warming is coming even faster than expected (Jansen et al. 2020).

Climate change has also contributed to devastating wildfire seasons in other parts of the world. For example, fires in Australia (late 2019 to early 2020) burned 186 000 km² and led to the death of an estimated 143 million mammals, 180 million birds, 51 million amphibians,

2.5×10^9 reptiles, and an unmeasurable number of insects. The fires also produced 306 million tons of CO₂ emissions, contributing to the climate change that helped nurture the wildfires (Readfearn and Morton 2020). Globally, wildfires are increasing in length, intensity, and severity as climate change also hits Brazil, western North America, southern Europe, and various parts of Africa. The wildfires are producing smoke that contains numerous air pollutants, including fine particulates that can cause serious lung damage that increases susceptibility to infection from COVID-19 by about 10% (Henderson 2020), and increased COVID-19 mortality by 9% in California (Petroni et al. 2020). Some of the drivers of climate change—such as emissions of black carbon, sulfur dioxide, nitrogen oxides, and carbon monoxide—are already causing at least eight million fatalities per year, far more deadly than COVID-19 (DeRidder 2020).

One of the lessons of COVID-19 is that acting too late carries serious costs to both people and the economy. Climate change is not just a concern for the future, but very much a current problem that requires urgent action that can be encouraged by linking climate change to biodiversity loss and the hazards of emerging infectious diseases such as COVID-19.

ENVIRONMENTAL IMPACTS OF THE COVID-19 PANDEMIC

Policy responses to COVID-19 have had profound effects on the environment as well. Some impacts, such as the closing of borders, restrictions on travel, and stay-at-home orders have had a combination of damaging and positive elements. Much depends on what happens next.

Nature's resources are easier to exploit when budget cuts such as those from responding to COVID-19 weaken environmental protection agencies. This came at a time of rising hunger in rural areas, so poaching of wildlife and timber has become a major problem in many tropical countries (Badola 2020; Gardner 2020). The illegal harvest of wildlife, including rare and threatened species, is increasing; for example, both African species of rhinoceros, the Critically Endangered black (*Diceros bicornis*) and Near Threatened white (*Ceratotherium simum*), are being poached to meet the demand for rhino horn used in traditional Chinese medicine as a treatment (unproven) for the COVID-19 virus (Somerville 2020).

Illegal logging, land clearing, and mining are increasing in countries with biodiversity-rich tropical forests. In Brazil, for example, forest clearing in the Amazon increased 34% in 2020, amounting to 10 100 km² lost (Fig. 3), encouraged in



Fig. 3 Clearing of forests in Indigenous territory in Amazonia is especially troubling because these lands had been protected by the forest-dwelling people, and invading loggers and miners are polluting the land and spreading COVID-19 to Indigenous forest dwellers who have little access to medical care. Photo by Felipe Werneck/Ibama via flickr via AP (Illegal logging on Pirititi Indigenous Amazon lands with a repository of round logs on May 8, 2018, by Quapan licensed under CC BY 2.0)

part by the lack of field agents who have been reassigned elsewhere (Escobar 2020). Most of the cleared land was converted to pastures for grazing cattle that feed Brazil's beef exports, and burning the cleared vegetation resulted in thick smoke that led to lung and heart problems that further heightened the impact of COVID-19 that had claimed over 160 000 Brazilian deaths by October (second only to the USA).

A side effect of encouraging working from home and discouraging travel has been a significant reduction of visitors to national parks and other protected areas. From supporting 800 million visits, generating US\$ 600×10^9 , and providing nearly 22 million jobs per year, visits to protected area systems in many countries have been ground to a halt by COVID-19. In the absence of visitors, many protected areas have lost their expected income from tourism and resulting staff reductions mean that patrolling, research, and routine habitat management activities are being neglected. The thousands of local communities that are economically linked to protected areas through sharing of tourism benefits are also suffering, and their new circumstances may force them into a more exploitative relationship with the protected area species and ecosystems (Hockings et al. 2020).

In some parts of the world where tourism has significantly affected wildlife behavior, wildlife is responding to the significant decline of tourists from their habitats by spreading into areas they had previously avoided. Behavioral changes from wildlife in response to newly favorable conditions indicate their inherent resilience to anthropogenic pressures (Derryberry et al. 2020).

Some of the restrictions designed to address COVID-19 have led to environmental benefits such as a remarkable, if transitory, improvement of air quality, especially in cities. Data collected by Apple and Google found that more than half of the world's population reduced travel by more than 50% in April 2020 and mobility declined by at least 10% in almost all of the 125 countries tracked, with some countries showing a decline of 80% or more (Forster et al. 2020). This decline in transportation and commercial demand for electricity significantly reduced consumption of globally traded greenhouse gas-producing fossil fuels (oil, gas, coal) and increased the share of energy provided by local sources such as solar and wind power (IEA 2020a). This has indicated that renewable forms of energy could fuel the future, with China and the EU already seeking to create green jobs and phase out fossil fuels to decrease greenhouse gas production.

COVID-19 has distracted both governments and the public from the many other environmental problems that are worsening, especially the loss of biodiversity and the damaging ecological impacts from climate change. These

linked problems inevitably will intensify unless serious policy attention generates effective action to address them.

In short, COVID-19 has distracted both governments and the public from the many other environmental problems that are worsening, especially the loss of biodiversity and the damaging ecological impacts from climate change. These linked problems inevitably will intensify unless serious policy attention generates effective action to address them. On the other hand, COVID-19 has exposed some of the major environmental problems caused by the dominant economic model that has been pushing global growth in resource consumption for the past 75 years. A response to COVID-19 that incorporates measures to address the resource consumption problems facing climate change and biodiversity loss along with human health can provide a solid foundation for a sustainable future.

FROM COVID-19 TO A NEW FLOWERING OF HUMAN SOCIETY

The social energy generated by the COVID-19 pandemic provides an opportunity to design and implement a wide diversity of new ways to build a sustainable and adaptable relationship between people and the rest of nature. The public may well be ready for a recovery that will include an effective and sustainable biodefense with elements that address human health, biodiversity conservation, and adaptation to climate change as a package based on principles of sustainable development. Here are 10 linked policy directions to consider as part of biodefense and human well-being.

1. Support the One Health approach in all relevant sectors

“One Health” has become a mainstream approach to recognize the intimate connections among humans, animals, ecosystems, and economies (Osofsky et al. 2005; SCBD 2017; WHO, OIE, and FAO 2019). One Health builds collaboration among a wide range of expertise on all aspects of human, animal, and plant health, calling for actions, policies, legislation, and research that incorporate environmental sustainability into economic planning. It can connect all layers of society, from rural villagers to modern researchers (Cook et al. 2004). This is contributing to a more resilient future that minimizes the threats of global pandemics while also addressing action to conserve the critical biodiversity infrastructure that supports life on Earth (Wildlife Conservation Society, WCS 2019). Protected areas are also contributing with a “Healthy Parks, Healthy People” initiative (Maller et al. 2002).

Supporting the One Health approach can build on a new International Biosecurity Network (IBN) of experts from all relevant disciplines in a collaborative effort to support research and communication about how to support a healthy environment. An IBN could provide technical advice that is relevant and culturally appropriate while conserving the diversity of nature.

As a practical contribution, an IBN could establish a global One Health system of wildlife monitoring and surveillance that includes population status, interactions with humans, and potential for identifying infectious diseases as they emerge and before they become costly global pandemics. Such a system could use local people trained to monitor the health of the wildlife (with a specific focus on designated high-risk species such as bats) living in their area and be alert to any signs of emerging infectious diseases and any other human-wildlife issues, much like community participation in Ebola control in West Africa (Karesh and Cook 2009).

2. Build closer collaboration among agricultural agencies, farmers, and researchers to promote a healthier approach to agriculture

Agricultural drivers have been linked to more than half of all zoonotic infectious diseases since 1940, and this proportion is expected to increase as agriculture becomes even more intensified (Rohr et al. 2019). Transforming food production systems away from destroying forests and depleting biodiversity could involve indoor farming (Fig. 4), agroforestry, sustainable production practices, minimum tilling, precision fertilizer application, restoring productivity of degraded agricultural land, reducing food



Fig. 4 A more sustainable approach to using land to produce food draws on technologies such as hydroponics to provide water to the roots of the cultivar, greatly enhancing productivity. The Netherlands is a global leader in technologically intensive agriculture, with remarkably dense production on a limited land area that is densely populated. Photo by Aqua Mech (Hydroponic vegetable licensed under CC BY 2.0)

waste, applying modern biotechnology, and expanding home gardens. Agricultural businesses could take the lead in committing to sustainable use of their land and commit to no further deforestation (FAO and UNEP 2020).

Innovative approaches to sustainable agriculture could include: compensating farmers for their contribution to ecosystem services such as watershed protection and carbon sequestration; adopting closed production systems with negligible waste; using market mechanisms to subsidize crop rotation that replenishes soils; establishing wildlife habitats in working landscapes; growing buffers of native vegetation around agricultural fields; and incorporating measures to combat the transmission of zoonotic diseases in food safety regulations that cover the full production chain including planting, growing, harvesting, and marketing (FAO 2018).

3. Adopt healthier diets

Consumers can also play their part. Unhealthy diets contribute to many of the medical conditions that make some people especially vulnerable to infection from COVID-19, such as obesity and diseases of the heart, lungs, liver, and kidneys. A shift to healthier diets would have substantial benefits for consumer health, limitation of coronaviruses, and climate change (Loken and DeClerck 2020).

The EAT-Lancet Commission on healthy diets from sustainable food systems recommends eating mostly vegetables, fruits, whole grains, legumes, nuts, and unsaturated oils, a low to moderate amount of seafood and poultry, and a minimal quantity of red meat, processed meat, added sugar, refined grains, and starchy vegetables. Such a diet would provide major health benefits and draw on sustainable agriculture that would not require any further clearing of forests, safeguard existing biodiversity, reduce consumptive water use, substantially reduce nitrogen and phosphorous pollution, produce net-zero carbon emissions, and cause no further increase in methane and nitrous oxide emissions (Willet et al. 2019).

A declining market demand for meat is an important element in a post-epidemic sustainable society so new ways of protein dining are being explored. For example, sales of plant-based meat substitutes were US\$ 19.5×10^9 in 2018 and are growing at 20% per year; fast-food chains are already offering plant-based hamburger and chicken substitutes. Tesco-Lotus, an international supermarket chain, has set a target of 300% higher sales of plant-based alternatives to meat, responding to consumer demand. Since some 70% of the global agricultural estate is devoted to grazing livestock or producing concentrates for feeding them, a transition to a more plant-based diet would require significantly less land and thus enable a much greater natural area.

4. Improve human relations with animals

Humans seem to have an innate fondness for wild animals, sometimes called “biophilia” (Wilson 1984). People in all parts of the world enjoy documentaries of wild species, birdwatchers gain happiness from their hobby, wildlife conservation organizations are found in virtually all countries, and children need nature to develop their full potential (Louv 2005). Electronic citizen science platforms such as eBird and iNaturalist are helping to nurture biophilia. All such initiatives deserve strong encouragement, especially in recognizing the many ecosystem services that are provided by nature, and how nature’s diversity helps *Homo sapiens* stay healthy and able to adapt to changing conditions.

People also need more opportunities to nurture their biophilia, especially by visiting nature without harming wildlife. The tourism industry has prepared guidelines for responsible treatment of wildlife (ABTA 2000). As national parks and other protected areas re-open, new approaches to managing tourism could include identifying important breeding grounds as sanctuaries where visitors are not allowed in person but have access to live video from remote cameras that monitor the wild animals and protect them from human disturbance; and seasonal or occasional closing of protected areas could enable breeding seasons and predator–prey relations to play out with limited disturbance.

5. Restore and expand the land and water supporting wild biodiversity

Visiting natural areas is an important way to promote health and feelings of well-being, so urban protected areas are an essential part of public health infrastructure (Trzyna 2014), especially during the COVID-19 pandemic. In the longer term, greener cities will be a critical part of a sustainable future, as urban dwellers use their protected areas as social nodes to meet in natural landscapes that improve health (Tan and Jim 2017).

The CBD’s Aichi Target 11 called for the protected area estate on land to be increased to 17% (SCBD 2010), a figure that has been met by at least 88 countries. Increasing this to 25% could help address the overcrowding from tourism as well as deliver the many other ecosystem services protected areas provide. Expanding the protected area estate and managing it effectively could use interdisciplinary approaches to establish connectivity of ecosystems in the larger landscapes in which protected areas are found (Nyström et al. 2019), and give more attention to protected area management categories that permit a resident population that does not disrupt the delivery of ecosystem services (IUCN 2013; Xu et al. 2017).

But why stop there? It may be time to put E.O. Wilson’s vision of “Half Earth” into practice (Wilson 2016). It seems entirely feasible to devote half of Planet Earth’s land to environmentally sound management, with the top 25% of the land in legally protected areas managed by national or provincial conservation agencies. Already, four countries have devoted half their land to conservation (Bhutan 48%; New Caledonia 54.4%; Slovenia 53.6%; and Venezuela 54.1%) (UNEP-WCMC, IUCN and NGS 2019).

To meet the public demand for access to nature, more of the landscape needs to be devoted to ecosystems where the human footprint is small, and where nature-based solutions to development problems lead to a net gain in biodiversity, ecosystem integrity, and human well-being (IUCN 2020). Beyond the protected areas managed by government agencies, the other 25% of Half Earth could include other effective area-based conservation measures (OECM), geographically defined areas other than protected areas that are governed and managed in ways that conserve biodiversity and ecosystem services and provide cultural, spiritual, and socio-economic benefits (SCBD 2018). At least some of the 370 000 km² of community-based forest management regimes (Hayes and Ostrom 2005) are possible OECM, and lands and waters owned or managed by Indigenous peoples might also qualify, and receive enhanced protection if these lands are considered part of Half Earth (Dudley et al. 2018). Dinerstein et al. (2020) have provided a blueprint for a “Global Safety Net” that would manage 50% of the land designed to stabilize the planet’s climate and reverse biodiversity loss that would also discourage zoonotic diseases from emerging; and Anser (2020) has identified the best places to fight climate change and biodiversity loss by reaching the 50% target.

Expanding environmental protection to even 30% of the land would generate up to US\$ 450 × 10⁹ per year by 2050; and an economic analysis found that the value of ecosystem services of the conserved natural vegetation would amount to US\$ 170–534 × 10⁹ per year by 2050, based on avoided flooding, adapting to climate change, preventing loss of soil, and protecting against storm surges (Waldron et al. 2020).

The oceans, too, need enhanced protection to ensure that marine resources remain productive, with coral reefs especially threatened (Hoegh-Guldberg et al. 2017). Some island nations, such as Palau, allow fishing only by their citizens and have established 80% of their territorial waters as no-take zones closed to fishing. An ambitious, but feasible, target is to protect a third of the oceans to replenish fisheries, conserve biodiversity, and sequester carbon to support climate change adaptation (Sala and Giakoumi 2017). The benefits from such protection include an increase in the global fish catch by 10 million metric tons (Warne 2020), and the delivery of new pharmaceuticals

from the sea, especially antivirals that could help respond to EID such as COVID-19 (Walsh et al. 2008).

6. Accelerate the change toward sustainable forms of energy

The International Energy Agency expects governments to be spending at least US\$ 9×10^{12} in the second half of 2020 in an effort to rescue their economies from the impacts of COVID-19. It has called on governments to guide these investments into a green recovery that would support reducing carbon emissions as a contribution to addressing climate change, especially through support for solar power and wind-generated energy. Green investments would also support energy-modernizing electricity grids and efficiency improvements to buildings and industries (IEA 2020b), along with more investment in photovoltaics, battery technology, and energy management (O'Meara 2020). A global effort to expand solar power to all households, factories, and commercial buildings would be a sound investment as well as a source of employment post-COVID-19; solar power has already increased from 40 GW in 2010 to 627 GW in 2019, a 15-fold increase while prices for solar modules declined by 90% (Goldthau and Hughes 2020).

Solar power can be a critical part of a wind-water-solar Green New Deal to replace at least 80% of fossil fuel energy by 2030 and a complete transition by 2050. Roadmaps for 143 countries show how they can meet this target, reduce private energy costs by 61%, and reduce aggregate social costs that include energy, health, and climate adaptation by 91% while providing over 28 million full-time jobs (Jacobson et al. 2019).

Such an effort could be financed by phasing out subsidies to fossil fuels, which amounted to US\$ 5.2×10^{12} in 2017 (Coady et al. 2019), even as oil becomes a smaller part of national economies. The International Monetary Fund has projected that halting phasing out these subsidies and adopting efficient fossil fuel pricing would reduce global CO₂ emissions by 28% and deaths from fossil fuel-related pollution by 46%, while increasing government revenue. Such a change needs to be responsive to public dependence on fossil fuels and the speed of replacing them, but major oil companies are already moving in this direction as their profits have fallen significantly during the COVID-19 pandemic (Strauch et al. 2020). Economic recovery focused on green investments and reduction of fossil fuels could limit global warming to 0.3 °C by 2050 (Forster et al. 2020). And the Energy Transitions Commission, with a distinguished international membership from energy producers, financial institutions, research

agencies, academia, and insurance companies, has presented a plan for a net-zero carbon emissions economy by mid-century (ETC 2020). Such an economy would improve human well-being, with lower energy consumption but higher-quality and more durable consumer goods.

7. Reinvent globalization by implementing international environmental agreements

Globalization fueled an economy that enriched many people, but COVID-19 set international cooperation back as borders were closed (MacMillan 2020) and countries mostly responded individually to COVID-19 and its economic impacts (Haass 2020). Now a new collective ability to respond is needed, to support sustainability and the capacity to adapt to environmental challenges that affect human well-being. While private enterprise will drive most innovation, the broader public interest needs to be better served by stronger and more efficient international bodies. Here are some possibilities among many that could be considered:

- Significantly enhance the capacity of the World Health Organization so that it can respond quickly and effectively to any future disease outbreak with pandemic potential. An operational capacity would include the necessary staff, supplies, and international support to provide a vigorous response to any threatening epidemic before it can become a pandemic.
- Drawing on a new level of international cooperation, Dobson et al. (2020) have presented some effective ways to control deforestation and wildlife trade to reduce the risks of future coronavirus pandemics, at a cost of about US\$ 260×10^9 over ten years, just 2% of the estimated US\$ 11.5×10^{12} damage caused by COVID-19. Recognizing the dependence of humans on healthy ecosystems, it would seem reasonable to implement the call for a renewed global commitment to avoiding the Sixth Extinction (Corlett et al. 2020; Dinerstein et al. 2020).
- The 2021–2030 Global Biodiversity Framework should include conserving genetic diversity that would help farmers, health workers, researchers, and resource managers (Hoban et al. 2020); adopting a global biodiversity target of no more than 20 vertebrate species extinctions per year, thereby inspiring new approaches for monitoring the status and trends of species in all parts of the world (Rounsevell et al. 2020); and specific support to address the hazards posed by EIDs and the health benefits of biodiversity (among others).

8. Ensure that the post-COVID-19 approach to development is equitable and sustainable

The Intergovernmental Science-Policy Panel on Biodiversity and Ecosystem Services has called for fundamental, system-wide reorganization across the economic and social sectors (IPBES 2019). Transformative changes could include greater attention to how nature's benefits are being distributed, how the costs of environmental degradation are being paid, and “steering away from the current limited paradigm of economic growth.”

This is where sustainable development joins the discussion of biodiversity conservation, climate change, and human health. The United Nations Sustainable Development Goals (Griggs et al. 2013) were sidelined by COVID-19 and are now being reconsidered by governments that have recognized some of the weaknesses of the SDGs (Nilsson et al. 2016), including their negative impacts on biodiversity (Zeng et al. 2020). The SDGs depended on sustained economic growth, based on globalization of human movement, interconnectedness, finance, trade, resource exploitation, and investment in infrastructure that reached into the world's remaining forests and other natural habitats. The SDGs may well have contributed to conditions that enabled COVID-19, so the new development path should be decoupled from the growth issues (Naidoo and Fisher 2020) and focus on building improved well-being with renewable resources, clean air and water, a stable climate, human health, and ecological sustainability—in other words, a high quality of life.

Especially during times of crises like COVID-19, sustainable development must reach out to the most remote and marginal communities to promote alternative livelihood options and food production that reduce consumption of wild species that may be reservoirs of zoonotic diseases. Indigenous peoples exercise traditional use rights to about 38 million km², intersecting with about 40% of terrestrial protected areas (Garnett et al. 2018). Their adaptability, though, is being tested by COVID-19 and the global push for resources that threatens their way of life (Ford et al. 2020), so special attention needs to be given to ensure their sovereignty over their resources. This supports the growing interest in forming productive collaboration among Indigenous and local communities, protected area managers, and relevant government environmental agencies as a significant contribution to a sustainable future.

9. Design and implement a system of nature-compatible international trade

COVID-19 is having a major impact on global trade that complicates the political problems the world is facing. Trade has already been challenged by manufacturing being

essentially shut down for at least several weeks to several months in many countries, and the closing of many borders (both domestic and international) as a means of slowing transmission of the virus. Growing protectionism means that the future of global trade is likely to be very different than it was before the COVID-19 epidemic (Brown 2020), including shorter supply chains that will yield significant environmental benefits.

Sustainable trade will require consumers to be well informed about the environmental impact of the products they are purchasing, and policies that are coordinated at the producing, trading, and consuming levels. Protecting species of plants and animals from trade using CITES needs to be streamlined by measures directed at certified sustainable trade in commodities such as tropical forest timber, beef, and palm oil that ensures their production did not destroy biodiversity, had positive impacts on climate change, and did not contribute to EIDs such as COVID-19.

A well-designed legal system of regulated wildlife trade and captive breeding that would not threaten the survival of any species or contribute to future zoonoses would need to be consistent with the CBD and CITES and draw on data from the IUCN Red List of Threatened Species (Ceballos et al. 2020). Note that nearly two-thirds of the species identified on the Red List as being threatened by trade are not promptly protected under CITES, a process that needs to be accelerated (Frank and Wilcove 2019). The new system should include measures to halt the spread of invasive alien species, give strong protection to the wild species that warrant it, monitor the impacts of trade from captive breeding in markets and in natural habitats, compile accurate and timely data on wildlife trading and consumption, prevent the flow of species carrying potential pathogens, enforce health regulations on the handling of wild and domestic species, and mobilize artificial intelligence and machine learning to detect and disrupt illegal trade (Di Minin et al. 2018).

Action at the demand side also needs to be part of addressing the problem of wildlife trade. A social media campaign that highlights the dangers of trade-linked EIDs and damage to biodiversity could weaken especially the illegal aspects of this market, using socially relevant media and approaches (Thomas-Walters et al. 2020).

10. Build cooperation to address climate, biodiversity, and emerging infectious diseases together

A biodefense approach addressing the COVID-19 pandemic, biodiversity loss, and climate change crises together could use economic incentives for greening national economies. Investments to support their recovery could include effective responses to climate change rather than

supporting fossil fuels (especially coal); such green investments yield more jobs per dollar invested than do fossil fuel investments and are being embraced by the mayors of large cities in many parts of the world (McCormick 2020). The co-benefits for health could provide stronger support for strong climate change mitigation measures (Haines 2017) that also benefit wild species and ecosystems.

Other useful steps include providing tax incentives for reforestation on private lands; removing subsidies from construction in areas vulnerable to climate change; ensuring that all new infrastructure is designed and built to address the climate changes that are coming (Aizawa 2019); locating solar and wind installations away from important wildlife habitats and migration corridors; remediating degraded natural habitats and supporting the outdoor economy; and supporting research on long-term carbon sequestration and adaptation to climate change.

CONCLUSIONS

COVID-19 has focused the world's attention on a global threat, and globalization has enabled the spread of the pandemic. So can today's world respond by generating a new approach that will set Planet Earth on a new path to sustainable development? As a start, the global crisis of COVID-19 calls on governments, the private sector, international organizations, and public interest groups to address the major global environmental problems together, as a package of traditional knowledge and science-based responses that can earn the confidence of all sectors of society and to which all can contribute to the extent of their capacity.

COVID-19 provides a powerful incentive and opportunity to address the interconnected issues of human health, climate change, and biodiversity loss in a coordinated and effective manner: to develop a biodefense system for Planet Earth.

The biodefense can start by ensuring that substantial post-COVID-19 stimulus funding is provided to environmental issues that could include: investments to conserve biodiversity and ecosystem services that serve significant public needs both immediately and in the long term; support rural livelihoods that encourage sustainable production and consumption that includes agriculture and forest conservation; provide means to enable urban people to become reintroduced to nature; address national climate change objectives, especially using distributed and low-carbon options such as solar power; and support cultural diversity that can apply traditional knowledge to modern sustainable development activities.

The Convention on Biological Diversity is in the midst of preparing a new 10-year Global Biodiversity Framework, and this provides an opportunity to discuss innovative ideas, such as Half Earth, and seek broader support for global cooperation to support a more equitable and environmentally sound form of sustainable development. The many other such initiatives that will be helping the world recover from COVID-19 should learn from its lessons: sound preparation, sound science, public participation, and early response are keys to successful responses to the global crises that are arriving at an accelerating pace. COVID-19 can be a catalyst to set the global society on a new path to a sustainable relationship between people and the rest of nature: a greening of human society.

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