Environmental Science and Policy 111 (2020) 7–17

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

The role of ecosystems in mitigation and management of Covid-19 and other zoonoses

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ARTICLE INFO

Keywords:
Zoonotic diseases
Ecosystem services
Water security
DPSIR
Socio-Ecological systems
Regeneration

ABSTRACT

There is rising international concern about the zoonotic origins of many global pandemics. Increasing human-animal interactions are perceived as driving factors in pathogen transfer, emphasising the close relationships between human, animal and environmental health. Contemporary livelihood and market patterns tend to degrade ecosystems and their services, driving a cycle of degradation in increasingly tightly linked socio-ecological systems. This contributes to reductions in the natural regulating capacities of ecosystem services to limit disease transfer from animals to humans. It also undermines natural resource availability, compromising measures such as washing and sanitation that may be key to managing subsequent human-to-human disease transmission. Human activities driving this degrading cycle tend to convert beneficial ecosystem services into disservices, exacerbating risks related to zoonotic diseases. Conversely, measures to protect or restore ecosystems constitute investment in foundational capital, enhancing their capacities to provide for greater human security and opportunity. We use the DPSIR (Drivers-Pressures-State change-Impact-Response) framework to explore three aspects of zoonotic diseases: (1) the significance of disease regulation ecosystem services and their degradation in the emergence of Covid-19 and other zoonotic diseases; and of the protection of natural resources as mitigating contributions to both (2) regulating human-to-human disease transfer; and (3) treatment of disease outbreaks. From this analysis, we identify a set of appropriate response options, recognising the foundational roles of ecosystems and the services they provide in risk management. Zoonotic disease risks are ultimately interlinked with biodiversity crises and water insecurity. The need to respond to the Covid-19 pandemic ongoing at the time of writing creates an opportunity for systemic policy change, placing scientific knowledge of the value and services of ecosystems at the heart of societal concerns as a key foundation for a more secure future. Rapid political responses and unprecedented economic stimuli reacting to the pandemic demonstrate that systemic change is achievable at scale and pace, and is also therefore transferrable to other existential, global-scale threats including climate change and the 'biodiversity crisis'. This also highlights the need for concerted global action, and is also consistent with the duties, and ultimately the self-interests, of developed, donor nations.

1. Introduction

Zoonotic diseases – diseases that pass from an animal to a human – have gained international attention in recent years (UNEP, 2020). In addition to the SARS-CoV-2 virus causing the global Covid-19 pandemic, still developing at the time of writing, some of the other diseases transferred from animals to humans over recent years include Ebola, avian influenza ('bird flu'), H1N1 flu ('swine flu'), Middle East respiratory syndrome (MERS), Rift Valley fever, sudden acute respiratory syndrome (SARS), West Nile virus and the Zika virus. Many serious emerging zoonotic infections have originated from bats, including Ebola, Marburg, SARS-coronavirus, Hendra, Nipah, and a number of rabies and rabies-related viruses (Wood et al., 2012). Although these diseases exhibit a diversity of characteristics, including in their mode and rapidity of transmission, all have carried the threat of pandemics, with some of those threats having been realised in the form of many thousands of excess deaths[1] and economic losses in the billions of dollars. The majority of human infectious disease events that have emerged in recent decades have their origins in wildlife (Jones et al., 2008), with 65% of all human pathogens discovered since 1980 having

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[1] Epidemiologists use the concept of 'excess deaths' to refer to deaths that occur over and above normal background morbidity levels.

https://doi.org/10.1016/j.envsci.2020.05.017
Received 8 May 2020; Received in revised form 19 May 2020; Accepted 21 May 2020
Available online 26 May 2020

been identified as zoonotic viruses (Woolhouse, 2002). Through a review of the literature available at the time, Taylor et al. (2001) identified 1415 species of infectious organism known to be pathogenic to humans, 61% of these zoonotic. That analysis also concluded that 75% of emerging pathogens were zoonotic, with zoonotic pathogens twice as likely to be associated with emerging diseases than non-zoonotic pathogens. Pathogen transfer from wild species appears to be particularly prevalent, despite contact between humans and wildlife being rarer than with domestic animals. Kreuder Johnson et al. (2015) concluded that 86 of 95 zoonotic viruses (91%) were transmitted from wild animals, 24 of these potentially transmitted by both wild and domestic animals, and only 8 uniquely from domestic animals. This implies that 62 out of 95 (65%) are uniquely derived from wild animals. UNEP (2016) recognised a global increase in zoonotic epidemics, including 75% of emerging infectious human diseases, the origins of which were identified as closely linked with environmental changes and which were emerging at a rate of, on average, one new infectious human disease every four months. Khabbaz et al. (2015) recognised 25 emerging or re-emerging infectious disease threats linked to wildlife between 2000 and 2013.

According to these analyses, a key contributory factor in the increase in number and diversity of zoonotic diseases has been the extent to which humans are increasingly interacting with, and impacting upon, ecosystems, given the close relationships between human, animal and environmental health. For example, land use change has been estimated by the EcoHealth Alliance (2019) to be linked to 31% of outbreaks of emerging infectious diseases (EIDs), including HIV, Ebola, and Zika virus, which are considered connected to anthropogenic changes in tropical rainforests, with 15% of these EIDs linked to agricultural changes.[2] Virus transmission risk has been recognised as highest from animal species that have increased in abundance and/or expanded in range by adapting to human-dominated landscapes, with domesticated species, primates and bats identified as carrying the greatest risk of zoonotic virus transmission (Kreuder Johnson et al., 2020). In essence, the Anthropocene (Crutzen and Stoermer, 2000) has unwittingly created new propagation pathways by overriding or degrading those ecosystem services that might otherwise help to suppress disease propagation. Simultaneously, ecosystem degradation driven by intense human activities has undermined ecosystem services such as fresh water provision, essential for hygiene to prevent human-to-human transmission and for treating resultant infections. Intrusion into and conversion of habitats by humans promotes propagation pathways by degrading natural barriers in ecosystems, and by facilitating practices such as the bushmeat trade and 'wet markets'[3] that increase the risk of animal-human contact in developing world settings.

Humanity's relationship with the natural environment will inevitably include interaction with zoonotic diseases, and can also define (and currently all too often limit) our ability to respond to them.[4] Overexploitation of ecosystem services beyond natural carrying capacities, especially where these have been converted by human activities into disservices, potentially heightens risks of zoonotic diseases. Conversely, regeneration of ecosystems constitutes investment in foundational natural capital providing greater human security and opportunity, as evidenced by fragmented ecosystem-based socio-ecological regeneration schemes around the world (Everard, 2020). Whilst some nature-based solutions may exacerbate disease risks if poorly planned, for example inappropriately sited and managed open water systems potentially promoting malaria in urban areas, both restored ecosystems and nature-based methods emulating natural functions can enhance disease regulation as part of a linked set of societally co-beneficial ecosystem services (Medlock and Vaux, 2015). By reinstating lost ecosystem processes, these nature and nature-based solutions may potentially rebuild barriers to disease organisms transferring from animals to humans. In addition, these forms of regeneration of ecosystem functions could, if combined with sustainable management of human activities and infrastructure, enhance benefits such as access to adequate supplies of clean water, which have significant roles to play in the management of disease outbreaks. The globally-coordinated *UN Decade on Ecosystem Restoration 2021–2030* (UN, 2019a) is an attempt to respond to the loss and degradation of habitats through programmes to rebuild and restore humanity's relationship with nature.

In this paper, three aspects are examined through the lens of the DPSIR (Drivers-Pressures-State change-Impact-Response) framework populated by evidence from the literature, with a view to identifying a set of appropriate response options: (1) the significance of disease regulation ecosystem services and their degradation in the emergence of Covid-19 and other zoonotic diseases and of the protection of natural resources as mitigating contribution to both (2) regulating human-to-human disease transfer; and (3) treatment of disease outbreaks.

2. Methods

The DPSIR framework – comprising Drivers-Pressures-State change-Impact-Response elements (see Fig. 1) – has been developed since the 1990s (European Environment Agency, 1999) as a policy-relevant organising tool for describing, communicating and analysing complex systemic interrelationships between society and the environment, and thereby for addressing cause-effect pressure-state change links. The principal components comprise Drivers or driving forces (socio-economic sectors that drive human activities), Pressures (human activities that stress the environment), resulting environmental and ecological State change (changing conditions of the natural and living phenomena), Impacts on services and values (effects of environmental degradation of ecological attributes and ecosystem services), and Responses to those impacts (policies and responses) (Bradley and Yee, 2015). The DPSIR framework has subsequently been used by other bodies, for example, adoption by the United Nations (UNEP, 2007) and the US Environmental Protection Agency (EPA) (Bradley and Yee, 2015), and applied to management problems in a diversity of agricultural, water resource, land and soil, biodiversity, marine, human health and other settings. There are now 25 derivative schemes and a widespread and increasing usage of the DPSIR-type conceptual framework as a means of structuring and analysing information in management and decision-making across ecosystems albeit subject to variations in interpretation mainly between natural and social scientists (Patrício et al., 2016). The DPSIR framework is used here as a conceptual basis for analysing the human-environmental linkages entailed in facilitating zoonoses, including Covid-19, leading to recommendations for strategic responses to current and future threats.

Our starting point in this case is the identification of a set of pressures facilitating the emergence of infectious diseases, including zoonoses, which can be linked back to some over-arching primary drivers. Pressures increasing contact between wild animals, domestic animals and humans are of particular interest in this analysis. Pressures identified include deforestation and other land use changes, intensified agriculture and livestock production, illegal and poorly regulated

[2] There is a distinction between, on the one hand, Ebola that has emerged and re-emerges periodically as a consequence of direct contact between humans and wild animals and, on the other, HIV which transferred to humans from animals decades ago and has since spread massively in humans such that it is no longer a zoonosis (though initially of zoonotic origin) but is currently an anthroponosis (Hubálek, 2003).

[3] 'Wet markets' are widely defined as those that sell fresh vegetables and animals, many live, particularly where refrigeration is not available. However, in this context we apply the term particularly to markets that trade in live wild animals sold for food.

[4] Historically, bubonic plague, which has killed more than 100 million people in several pandemic waves since the 6th century 'Plague of Justinian', may be the best known and most impactful zoonotic disease. Transmitted from rodents to humans by a flea vector, the *Yersinia pestis* bacterium has been found in archaeological investigations as far back as the Bronze Age.

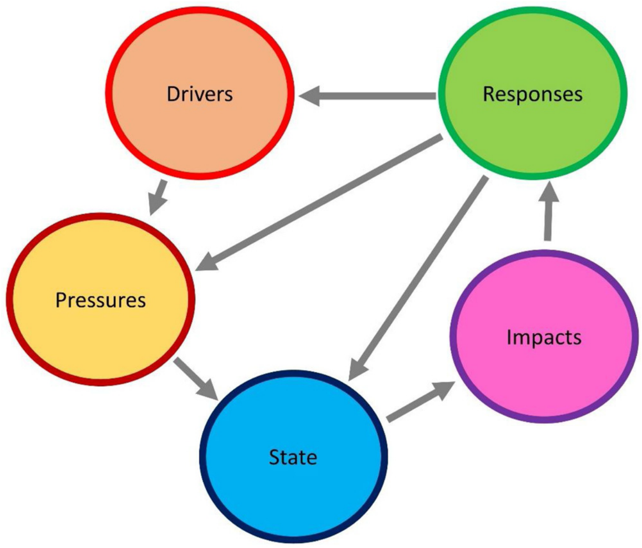

Fig. 1. The DPSIR model.

wildlife consumption and trade, and land use changes for purposes other than agriculture (UNEP, 2020; Kreuder Johnson et al., 2020). Jones et al. (2013) found strong evidence through literature review that agricultural intensification and environmental changes increase epidemiological interactions between wildlife and livestock, contributing to zoonotic transfer. These pressures are further exacerbated by, for example, cavalier use of antibiotics stimulating antimicrobial resistance, as well as by the background of ongoing climate change acting as an aggravating factor (UNEP, 2020; Kreuder Johnson et al., 2020). Relationships between climate variables and the emergence and re-emergence of infectious diseases are complex. Some risks are expected to decline, such as those from water-vectored diseases under drier conditions in hotter climates, whilst others may increase, for example, the spread of some disease vector species to higher latitudes. A range of other factors, including different levels of access to education and capacities for adaptation (Khan et al., 2019), may contribute further to differing community vulnerabilities. Overall, the WHO (2003) expresses high confidence that the negative health effects of climate change outweigh positive effects at the global level, necessitating mitigation of climate change as well as adaptation measures, such as improving institutional and technological capacity, to strengthen health resilience to climate change. UNEP (2020) also identify population growth, urbanisation and globalisation[5] as important driving factors behind the emergence of novel infectious diseases in humans.

3. Results

This Results section draws upon evidence of Drivers, Pressures, State-change and a disaggregated set of Impacts, leading on to considerations of Responses which are substantially addressed in the Discussion section that follows.

[5] The term used by UNEP is actually ‘internationalisation’. Internationalisation comprises increasing importance of trade, relations, treaties, alliances and other exchanges between nations, whilst globalisation refers to the growing trend towards economic integration of formerly national economies through vectors such as free trade, capital mobility and facilitated migration (Daly, 1999). Expansion on these distinctions is peripheral to the thrust of this paper, so the term ‘globalisation’ is used synonymously with ‘internationalisation’ throughout.

3.1. Drivers

The vast growth in the human population, particularly since the start of the twentieth century, means that there are some 7.8 billion humans on the planet in 2020 with numbers still climbing by some 8.1 million per year (Anon. Worldometers.com, 2020). This has correlated strongly with *inter alia* historical and current declines in global forest cover (d’Annunzio et al., 2015), increasing rates of land degradation, and elevated rates of species extinction (Scott, 2008) as headline indicators of ecosystem degradation. IPBES (2019) found that 75% of the global land surface is already significantly altered, and 66% of oceanic areas are experiencing increasing cumulative impacts from human activities, while over 85% of global wetland area has been lost. Human resource appropriation in 2007 already accounted for 23.8% of potential net planetary primary productivity (Haberl et al., 2007), since which date the human population has increased by more than 15% (one billion people) on a planet with continuously degrading resources. Today, well into the Anthropocene (Crutzen and Stoermer, 2000), an estimated 96% of all mammalian biomass on Earth comprises humans and their livestock (Bar-On and Phillips, 2018). Industrial nitrogen fixation has increased exponentially since the 1940s, essentially doubling the amount of nitrogen fixed globally, with the amount of nitrogen fixed by human activities predicted to exceed that fixed by microbial processes by 2030 (Vitousek et al., 1997). Resultant eutrophication changes ecosystem structure, function and resilience (Chislock et al., 2013). In short, our cumulative activities exert a dominating influence on ecosystem structures and function (Millennium Ecosystem Assessment, 2005).

Cumulative demands of contemporary global society effectively consume an equivalent of the annual production of natural resources of 1.7 ‘Planet Earths’ (Global Footprint Network, 2020), as anthropogenic pressures on the Earth System transgress planetary boundaries beyond which abrupt global environmental change can no longer be excluded (Rockström et al., 2009). Ecosystems are consequently now in precipitous decline globally, threatening the viability of the natural world and the diversity of ecosystem services essential for continuing human security and opportunity. Seriously declining trends in global biodiversity and, consequently, the capacities of natural systems to support human wellbeing are detailed by the Millennium Ecosystem Assessment (2005) which concluded that, in the preceding 50 years, humans had changed ecosystems more rapidly and extensively than in any comparable period of time in human history.

Loss of biodiversity is proceeding at such a rate that we appear to be facing a mass extinction event (Barnosky et al., 2011), an irreversible loss to the planet that also threatens humanity’s life support system (Díaz et al., 2006; Cardinale et al., 2012; Hooper et al., 2012). Populations of many wild animal species are well under half the size they were in 1970 (WWF, 2018). Beyond the sheer loss of numbers of individuals and of species, we are also seeing unprecedented ‘biotic homogenisation’, in which the introduction of non-native species and the extinction of local biodiversity decreases the genetic, taxonomic and functional diversity of different locations (McKinney and Lockwood, 1999). The net result is to simplify ecosystems and to make them progressively less reflective of their original, local state. In turn, these increasingly vulnerable ecosystems are only capable of generating a narrower set of the ecosystem services on which human society relies. Despite various commitments intended to address these pressing problems, most indicators of the state of biodiversity have shown continued rates of decline with no significant recent slowing of the trends. Accurate or meaningful estimates of extinction rates are notoriously elusive, rates varying between taxa and geography. However, Ceballos et al. (2015) applied conservative assessments to calculate that average rate of vertebrate species loss over the last century is 100 times higher than the background rate, indicating that a sixth mass extinction is under way.

Urbanisation and globalisation constitute linked drivers. In 2018, 55% of the world's population was living in urban areas, a proportion expected to increase to 68% by 2050, adding another 2.5 billion people to those already inhabiting urban areas with close to 90% of this increase taking place in Asia and Africa (UN, 2018). Globalisation, a trend arguably initiated in the 'silk roads' of the 1st century BC, accelerated rapidly from the 2000s when global exports rose to about a quarter of global GDP, in a global economy in which countries including Singapore and Belgium handle trade exceeding 100% of their national GDPs (Vanham, 2019). By making demands on increasingly remote hinterlands or extended supply chains, intensifying urbanisation and globalisation trends erode perceptions of close dependence and likely impacts on ecosystems, and the need for their sustainable management (Girardet, 2014).

Further compounding driving factors adding to pressures on global ecosystems include the burgeoning middle class. In 2020, approximately half of the world's population of in excess of 7.7 people globally were defined as "middle class" of "rich" (World Data Lab, 2020). Although development confers many benefits for its recipients, growth in per capita material consumption and use imposes additional pressures upon ecosystems. This is illustrated, for example, by the finding that the carbon footprint of middle class UK households is generally 50% higher than borderline poor households (Minx et al., 2009).

Changing geographies of human settlement create further drivers. Although half of the world's population lives on just 1% of the land surface (Misra and Citylab, 2016), and large established cities are still growing, the world is also experiencing a proliferation of medium-sized towns and cities. Furthermore, 95% of the Earth's land surface has some indication of human modification, while 84% has multiple human impacts (Kennedy et al., 2019). The net effect of this is that a decreasing extent of the Earth's surface is distant from human settlement, reducing barriers to contact and even driving cohabitation between people and wild animals.

3.2. Pressures

The drivers described above change both the wider environment and the ecosystem processes taking place within it. Degradation of the buffer zones that normally act as natural 'firewalls' separating humans from wild animals substantially increase opportunities for pathogens to spill over, exacerbating rather than regulating inter- and intra-species transmission of disease-causing organisms. A further facet of degraded ecosystems is that their associated ecosystem services, upon which people depend to better manage disease, also tend to be undermined.

UNEP (2020) recognised five principal pressures increasing the emergence of zoonoses: deforestation and other land use changes; antimicrobial resistance; intensified agriculture and livestock production; the illegal and poorly regulated wildlife trade; and climate change. Habitat changes, mainly through modification for human uses, include deforestation and increasing 'land take' for agriculture, habitation and civil infrastructure. These changes directly bring wildlife and people into closer proximity, simultaneously also degrading ecosystem services, including disease regulation, through degrading natural barriers to transmission as well as undermining water security, which reduces opportunities for good hygiene practices. Risks of zoonotic diseases transferring to humans are particularly elevated in tropical forests, which naturally support high biodiversity, when subject to significant changes in land use that bring formerly isolated wild animals into closer proximity to humans (Allen et al., 2017). Numerous emergent infectious diseases are connected to human-induced changes in tropical rainforests (EcoHealth Alliance, 2019). For example, deforestation and landscape fragmentation have been observed to accelerate direct contact and transmission of zoonotic infections between wild nonhuman primates and humans in Ugandan forests (Bloomfield et al., 2020). Road construction supporting selective logging of relatively intact forest areas also increases contact between scattered village and urban populations with access to international travel, facilitating and accelerating the spread of emerging diseases (Wolfe et al., 2005). Deforestation is one of many negative trends – along with *inter alia* soil erosion, water resource depletion and eutrophication, emissions of climate-active gases, and deterioration of air quality – that together result from a combination of population, lifestyle and other pressures. Many of these pressures have arisen from technically efficient exploitation of ecosystems with scant or no regard for their renewability, or for the overall sustainability of those activities, leading to a degenerative socio-ecological cycle in which essential natural resources become progressively liquidated for short-term gains whilst undermining the capacities of ecosystems to provide security and opportunity for many in society (Everard, 2020).

Cavalier use of antibiotics, another of the key pressures identified by UNEP (2020), tends to favour mutations, increasing the resistance of microbial organisms to control agents over time. The expansion and growing intensification of livestock production, often as 'monocultures' of narrow genetic diversity, may be of particular concern in this regard, especially where this takes place in close proximity to high human populations. Although antibiotics are not effective against viruses, approximately 60% of infectious diseases in humans are caused by other zoonotic pathogens, many of which may develop antibiotic resistance as they are transferred to humans (Dafale et al., 2020).

Depletion of natural resources and ecosystem service flows increases pressure from people exploiting alternative food sources. It also undermines vital resources necessary for maintaining health, particularly access to safe, fresh water. Frequent washing has been identified as a key factor in slowing the spread of Covid-19 and other pathogens (UNICEF, 2020), reiterating long-standing basic disease management guidance (WHO, 2009). This is particularly the case for coronaviruses, as using soap breaks down their fatty outer layer. Degradation of water systems therefore plays a significant role in the potential spread of infections, including zoonotics, particularly for the least advantaged in society through undermining access to safe water and sanitation. Recognising such challenges, and in response to the unfolding Covid-19 pandemic, the WHO (2020) has recently made recommendations to improve hand hygiene practices to help prevent transmission, such as by: (1) providing universal access to public hand hygiene stations and making their use obligatory on entering and leaving any public or private commercial building and any public transport facility; and (2) improving access to hand hygiene facilities and practices in health care facilities. Many health agencies recommend washing hands for a minimum of 20 s up to 8–10 times per day. Taps in the average hand basin run at 2–3 litres per minute, implying a total water requirement of 7–8 litres of clean water per person per day, as well as appropriate soap and safe drying facilities, in order to maintain hand hygiene alone (Staddon et al., 2020). These targets may be easy to achieve in wealthier and wetter parts of the world, yet as many as 1 in 5 people around the world lack access to a sufficient and secure supply of safe water. This is especially the case in parts of Africa, Asia and Latin America and in megacities elsewhere, particularly where overcrowded slum housing conditions prevail or peri-urban settlements lack infrastructure, with the consequence that such communities bear a disproportionate share of resultant global health burdens (UNICEF and WHO, 2019). For example, three people die every minute of diarrheal illnesses (1.5 million per year) and six people die every minute from respiratory diseases (3 million per year), risks substantially exacerbated by the Covid-19 pandemic, especially if the strategy of viral suppression cannot be supported through basic hand hygiene (Staddon et al., 2020). Problems of water insecurity also extend into higher-income countries, with an estimated 57 million people across Europe and North America lacking piped water at home (WWAP, 2019). Furthermore, 'forgotten' and neglected populations, including prisoners, the homeless, refugees, undocumented migrants and displaced people are all at heightened risk of disease exposure and transmission due to their reliance on precarious water, sanitation and hygiene facilities (Panhuis, 2018). UN (2015) Sustainable Development Goal No.6 (SDG6) refers specifically to

"Ensure availability and sustainable management of water and sanitation for all". A report on SDG6 in 2019 found that, despite some progress, billions of people still lack safe water, sanitation and handwashing facilities with most countries unlikely to reach full implementation of integrated water resources management by 2030. 785 million people were still lacking even basic drinking water services in 2017 (UN, 2019b). Accelerated transmission of Covid-19 and other zoonoses through underprivileged sectors of society leads to direct impacts for those individuals, families and communities, as well as creating potential reservoirs for subsequent transfer and resurgence of infections within wider populations. In an increasingly interconnected world, the resilience benefits of universally enhanced hygiene may provide a bulkhead against future health crises everywhere on earth, with international aid conferring mutual benefits to both recipients and donors.

Increasing travel related to globalisation, including improved connectivity to more areas of the Earth, can also clearly act negatively as a potent vector for subsequent human-to-human transmission. Changes in dietary preferences may also increase still further animal-human exposure, such as, for example, in the cases of avian influenza, SARS and Ebola in which livestock served as an epidemiological bridge between wildlife and human infections.

3.3. State

The ecosystem service of 'disease regulation' is a core element of the Millennium Ecosystem Assessment (2005) classification of ecosystem services underpinning human wellbeing, and is also incorporated in various subsequent ecosystem service reclassifications. The Millennium Ecosystem Assessment (2005, p.91) also recognises the existence of "*… established but incomplete evidence that changes being made in ecosystems are increasing the likelihood of non-linear changes in ecosystems (including accelerating, abrupt, and potentially irreversible changes) that have important consequences for human well-being*", including disease emergence. The Assessment goes on to conclude that changes in ecosystems, including through anthropogenic climate change, can directly change the abundance of human pathogens. Naturally, ecosystems are inherently resilient and adaptable, including in their capacities to regulate diseases.

Ecosystem disturbance and depletion can affect emergence of zoonotic pathogens where natural vertebrate hosts and disease vectors with generalised feeding habits become dominant (Ostfeld and Keesing, 2000). High vertebrate diversity within ecosystems exerts a 'dilution effect' on the impact of small proportional populations of principal disease reservoir species, thereby reducing risks of disease transfer to humans (Ostfeld and Keesing, 2000; LoGiudice et al., 2003). Predation on these principal vertebrate disease reservoir species may also play an important role in reducing risks of disease transfer (Khalil et al., 2016). UNEP (2020) concluded that greater biodiversity makes it more difficult for one pathogen to spread rapidly or dominate but, conversely, human modification of wildlife population structures (including an unprecedented rate of biodiversity reduction) produces conditions favourable to particular hosts, vectors and/or pathogens. Increasing incidences in recent years of novel zoonotic diseases suggests that global risks are being poorly managed at present.

Ecosystems naturally produce a wide diversity of services in addition to disease regulation. Consequently, the currently degraded state of ecosystems along with their associated services results in a declining availability of natural resources. Shortages in the state of some of these resources, particularly including fresh water vital for hygiene and sanitation, can seriously compromise the meeting of health care needs, disproportionately so in developing nations. There is growing recognition of the importance of ecosystem health as a key underpinning factor in human health, although it has to date been poorly represented in, or largely absent from, strategies to manage human health (Convention on Biological Diversity and World Health Organization, 2015; Lu et al., 2015).

3.4. Impacts

Impacts arising from these drivers and pressures can be stratified using the STEEP (social, technological, environmental, economic and political/governance) framework. STEEP was adapted from a range of allied classification schemes (Morrison and Wilson, 1996), primarily for analysis of an organization's operating environment and preparing for organizational transitions (Schmieder-Ramirez and Mallette, 2007). However, the framework has since been applied to analyse interconnections between domains of human activity, in particular with regard to meeting the goals of sustainability (Steward and Kuska, 2011), and applied as a systems framework addressing systemic interdependences between constituent elements to evaluate water systems and associated ecosystem services (Everard et al., 2012; Everard, 2013, 2015).

Social impacts of current exposure to animal-human pathogen transfer include increased health threats, particularly for the least affluent and most vulnerable in society. These same societal sectors suffer the greatest threats from degraded ecosystem services that would otherwise be capable of regulating diseases and of providing sources of safe water and food. They also lack engineered infrastructure facilitating provision of adequate water for washing and for sanitation.

Technological impacts include some damaging positive feedbacks through increasing use of technically efficient extractive technologies. Examples include legal and illegal felling of forests depleting this primary resource and its associated ecosystem services, mechanised tube wells chasing increasingly receding groundwater, and appropriation of water from rural areas by dam-and-transfer schemes favouring the demands of cities and other intensive water users whilst depleting the natural resource (Everard, 2019). Technological solutions tend to be developed and implemented to favour privileged and more influential sectors of society, thereby deepening both societal inequities as well as longer-term vulnerabilities to natural resource depletion.

Environmental impacts also include positive feedback loops that can accelerate current downward trends on the integrity of ecosystems and their services, for example with degrading food availability driving more intensive and/or remote foraging for bushmeat. Pressures from technological intensification and market economics further compound impacts on ecosystems. These factors have the cumulative effect of progressively decreasing ecosystem structure, processes and flows of essential ecosystem services. Negative impacts are visited disproportionately on underprivileged sectors of society eking out a living by exploitation of marginal ecosystems, which may also result in increasing susceptibility to novel diseases through greater reliance on practices such as bushmeat hunting.

The dominant market economic model is a source of multiple impacts across the STEEP system. However, impacts upon the economy are seen in the current economic melt-down caused by the Covid-19 pandemic. Unprecedented market intervention and aid packages by central banks and national governments worldwide exceed, in both scale and their radical nature, the economic responses to the near-global recession of 2007 – 2009. The lessons of history suggest that these effects will be long-term, some even permanent. The World Bank (2020) estimates that the Covid-19 'shock' will have serious impacts on poverty, with nearly 24 million fewer people escaping poverty across the East Asia and Pacific region in 2020 than would have in the absence of the pandemic (using a poverty line of US$5.50/day). Furthermore, if the economic situation deteriorates further, it is estimated that poverty may actually increase by around 11 million people. During 'lock-down' restrictions imposed to slow the pace of disease transmission, employed and volunteer activities by many of the least well-remunerated in society – in healthcare, the food chain, delivery drivers, providers of vital water, power and telecommunications services, etc. – are proving the most vital to maintaining civil operations (although data on this at the present time are elusive). Relative poverty also correlated with higher age-standardised mortality involving Covid-19, rates in the most deprived areas of England over twice that compared the least deprived areas, and almost twice as high in Wales (ONS, 2020). Conversely, many of the best-paid play minor, no or superfluous roles in maintaining the functioning of society, reflecting an imbalance in recognition and rewards under established markets.

Political/governance impacts related to disease transfer and regulation and natural resource protection have largely prioritised economic growth over ecosystem protection to date, at least across developed world economies. In a globalised economy, this has tended to serve as a driver of degradation, creating a positive feedback loop in the DPSIR system, rather than securing the foundational capital of natural resources and regulating disease origination and management. Emergent political responses at the time of writing, including 'lockdown' measures and social distancing enforced on a statutory basis, are seeking to break links in the transmission chain, whilst there are many instances of civil society organising on an informal basis to help the most vulnerable gain access to food and other essential resources. Erosion of trust in government is manifest in social and broadcast media. Ideally, this may broker momentum for strategic change in governance that addresses root causes, particularly including environmental responses, rather than the short-term measures that are nonetheless important in a time of crisis management.

These impacts all, in one way or another, relate to declining ecosystem services brought about by a range of pressures including forest fragmentation, increasing human-animal contact, connectivity through travel and trade, and degrading water systems and climate stability. Systemic relationships across the STEEP model are represented illustratively, if far from completely, in Fig. 2.

3.5. Responses

Under the DPSIR model, the feedback loops leading from Responses relate to addressing the Drivers, Pressures and State changes that have been identified (see Fig. 1). Under a 'business as usual' strategy, the tendency is for positive feedback, wherein dominant short-term market forces behind established societal norms and vested interests form the foundations of much policy development and globalisation trends, such that destructive trends are more likely to be exacerbated rather than lessened or reversed. For this reason, much of the Discussion section of this paper focuses on proactive Responses aimed at addressing current and likely future risks associated with and stemming from zoonotic disease in more systemic and sustainable ways.

4. Discussion

UNEP (2020) concludes that, in the last century, a combination of population growth and reduction in ecosystems and biodiversity has culminated in unprecedented opportunities for pathogen transmission from animals to people. Simultaneously, nature's capacities to support multiple dimensions of human wellbeing (e.g. clean air, water, etc.) are also in sharp decline, compromising the meeting of varied human needs (Millennium Ecosystem Assessment, 2005; IPBES, 2019). This 'perfect storm', of increasing propensity for zoonotic disease generation and declining ecosystem capacities to provide essential services such as fresh water for washing and sanitation, exacerbates overall risks to humanity (see Fig. 3).

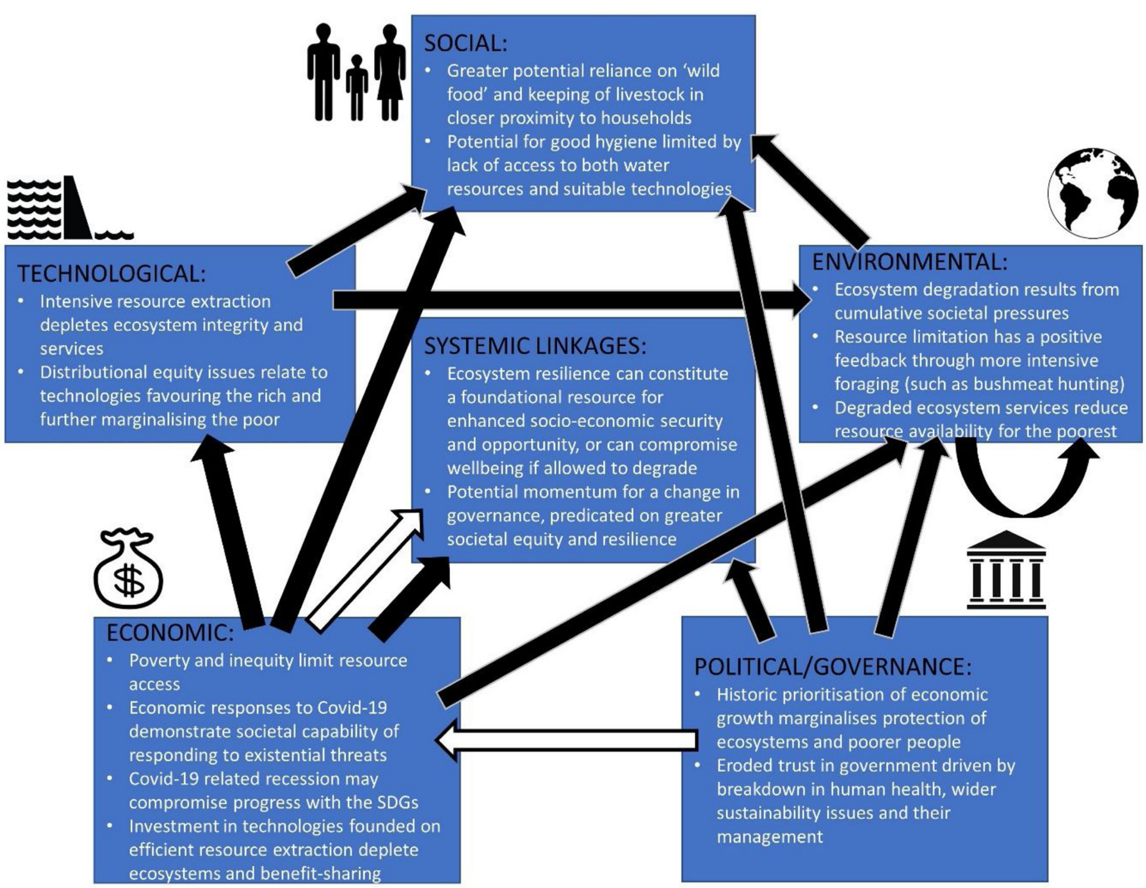

Fig. 2. Illustrative representation of systemic relationships across the STEEP system of current impacts leading to a degrading cycle in the socio-ecological system, including increasing vulnerability to zoonoses. Solid arrows represent negative influences; hollow arrows represent potentially positive influences.

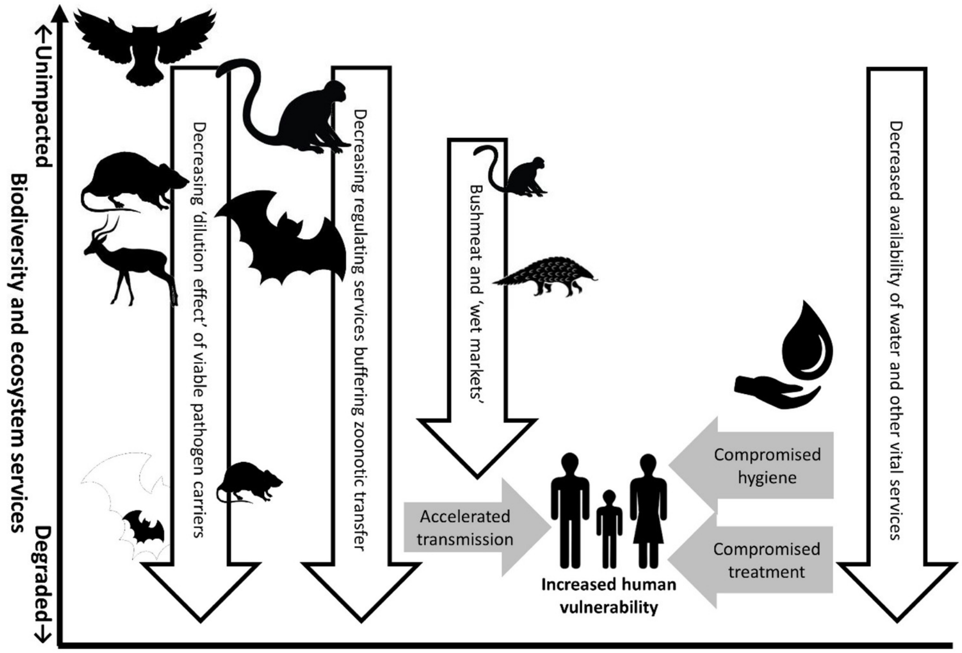

Fig. 3. Degradation of ecosystem services increases likelihood of zoonotic transfer simultaneously with declining water and other vital resources available to reduce human-to-human transmission and disease treatment.

4.1. Ecosystem restoration as a strategic response to zoonotic disease regulation

As ecosystems in a disturbed or depleted state can affect emergence of zoonotic pathogens in part due to a reduced 'dilution effect' on principal disease reservoir species (Ostfeld and Keesing, 2000; LoGiudice et al., 2003), ecosystem protection and restoration can play roles in improving natural regulation of disease transfer. Responses to address the five pressures discussed above – deforestation and other land use changes; antimicrobial resistance; intensified agriculture and livestock production; illegal and poorly regulated wildlife trade; and climate change – are all in one way or another already addressed under international commitments, the delivery of which has nonetheless been under-whelming to date. Deforestation and land use change, the impacts of agriculture, and the poorly regulated wildlife trade directly recognise the significance of ecosystem conservation, which also plays significant roles in reducing emissions as well as sequestering climate-active gases.

As one example, internationally concerted implementation of programmes and solutions already agreed will be essential to control atmospheric emissions contributing to climate change, and yet progress to date has been painfully slow (Tollefson, 2019). Urbanisation and internationalisation are also evident trends that may be difficult or impossible to control, so require some form of mitigation. This mitigation necessarily includes taking far greater account of the ecosystem interdependencies of urban populations in policy and financial systems, working to ensure greater circularity of resource use and reuse reflective of natural cycles and their sustainable limits in a desirable future 'ecopolis' (Girardet, 2014). This could form part of a regenerative model of ecosystem use, to replace the current trend of unsustainable exploitation without due account for regenerative capacities, establishing a new norm of considering and protecting foundational ecosystem services and capacities as a necessary underpinning across all societal policy areas (Everard, 2020).

The Covid-19 pandemic should stimulate far greater recognition that causal linkages between pressures on natural systems and outcomes for people are far from merely theoretical. Rather, they need to be addressed with urgency and at a systems level in order to safeguard future human wellbeing. The preceding analysis of pressures recognises that the currently declining state of natural resources and ecosystem service flows contributes to promoting zoonotic transfer and reductions in availability of adequate and sustainable water resources essential for basic washing and sanitation needs, emphasising the need to halt and then reverse current depleting trends. Further support for solutions to make these water resources available at household level are consistent with commitments under all seventeen of the UN (2015) Sustainable Development Goals, but particularly SDG6 to "Ensure availability and sustainable management of water and sanitation for all". The mutual benefits to both recipient and donor nations from aid to reduce reservoirs of novel and established diseases are self-evident.

4.2. The contentious issue of animal exploitation for zoonotic risk reduction

Responses to address the specific pressure of reducing or halting wildlife trafficking and consumption, both implicated in increasing risks of zoonotic transfer, are contentious. However, strategic action to reduce the associated risks cannot be avoided as hunting, eating and trafficking of wildlife poses a substantial risk for cross-species transmission. This threat is likely to grow in prominence globally as population density, habitat alteration, globalised trade and contact between humans and animals increases still further (Wolfe et al., 2005).

'Wet markets' in China and bushmeat in Africa in particular are strongly implicated in many recent zoonotic transfers, emphasising the need for responses that are both effective and can be implemented and supported at community level. Internationally, the Convention on Biological Diversity has called for a move to reduce the number of live animals in 'wet markets' and for stricter controls on the sale and consumption of wild species (CBD, 2020). The CBD (2020) also recognises that these markets are important for sustaining the livelihoods of millions of people, and that an outright ban might increase illegal trade in wild animals including already threatened species. Similar considerations apply to the regulation of bushmeat sources, particularly in Africa, where heavy-handed responses to the 'bushmeat crisis' can manifest as a 'cultural imperialism' imposed on societies with different value systems and subsistence needs (van Vliet, 2018). Some nature conservation measures in the Republic of Congo have become associated with significant human cost (Ayari and Counsell, 2017), influencing funding agencies to foster greater consideration of human rights-based approaches to their conservation programmes (van Vliet, 2018). Acknowledging conflicts between harvesting of wild meat for food security, livelihoods, traditions and nature conservation, and noting disease risks, CBD (2017) proposed measures to promote a controlled, sustainable wild meat sector.

Reform is also required in many dimensions of livestock farming in both the developed and developing worlds, as current intensive farming practices have been shown to increase risks of epidemics (Mourkas et al., 2020). Greenpeace (2018) calls for a more radical approach to farming and the human food chain with a vision of the meat and dairy system towards 2050 that lowers dependence on farmed animals, with improved, humane and more biosecure stewardship of lower livestock densities. Jones et al. (2013) concluded that the rate of future zoonotic disease emergence or re-emergence will depend heavily on the ways in which the agriculture–environment nexus will evolve in both policy and practical terms. The additional stressor of anthropogenic climate change influences temperature, humidity and seasonality, directly affecting microbial survival in the environment and the ranges of potential insect vectors of disease, both positively and negatively, and so acts as an amplifier on other pressures.

4.3. Responses to the Covid-19 pandemic

It is likely that Covid-19 will become a recurrent threat after the initial waves of the current pandemic have passed. However, widespread recognition of this reality creates opportunities for societal change. It is crucial that formerly established norms of politics, policy formulation and governance, with all of their inherent pressures exacerbating risks, are not allowed simply to revert to their former state under the pressure of vested interests. These would merely reinstitute the degenerative socio-ecological cycle from which multiple sustainability issues arise, including that of Covid-19 re-emergence.

Responses to impacts of the Covid-19 outbreak so far have included massive economic stimulus packages in nations around the world (reviewed for example by Alpert, 2020; The Economist, 2020). These include such measures as wage subsidies, interest rate cuts, quantitative easing, municipal bonds, expanded unemployment benefits, additional funds for medical care, lending facilities for smaller businesses, additional payments for people collecting government welfare support as well as the self-employed, child-care subsidies, job retraining for those losing jobs, and expanded insurance for health care workers. However, much of the world's population lives beyond the reach of such programmes (as examples, India and Uganda offered little social support beyond food aid) and the primary influence of market economics. These overlooked people include the world's large population of day labourers, dependent on finding work on a daily basis to earn money to buy food and other subsistence necessities, who cannot therefore easily lock themselves and their families down. Threats from both job and food insecurity may further increase vulnerabilities to infectious diseases. As one prominent example, following the introduction of a national lockdown throughout India on 24 March 2020, thousands of daily wage labourers started to migrate back to their home villages and towns, often walking tens or hundreds of miles, thrown into close proximity as a result and facing acute food and water insecurity both *en route* and on arriving home. The contribution of this migration to transmission of the virus is yet to be determined. As insecurity of water, food and livelihoods in home villages are major factors behind worker migration in India, a key strategic response to managing risks of disease transmission would be measures to restore ecosystem functioning to enhance village-level resource security, livelihood opportunities and self-sufficiency, preventing the need for distress migration whilst also enhancing hygiene.

Fish et al. (2011) reflect that history offers numerous high-profile lessons where, during moments of crisis, the inadequacies of rigid procedural rationality have been exposed. Fish et al. (2011) also highlight that, although technical innovation has important roles to play in zoonotic disease management, policy and governance need to be informed reflexively by broader social and natural science perspectives that also acknowledge inherent uncertainties. Two major essential transitions are proposed in a re-imagined, post-pandemic society. Firstly, a more concerted and rigorously applied ecocentric basis is required for decision-making across society, to reverse the current norms that tend to externalise, and thereby serve as drivers of, degeneration of ecosystems and their vital services. This in essence entails returning ecosystems to a more unimpacted state, as illustrated in Fig. 3, be that by restoration or by emulation through multi-beneficial nature-based solutions (Everard, 2020). Secondly, a more pro-social and equitable basis is also required. This includes recognition in development decisions and options appraisal of consequences for all in society, not just privileged and more influential sectors, with economic rewards recognising those integral to the smooth operation of society as demonstrated by those groups upon which society is now most dependent during pandemic management.

Economic stimuli post-pandemic, aimed at staving off impending global recession, can either attempt to revive existing economic models, or may alternatively be founded on a novel, more enlightened and sustainable model. Many established pre-pandemic assumptions and norms are inherently founded on ecosystem liquidation for rapid generation of rewards, driving a degrading socio-economic cycle (Everard, 2020). The stark choice is between perpetuating or accelerating feedback in the DPSIR system driving this degrading cycle by undermining the foundational infrastructure of ecosystems and services critically including disease regulation and water security, or alternatively recognising ecosystems and their services as critical natural infrastructure integrated into economic and political thinking to underpin a potentially regenerative cycle.

4.4. Establishing the ecosystem foundations of a changing world

There is growing recognition internationally that Covid-19 is not an isolated incidence, but is part of a pattern of increasingly frequent epidemics that have coincided with globalisation, urbanisation and climate change (Whiting, 2020). Looking beyond the current Covid-19 crisis to a world more alert to the potential for recurrent and novel infections, strategic changes in direction are necessary. The foundational roles of ecosystems and their services in regulating zoonotic emergence and providing water and other resources essential to suppress transmission and facilitate disease treatment are also pertinent to a range of linked sustainability challenges arising from currently degrading socio-ecological cycles. These linked issues include, for example, concerns for climate change, food and water insecurity, distress migration and environmental refugees, potential conflict sparked by resource scarcity and the 'biodiversity crisis'.

The scale of current emergency legislation and stimulus packages in response to the Covid-19 pandemic, and the pace at which they were introduced, demonstrate an institutional and societal capacity for substantial and timely response in the face of existential threats. The pressing issues of climate change and 'biodiversity crisis' are no less, and are arguably more, existential in nature, albeit perceived as approaching at a different pace. They are also indivisible from strategic solutions reversing the degradation of ecosystem services that currently exacerbates risks of zoonotic disease transfer and transmission. If these closely interlinked pressing issues are to be taken seriously, consistent with political pronouncements and stated commitments, a similar level of focus should be applied to implement proportionate response measures underpinning a more secure future.

In the context of climate change, the UK's Committee on Climate Change argue that economic stimuli packages with a focus on decarbonisation may be a more strategic approach during recovery from the coronavirus pandemic (Engineering and Technology, 2020). This is also consistent with messages from some lawmakers and campaigners in the UK and US concerning the need for a 'Green New Deal' (Engineering and Technology, 2019) or a 'Green Industrial Revolution' entailing substantial public investment in green infrastructure to meet climate commitments within a safe timescale. Successful examples of economic and social regeneration of post-industrial city-regions, based not on simply bolstering now-declining industries but instead on targeting of novel, self-sufficient water and energy systems and enhanced tree cover as elements of a wider renewable 'green' economy, include the 32-point, Australian Government-supported plan by the city of Adelaide (Girardet, 2014). Other examples include the successful building of 'green jobs' in realization of a visionary renewable energy economy under Germany's 'Energiewende' yielding simultaneous benefits for business and the environment (Federal Foreign Office, 2020), as well as under the Welsh Government (2018) 'Our Valleys, Our Future' programme. Stimuli with alternative, more resilient and ecologically informed aims, beyond simply attempting to resurrect an anachronistic development model, ultimately offer greater potential for a sustainable future.

The foundational role of ecosystems and their services in providing resilient solutions to current and likely future zoonotic emergence and management must not be overlooked. Recognition that the Covid-19 pandemic is also a biodiversity and a water crisis is central to strategic responses both to the immediate crisis and reduction of future risks.

As humanity enters a new chapter in our history and relationship with supporting ecosystems, with unparalleled political, administrative and scientific resources necessary to attempt to deal with a global pandemic in real time, this is an urgent call to enact fully and rapidly the many long-existing commitments relating to humanity's dependence upon global ecosystems: from commitments under the 1987 'Brundtland Commission' (WCED, 1987) to the 1992 Convention on Biological Diversity (CBD, 1992) and responses to the Millennium Ecosystem Assessment (2005). All of this would be entirely consistent with the aspirations of the *UN Decade on Ecosystem Restoration 2021–2030* (UN, 2019a), responding to the loss and degradation of habitats and rebuilding and restoring humanity's relationship with and support from nature. This current pandemic sharply highlights how universal access to clean water is a vital tool in addressing the spread of the pandemic, also consistent with global commitments under UN Sustainable Development Goal No.6. The World Bank (Hutton and Varughese, 2016) estimated that meeting SDG6 could cost $US116 billion/year through to 2030, which is only a fraction of the amounts wealthy countries have already pledged to invest in stimuli to recover from the Covid-19 pandemic (Staddon et al., 2020).

There will doubtless be downward pressure on donor country budgets in the wake of the global recession that will follow the Covid-19 pandemic. However, can we really miss this opportunity to change the collective view of universal access to safe and clean water from something that would be 'good to have' into something that is imperative to achieve for the wellbeing of all, including ongoing risks of retransmission to donor countries if disease reservoirs persist or emerge even far overseas?

4.5. Transferrable tools

This paper has applied the DPSIR model to address the three aspects of the role of the environment in accelerated disease transfer: (1) the significance of disease regulation ecosystem services and their degradation in the emergence of Covid-19 and other zoonotic diseases; and of the protection of natural resources as mitigating contribution to both (2) regulating human-to-human disease transfer; and (3) treatment of disease outbreaks. The DPSIR model has proved useful as a framework for organising and assessing problems, and also for identifying contributory responses from the perspective of environmental considerations. This analysis reveals that emergence of the current Covid-19 pandemic, in common with many past and likely future zoonotic diseases, has roots in ecosystem depletion. Degradation of ecosystems and their services simultaneously increases risks of subsequent human-to-human transmission and effective care of the infected. It also highlights that strategic response options must necessarily include regeneration of the foundational resources of ecosystems and their services for greater future human security.

CRediT authorship contribution statement

Mark Everard: Conceptualization, Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Paul Johnston:** Conceptualization, Writing - original draft, Writing - review & editing. **David Santillo:** Conceptualization, Writing - original draft, Writing - review & editing. **Chad Staddon:** Conceptualization, Funding acquisition, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors have no competing interests.

Acknowledgements

Everard and Staddon are grateful for funding from the International Water Security Network, which is funded by Lloyd's Register Foundation, a charitable foundation helping to protect life and property by supporting engineering-related education, public engagement and the application of research.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2020.05.017.

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