Links between ecological integrity, emerging infectious diseases originating from wildlife, and other aspects of human health - an overview of the literature

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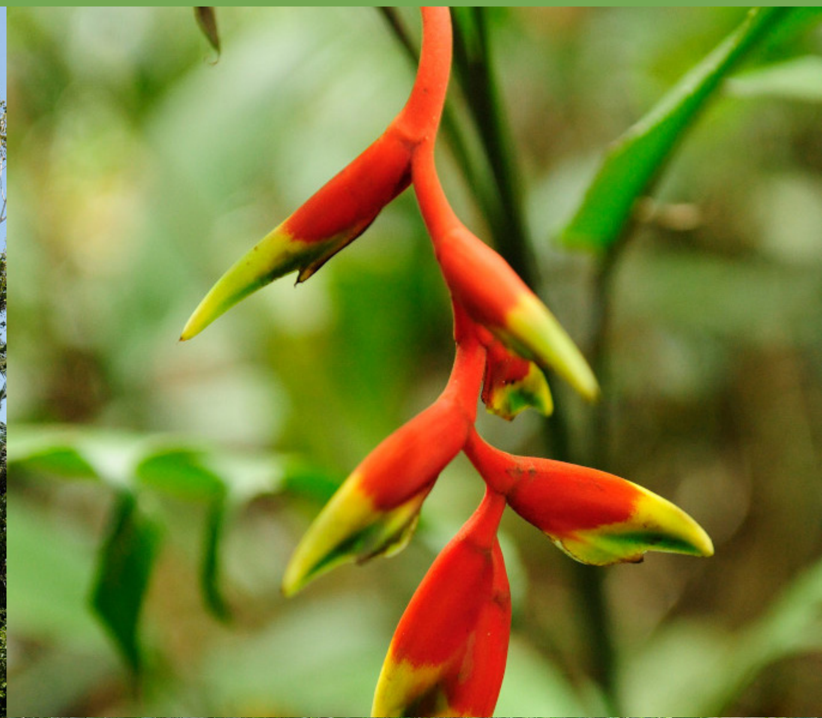

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SUMMARY

As a result of the COVID-19 pandemic, there is heightened public interest in the risk factors that lead to such events. This report contains an overview of the literature linking declines in the integrity of ecosystems to impacts on human health, in particular the risk of emerging infectious disease outbreaks that originate in wildlife. The review identified four key findings, as follows.

1. Degradation has significantly altered ecological systems worldwide and continues to expand into new areas.

2. The majority of emerging infectious disease[1] threats are zoonotic, originate from wildlife, and often cause major social and economic impacts.

3. Ecological degradation increases the overall risk of zoonotic disease outbreaks originating from wildlife.
   a. This relationship has been shown for multiple individual diseases, in regional and global studies and in theoretical models, although the proportion of cases of degradation that lead to substantially increased risk is not well understood.
   a. The increased risk results from multiple interacting pathways including increased human contact with pathogens and disruption in pathogen ecology.
   b. The key "ingredients" that accentuate the risk of an emerging infectious disease spillover event are activities (e.g., creation of new habitat edges, wildlife trade and consumption, agricultural intensification) in areas of high biodiversity that elevate contact rates between humans and certain high-risk wildlife species.

4. Degradation of ecosystems also has complex effects, feedback loops, and some notable negative impacts on many other aspects of human health, including: the prevalence of long-established (endemic) zoonotic diseases, the prevalence of vector-borne and water-borne diseases; air quality; nutrition; mental health; and access to traditional medicines; as well as effects on human health through the impacts of climate change.

Hence, avoiding ecosystem degradation (by keeping ecosystems as intact as possible and avoiding the creation of high-risk interface zones and high-risk activities that increase human-wildlife contact), combined with broader One Health[2] approaches that address the full range of risk factors, will help to reduce the risk to humanity from emerging zoonoses and can have other beneficial health outcomes as well.

Protecting ecological integrity should be a priority action within any comprehensive plan to avoid future zoonotic outbreaks, alongside other critical measures such as ending the commercial wildlife trade for human consumption, closing commercial wildlife markets, building surveillance and response systems, providing global access to health care, and mitigating disease risks associated with domestic animals.

A One Health approach, optimizing human health and ecological integrity, can be used to find solutions for different landscape contexts (e.g. remote intact landscapes, mixed, partly natural landscapes, and heavily human-dominated landscapes).

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[1] 'Emerging infectious diseases can be defined as infections that have newly appeared in a population or have existed but are rapidly increasing in incidence or geographic range' (Morse 1995).

[2] www.wcs.org/one-planet-one-health-one-future; www.onehealthglobal.net/what-is-one-health/

These conclusions are based on a range of evidence types including detailed case studies, global analyses, modelling, and broad expert consensus.

Whilst the key conclusions are clear, it is important to acknowledge that the science is still somewhat incomplete and it is difficult to make predictions at the scale of individual ecosystems, locations or infectious agents, especially as outbreaks are inherently rare events and the exact relationship between pathogen dynamics and ecosystem change is often context-specific and subject to interactions with many other environmental, socio-economic, political and cultural factors.

In addition to lowering disease spillover risk, avoiding environmental degradation has many related benefits, including: climate change mitigation; climate change adaptation and environmental resilience; maintenance of watersheds and rainfall patterns; biodiversity conservation; and the protection of the homelands and livelihoods of Indigenous Peoples and local communities.

INTRODUCTION

The devastating emergence of the virus causing COVID-19 has led to increased interest in the factors that result in pandemics and other disease outbreaks. There is an extensive body of literature on emerging infectious diseases that originate from wild animals, much of it built up since the SARS epidemic of 2002-2004 raised global awareness of the topic. The wildlife trade has been identified as one key risk factor and has rightly drawn a great deal of attention. This review examines information relating to another commonly postulated risk factor - damage to the integrity of ecosystems. It was developed to inform the institutional position WCS takes on this topic, and the advice we share with our many partners around the world.

The review, whilst not intended to be a comprehensive or systematic review, considers a wide sample of publications through to March 2020, with a focus on the peer-reviewed literature, and draws on the combined expertise of scientific and policy staff from across WCS, including our dedicated programs on wildlife health and on the conservation of intact forests.

In broad terms the integrity of an ecosystem is the degree of *naturalness* or, equivalently, degree of absence of human modification. A widely used definition of ecosystem integrity is 'the ability of an ecological system to support and maintain a community of organisms that has species composition, diversity, and functional organization comparable to those of natural habitats within a region (Parrish et al. 2003).

Damage to the integrity of ecosystems can take many forms, including deforestation, fragmentation, construction of linear infrastructure, mining, extraction of oil or gas, pollution, altered fire regimes, logging and the draining or flooding of natural habitats. As described below, such changes often increase the likelihood that humans will be exposed to unfamiliar and sometimes deadly micro-organisms. We do not review data on the wildlife trade in detail, but it is closely linked to the issue of ecological integrity, because so much of the wildlife trade is associated with areas where degradation is taking place, often enabled by increases in access to newly fragmented or exploited frontier regions. Furthermore, the loss of wildlife populations ('defaunation') is itself an important form of ecosystem degradation, disrupting many ecological processes.

Beyond the health aspects discussed here, high ecological integrity is also important for a wide range of other critical values and benefits to humanity, as reviewed recently by Watson et al. (2018) for forests.

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REVIEW OF THE EVIDENCE

The following sections cover the four linked points set out in the summary.

Point 1. Degradation has significantly altered ecological systems

Humanity has been reshaping Earth's ecosystems for millennia. We engage in large-scale conversion of natural habitats to agricultural crops and urban areas to feed and house our burgeoning population, and we change the state of natural systems through activities like hunting, logging, resource extraction, infrastructure construction, recreation and fire management. There has been a myriad of recent attempts to map the level of anthropogenic environmental degradation across the land and ocean with some estimates showing that ~80% of both realms have clear evidence of anthropogenic modification, varying in extent across particular ecosystems (Venter et al., 2016; Jones et al. 2018).

The IPBES global synthesis report released in 2019 (IPBES 2019) clearly outlined the recorded evidence of the multitude of impacts of human activity on ecological systems, including:

- significantly altered global patterns of species composition and abundance,
- loss and appropriation of primary productivity,
- changes in land-surface hydrology and albedo,
- alterations to the biogeochemical cycles of carbon, nitrogen, and phosphorus.

Many natural scientists argue that the anthropogenic degradation placed on ecosystems has meant Earth has entered a human-dominated geological era termed the Anthropocene (Malhi et al. 2014) and we are increasingly transgressing catastrophic environmental boundaries (Steffen et al. 2015).

Point 2. The majority of emerging infectious disease threats are zoonotic, originate from wildlife, and often have major social and economic impacts.

The World Organization for Animal Health (OIE) defines zoonotic diseases 'as infectious diseases that are naturally transmitted from vertebrate animals to humans and vice versa' (Wang and Crameri 2014). Emerging infectious diseases can be defined as infections that have newly appeared in a population or have existed but are rapidly increasing in incidence or geographic range (Morse 1995). An outbreak is the occurrence of one or more cases in a group of individuals in a defined region. Spillover occurs when an animal pathogen successfully jumps to humans.

2a) The majority of emerging infectious disease threats are zoonotic

- More than 335 emerging infectious disease outbreaks (involving 183 distinct pathogens) were reported worldwide during 1940-2004, more than 50/decade, and the rate of outbreaks is increasing (Jones et al. 2008).
- In recent years, 52% of all emerging infectious disease events originated in wildlife. Among emerging zoonoses specifically, 72% of outbreaks have originated in wildlife (with the rest from domestic animals). The frequency of outbreaks originating in wildlife is increasing. All facts under this bullet are from Jones et al. (2008).
- Populations of wild animals carry a high diversity of the types of infectious agents that could potentially jump to humans, with higher diversity of such agents where the diversity of host animals is higher (e.g. Anthony et al. 2017). Most diseases in wild animals remain very poorly studied, many pathogens remain unidentified, and many spillover events are overlooked (Johnson et al. 2020).
- The global connectivity of human society greatly increases the long-distance transport of disease vectors (Tatem et al. 2006) and of animals infected with infectious pathogens (Can et al. 2019), increasing the number of human-wildlife interfaces where pathogens can spill over into humans. Connectivity also facilitates subsequent human-human transmission.
- Less than 300 viruses from 25 high-risk viral families are known to infect people, yet scientists have estimated there are around 1.7 million viruses from these same viral families that are not yet discovered in mammals and birds, of which 700,000 are believed to have zoonotic potential (Carroll et al. 2018).

2b) Economic and societal impacts of zoonotic diseases

- Zoonoses of domestic and wildlife origin combined are mostly long-established as endemic threats. The 13 top ranked zoonotic diseases by scale of impact largely fall into this category and annually they are estimated to be responsible for over 2 million deaths and 2 billion illnesses (ILRI 2012).
- Emerging zoonoses have significant implications in terms of both public health and economic stability, with the costs of many individual recent major outbreaks such as SARS, MERS and Ebola reckoned in the tens of billions of US dollars and exceeding 1-2% of GDP in less wealthy countries (GPMB 2019).
    - The impact of the 2002-2004 SARS Coronavirus epidemic (774 deaths) on tourism, food and travel in mainland China alone was estimated at US$8.5bn (Beutels et al., 2009). The total global cost, associated with lost economic activity, is estimated to have been around $40 billion (Knobler et al. 2004).
    - The 2014 Ebola outbreak in West Africa cost an estimated US$2.2bn in GDP alone and wiped out many of the recent development gains in Guinea, Liberia,

and Sierra Leone, which had been among the fastest growing economies in the world (CDC, 2016; International Working Group On Financing Preparedness, 2017).

- The costs of a single severe future influenza pandemic, which are also indicative of the potential costs of a pandemic originating from wildlife, were predicted to reach US$1.5 trillion or 3.1% of global GDP for one year at 2006 prices (Burns et al. 2006), whilst the annualized cost to the global economy of occasional severe pandemics averaged over long periods was estimated at $80-$500 bn/year (up to 0.6% of global GDP) depending on whether or not deaths were ascribed an economic cost (Fan et al. 2018).
- Recent estimates suggest that the cost of the unfolding COVID-19 pandemic to the world economy, in purely monetary terms, will be US$1-2 trillion, possibly more (UNCTAD 2020), with huge additional costs to human life and wellbeing.

Point 3. Ecological degradation increases the overall risk of zoonotic disease outbreaks originating from wildlife

There are multiple interacting lines of evidence that support this conclusion, which is reflected in numerous recent reviews of the topic (e.g. Patz et al. 2004, Karesh et al. 2012, Gottdenker et al. 2014, Murray et al. 2016, UNEP 2016, Watson et al. 2018, DiMarco et al. 2020). The issue is also reflected in the recently issued 'Berlin Principles on One Health' white paper[3].

The land-use changes[4] that tend to elevate disease risk include deforestation, forest degradation (e.g. through logging), fragmentation, expansion of infrastructure (e.g. roads, railways, powerlines, dams), changes in drainage, and hunting and capture for trade (Patz et al. 2004, Loh et al. 2015). Risks are further multiplied by large movements of human populations, agricultural intensification near to natural areas, and climate change, among other factors (Gebreyes et al. 2014, Karesh et al. 2012).

The main lines of evidence summarized below are (a) case studies, (b) global/regional analyses and (c) theoretical modelling. They point to (d) a range of different pathways or mechanisms by which the effects take place.

a) Case studies

Multiple examples of zoonotic disease outbreaks from wildlife have been reported in the literature as being associated with forest degradation, human encroachment on forests, and wildlife trade chains that connect biodiverse forests to markets:

- **SARS and COVID-19.** The evolutionary host of the SARS virus (SARS-CoV) and the closely-related COVID-19 virus (SARS-CoV-2) are bats and in both cases, index cases were associated with wildlife markets. It is thought that SARS-CoV passed through civets (wild or farmed) before infecting humans and it is unknown at this stage if SARS-CoV-2 also passed through an intermediate host (Hu et al. 2017; Lu et al. 2020; Li et al., 2006). Here the main issue is the volume, mixing, unsanitary conditions, and overcrowding of wildlife that brought a bat virus into contact with a variety of animals in wildlife trade chains originating in natural habitats and ending at urban markets.

[3] https://www.wcs.org/one-planet-one-health-one-future

[4] Following the infectious disease literature, the term 'land-use change' is used here in a broad sense to include both damage to ecosystems (often called degradation) and ecosystem cover loss (e.g. deforestation)

- **Hendra virus.** In Australia, science suggests declining eucalyptus habitat has altered flying fox foraging behaviour and increased spillover risk of Hendra virus to humans (Giles et al. 2018).
- **Nipah virus in Malaysia.** The emergence of Nipah virus in 1998 is linked to the ecology of bats in changing landscapes. During this time period, Pteropid fruit bats experienced a large reduction of flowering and fruiting trees as a result of slash and burn deforestation and an ENSO-linked drought. This led to these bats ranging into cultivated fruit orchards that adjoined pig farms which had recently expanded into forest-edge situations (Chua et al. 2002).
- **Nipah virus in Bangladesh.** Case villages with Nipah virus spillovers had higher human population density than control villages and more forest fragmentation than other parts of the country. The number of bat roosts increased with fragmentation and was thought to be associated with home gardens of diverse fruit trees that may provide a more reliable food source than nearby intact forests (Hahn et al. 2014).
- **Ebola.** In Central Africa, an association was found between Ebola outbreaks and fine-scale measures of forest fragmentation, consistent with suspected transmission pathways from forest-dwelling bats to forest-edge human communities (Rulli et al. 2017, Wilkinson 2018).
- **HIV.** Human viruses responsible for AIDS have resulted from at least four cross-species spillovers of simian immunodeficiency viruses involving the Sooty mangabey, chimpanzee, and western gorilla, all of which live in extensive forests. These lentiviruses can penetrate mucous membranes so it is believed contact with ape bodily fluids associated with the hunting, butchering and consumption of animals in trade led to the spillovers. One of these transmission events, likely occurring between 1910 and 1930, gave rise to the HIV strain behind pandemic AIDS (Sharp and Hahn, 2011).
- **Malaria in Malaysia.** In Malaysian Borneo the main vector is *Anopheles leucosphyrus* and the malaria parasite is *Plasmodium knowelsi*, which primarily infects macaques. Since 2004 it appears deforestation has altered the dynamics of the entire system, impacting vector habitats as well as abundance and distribution of macaques and humans. Cleared land within 1 km and deforestation within 4-5 km of households influenced vector abundance and high historical forest loss is correlated with higher incidence of infections (Fornace et al. 2016; Brock et al. 2019).
- **Lyme disease.** In this system, home of the ‘dilution effect’, one reservoir host, the white-footed mouse, is more competent at transmitting the bacteria that causes Lyme disease to biting *Ixodes* ticks than other small-mammal hosts (which therefore provide a dampening or ‘dilution’ effect). The larval and nymphal ticks feed non-selectively so changes in host composition end up impacting human disease risk. In the presence of fragmentation, the white-footed mice are more abundant for the larval and nymphal ticks to feed on (and white-tailed deer are also more abundant for the adult ticks to feed on). Hence when biodiversity is lost, resilient species like the mouse are more prevalent, more ticks take more blood meals from the mice and subsequently have higher prevalence of the bacteria that causes Lyme disease (Keesing et al. 2009, Turney et al. 2014).

b) Global and regional analyses

There are few truly global-scale quantitative analyses of the relationship between emerging infectious disease risk and land-use change, but those large-scale studies that do exist support the conclusion that large-scale disturbance of ecosystems is associated with increased risk of spillover events.

- During 1940-2004 34% of emerging zoonoses were believed to be associated primarily with either land-use change or activities relating to bushmeat (Loh et al. 2015, UNEP 2016).
- Mapping outbreaks globally suggests that land-use change in tropical forest regions is one of the key risk factors associated with disease spillovers from wildlife into humans (Allen et al. 2017).
- Two regional multi-pathogen studies present strongly suggestive evidence that biodiversity decline and loss of ecosystem integrity play a role in driving zoonotic outbreaks, for the Asia-Pacific (Morand et al. 2014) and for Australia (McFarlane et al. 2013).
- The number of zoonotic diseases found in different wildlife species varies depending on a number of factors, including some which relate to threats to the ecosystems that they occupy. For example, more zoonotic diseases are found in threatened species facing declines in their habitat, or high pressure from exploitation, compared to those threatened for other reasons (Johnson et al. 2020).

Following biodiversity loss, abundant species with no extinction risk and increasing populations (e.g. adaptable or 'weedy' species that thrive in heavily modified landscapes) are also significant carriers of zoonoses, indicating that degradation of intact ecosystems is not the only pathway to increasing the risk of wildlife-human transmission (Johnson et al. 2020, Keesing 2010, Salkeld et al. 2013).

c) Theoretical modelling

Several recent modelling studies provide theoretical support to the plausibility of increased spillover risk being linked to ecosystem degradation (e.g. Myers et al 2013, Gortazar et al. 2014, Faust et al. 2018, Wilkinson et al. 2018, Borremans et al. 2019).

d) Mechanisms

Across these various lines of evidence, several multiple interacting pathways are known or suspected to lead to increased risk of disease transmission. These include:

- Increased contact between humans, livestock and pathogens along newly created edges
    - These edges represent areas where newly arrived human and livestock populations without immunity mix with unfamiliar pathogens, with contacts sometimes further increased by the movement of host species in response to the disrupted ecology of their habitat (Bloomfield et al. 2020, Brownstein et al. 2005, Johnson et al. 2020, da Silva-Nunes et al. 2008). Fragmentation has placed over 70% of the world's forests within 1 km of an edge (Haddad et al 2015) and is worsening across the tropics (Taubert et al. 2018).
- Increased contact with humans along wildlife trade chains.
    - Much wildlife trade originates from recently opened frontier areas where populations have not yet been significantly depleted by over-harvest. There is abundant evidence that large trade volumes, mixing of diverse species, and poor hygiene practices expose people all along these trade chains to increased risk of infection (Bloomfield et al. 2020, Greatorex et al. 2016, Pruvot et al. 2019).
- Changes to pathogen abundance due to changes in host abundance, diversity and susceptibility.
    - Degradation can cause increases in the local populations of host or vector species, raising the chance of transmission. Habitat damage can also place individuals under increased stress, making them more susceptible to infections (Levi et al.

2012, Civitello et al. 2015, Rulli et al. 2017, Olson et al. 2010, Vittor et al. 2006, 2009).

- Rapid evolution/mutation of pathogens due to novel conditions and novel hosts is also suspected to be a contributory factor (Zohdy et al. 2019).

It is also possible that changes in the biodiversity within ecosystems (e.g. extinctions or local extirpations of some species) can alter the likelihood of diseases being transmitted among the remaining species ('dilution' and 'amplification' effects), although there is insufficient evidence to confirm how common these alternative patterns are (Keesing et al. 2009, Randolph & Dobson 2012). It is well known for Lyme disease (see above) but has been looked for in other disease systems (Hanta virus and West Nile virus) with mixed results (Suzan et al. 2009; Luis et al. 2018; Tran et al. 2017; Koenig et al. 2010; Salkeld et al. 2013).

Point 4. Degradation of ecosystems also has complex effects, often negative, on many other aspects of human health

Vector-borne and parasitic disease

There are several studies of the prevalence of non-zoonotic vector-borne disease in relation to ecosystem change. Some show increases, others do not:

- **Malaria**
    - ***The Amazon.*** Deforestation has altered mosquito ecology, resulting in more larval breeding habitat and higher human biting rates of *Anopheles darlingi*, which is a highly competent vector for the more deadly falciparum malaria. This phenomenon is ephemeral and occurs at the frontier of deforestation events where new human migrants are also arriving.

    In one community, after adjusting for access to care, health district size, and spatial trends, a 4.3% increase in deforestation was associated with a 48% increase of malaria incidence (Olson et al. 2010, Vittor et al. 2009, 2006).

    - ***Africa.*** Although data were too limited to take a longitudinal approach, the latest data-rich assessment at multiple scales and using a pre-registered hypothesis testing approach (which makes it less subject to selective interpretation) shows no relationship between deforestation and malaria in Africa. Differences between Africa and the Amazon are attributed to the fact that forest-human associations in Africa are long-standing, and do not involve human migration to a deforestation frontier (Bauhoff & Busch 2020). There are a few local ecological studies from Kenya that suggest deforestation increases vectorial capacity of *Anopheles gambiae* through changes in microclimates that influence sporogonic development and mosquito reproductive fitness (Afrane et al. 2006, 2008).

- **Schistosomiasis.** In one studied region, dam construction degraded freshwater ecosystems and led to local extirpation of native prawns. Restoration of these prawns, which are 'voracious predators of the snail intermediate hosts for schistosomiasis', reduced snail host abundance and as a result, human schistosomiasis prevalence (Sokolow et al. 2017; Sokolow et al. 2015).

Water-borne disease

There are examples of water-borne bacterial disease increases associated with ecosystem degradation:

- **Diarrheal disease in children.** There is a significant association between tree cover in upstream watersheds and probability of diarrheal disease among rural children under age 5, as measured from a dataset from 35 developing countries. The effect of a 30% increase in upstream tree cover is similar to the effect of improved sanitation (Herrera et al. 2017).

- **Typhoid occurrence.** Fragmentation of riparian forests and density of roads crossing creeks within a watershed is significantly related to incidence of typhoid in Fiji (Jenkins et al. 2016).

Other established connections between environmental degradation and human health effects include air quality, nutrition, pharmaceuticals and biomedical discoveries, mental health, access to traditional medicines, endemic zoonotic diseases, and indirect effects on human health through the impacts of climate change. More detailed coverage of these topics can be found in the broad reviews by ILRI (2012), Romanelli et al. (2015), Rohr (2019), Kilpatrick (2017), and Whitmee et al. (2015).

Guide in the Budongo Forest, Uganda, Julie Larsen Maher © WCS

SOLUTIONS AND RESPONSES

As described above, there are multiple clear lines of evidence pointing towards the conclusion that declines in the integrity of ecosystems increase the global risk of zoonotic disease spillovers, and hence the risk of pandemics. Enough is already known to identify the broad steps needed to ensure that our interactions with nature occur in a way that lowers pandemic risk. It should be acknowledged that the science is not complete and there are important questions to answer before we know everything that we would ideally wish to know around the linkages between the integrity of ecosystems and emerging zoonotic diseases. However, the precautionary principle necessitates that strong action is taken while this additional research is undertaken

The One Health framework, adopted and championed by WHO, FAO, OIE, the Centers for Disease Control, the World Bank, WCS and many other organizations and institutions, is a widely applied approach to address zoonotic challenges (Waltner-Toews 2017; Gebreyes et al. 2014). The core One Health principle is that 'communicable and non-communicable diseases demand a truly comprehensive understanding of health and disease, and thereby a unity of approach that is achievable only through convergence of human, domestic animal, wildlife, plant, and environmental health, on a planetary scale'. One Health should be used as an umbrella framework to find convergence among ecological and human health challenges. The Berlin Principles[5] state, 'going forward...we must overcome sectoral and disciplinary silos; apply adaptive, forward reasoning, and implement multidisciplinary and multilateral solutions, while boldly integrating current uncertainties to address the opportunities and challenges ahead'.

Ecological changes are important factors in driving disease outbreaks and as such need increased levels of attention at international, national and local levels. One Health approaches relating to the integrity of ecosystems must be placed in the context of how much land degradation has already occurred in an area, and the 'three conditions' described by Locke et al. (2019) are one useful way to frame these solutions. This framing recognises that there have been diverse human influences on the Earth's surface and it is possible, at least broadly, to categorize landscapes by integrating nature-centric (what remains of nature) and human-centric (human land-use) assessments of drivers and pressures on biodiversity. Three broad "conditions" emerge:

- large, intact, mostly natural areas;
- 'shared', partially natural landscapes;
- farms and cities with very limited natural space remaining

According to each condition, broad suites of responses can be proposed to improve the state of ecosystem integrity, to secure nature's contributions to people, and minimise the risk of future pandemics. These responses are outlined below. To be achieved, they need to be placed in the appropriate policy, regulatory and legal frameworks, be supported by finance, engage the full range of stakeholders in effective ways and be supported by additional science. It is beyond the scope of this paper to discuss these critical aspects of implementation in detail.

In large wild landscapes we need to retain ecosystem integrity to the greatest extent possible as by doing this we will minimize the various pathways that increase the risk of pandemics and other spillover events.

- Maintaining ecosystem integrity means not modifying ecosystems beyond their natural range of variation, which in practice means avoiding the expansion of large scale extractive uses (e.g. industrial logging, large-scale harvest of animal and plant products), not fragmenting areas with infrastructure, pastures and farmland, and not disrupting natural fire and flood regimes.
- Since many of these areas are inhabited by, and protected by, Indigenous Peoples and local communities, we must strengthen health care infrastructure to meet the needs of these populations, and enhance emerging infectious disease surveillance in collaboration with them (Munster et al. 2018) as well as better understanding the patterns of exposure and immunity that they experience.

[5] https://www.wcs.org/one-planet-one-health-one-future

In shared landscapes we need to manage significant ongoing levels of contact between humans, wildlife and livestock, and be aware of factors (e.g. changing farm practices) that may increase these levels. In this context we should consider nature-based or 'One Health' solutions that support both human health and the restoration of ecosystem integrity to the fullest extent possible.[6] Solutions that benefit both human health and environmental targets have the advantage of contributing to multiple Sustainable Development Goals. A broad recommendation for shared landscapes is that infectious disease interfaces and pathways that have been created must either be removed or mitigated.

- Forest edges are an example of an interface that can be reduced in extent in some settings, e.g. through restoration that reduces fragmentation.
- In other settings forest edge contact zones may be a part of the landscape that cannot be reduced, in which case the focus should be on mitigating the risks they present.[7]
- The commercial wildlife trade is an example of a high-risk interface that can and should be removed in many cases, and whose risks should be mitigated in the remaining cases.
- Where restoration is not attainable, management decisions should nonetheless avoid any further degradation of ecological systems

In the 'third condition' of the Locke et al. (2019) framework - highly human-dominated, farmed and urban areas - there remain zoonotic diseases originating from wildlife, such as rabies from bats or skunks, West Nile virus from birds via mosquito vectors, as well as tularemia, plague, and hantavirus. Alongside these, such areas are also risky areas for emerging infectious disease outbreaks from wildlife due to connections between remote source areas and urban and peri-urban centres of demand for the wildlife trade.

- In these areas, commercial wildlife trade, particularly for human consumption, should be halted and other forms of domestic animal trade should be improved to ensure excellent hygiene standards. Public health, biosecurity and disease surveillance and response systems tend to be more robust for known pathogens in these places, but defences are less robust for the new, emerging pathogens that also occur in commercial wildlife markets.

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[6] see e.g. the Berlin Principles and IUCN's new standards for Nature-based Solutions

[7] For example, an intervention used after the discovery of Marburg, and Bombali and Zaire Ebolaviruses in West Africa was as simple as information and resources on how to exclude insectivorous bats from homes and cover food sources https://www.ecohealthalliance.org/living-safely-with-bats. In the case of Nipah virus in Bangladesh, a simple tree skirt can prevent bats from urinating in vessels that are used to collect tree sap (Khan et al 2012).

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