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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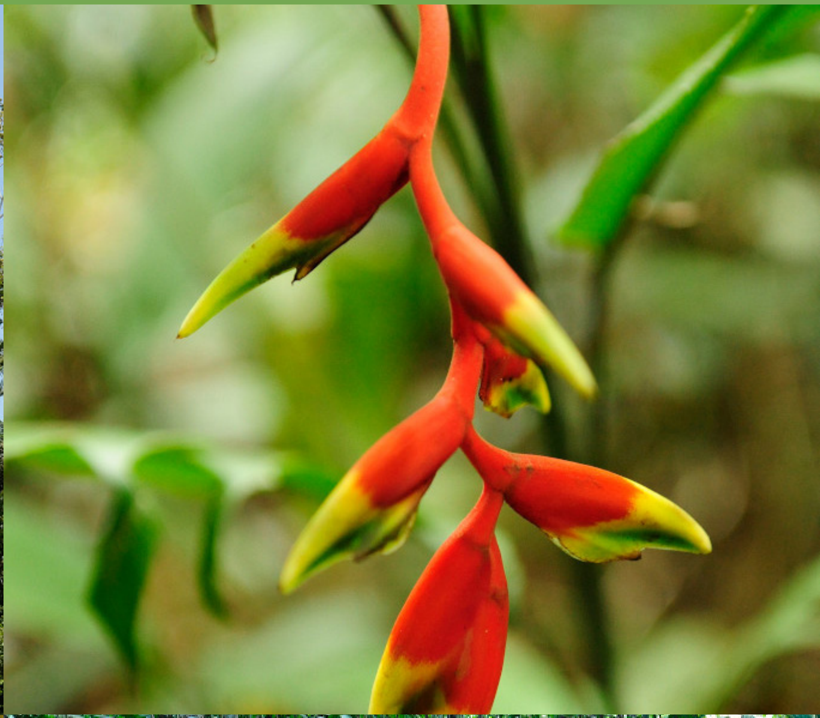

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SUMMARY

As a result of the COVID-19 pandemic there is heightened public interest in the risk factors that lead to such events. The commercial wildlife trade and associated commercial wildlife markets for human consumption have been widely recognized as a major risk factor, and are the subject of a WCS policy brief focused specifically on that topic[1]. The current report looks at the broader issues of ecosystem integrity and ecosystem degradation. The degradation of ecosystems is often linked to the commercial wildlife trade but also results in various other processes that affect zoonotic disease transmission.

The report contains an overview of the literature linking declines in the integrity of ecosystems to the risk of emerging infectious disease outbreaks that originate in wildlife, and also touches briefly on other impacts on human health. Four key findings are identified, as follows:

1. Degradation has significantly altered ecological systems worldwide and continues to expand into new areas.
2. The majority of emerging infectious disease[2] 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 multi-disease 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., land conversion, creation of new habitat edges, wildlife trade and consumption, agricultural intensification) in or linked to areas of high biodiversity that elevate contact rates between humans and certain 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 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. These all in turn can contribute to local and transnational conflicts over natural resources and undermine local and international security.

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[3] approaches that address the full range of

[1] https://www.wcs.org/get-involved/updates/a-primer-on-the-coronavirus

[2] '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).

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

risk factors and are integrated into public health policies, 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, through actions such as spatial planning, the creation and management of effective protected areas, support to ecosystem management by Indigenous Peoples and local communities, and policies to minimize threats caused by particular economic sectors. Other critical measures in addition to protecting ecological integrity include: closing commercial wildlife markets and commercial wildlife trade for human consumption, especially of birds and mammals; building disease 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).

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 major 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; enhancing food security, protection of the homelands, livelihoods and cultures of Indigenous Peoples and local communities; and conflict mitigation, stabilization and security.

A separate WCS brief explores some of the issues relating to Indigenous Peoples and local communities in the context of the COVID-19 pandemic[4].

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 commercial wildlife trade has been identified as one key risk factor and has drawn a great deal of attention, including a WCS policy position and evidence brief[5]. The current 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. A companion document explores some of the

[4] *The COVID-19 pandemic and Indigenous Peoples and Local Communities: protecting people, protecting rights*

[5] https://www.wcs.org/get-involved/updates/a-primer-on-the-coronavirus

issues relating to the rights and wellbeing of Indigenous Peoples and local communities in the context of the COVID-19 pandemic[6].

The current 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 field programs across 17 major ecological regions of the world as well as cross-cutting 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, as detailed in the following section. Such changes can increase the likelihood that humans will be exposed to unfamiliar and sometimes deadly micro-organisms.

We do not review data on the commercial wildlife trade in detail, but it is closely linked to the issue of ecological integrity, because so much of the wildlife trade (whether legal or illegal) 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 across all ecosystems, as reviewed recently by Watson et al. (2018) for forests.

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[6] *The COVID-19 pandemic and Indigenous Peoples and Local Communities: protecting people, protecting rights*

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 degrade the integrity of natural systems that have not been converted through activities like hunting, logging, extraction of oil, gas and minerals, infrastructure construction, livestock grazing, recreation, pollution, fire management, and the draining or flooding of natural habitats. We also seek to mitigate some of this damage - for example we create protected areas, community natural-resource management systems and integrated management in broader landscapes. 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), in contrast to *endemic infectious diseases*, which are well-established in the population and not rapidly increasing. *Zoonotic spillover* occurs when an animal pathogen successfully jumps to humans. An *outbreak* is the occurrence of one or more cases in a group of individuals in a defined region.

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 more than half (52%) of all emerging infectious disease events originated in wildlife[7] (Jones et al. 2008). Among emerging zoonoses specifically, 72% of outbreaks have originated in wildlife (with the rest from domestic animals; Jones et al. 2008). The frequency of outbreaks originating in wildlife is increasing (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 about 700,000 are predicted to have zoonotic potential (Carroll et al. 2018).

2b) Economic and societal impacts of zoonotic diseases are very high

- Zoonoses originating from domestic animals and wildlife are mostly 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 also 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$8.5 billion (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$2.2 billion in GDP alone, killed 11,316 people, 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).

- Only a small handful of emerging diseases, many of them emerging zoonoses, have become pandemics, with even higher impacts.
    - 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

[7] The remainder stem from domestic animals (including livestock), drug-resistant pathogens, and vector-borne pathogens.

pandemics averaged over long periods was estimated at $80-$500 billion/year (up to 0.6% of global GDP) depending on whether or not deaths were ascribed an economic cost (Fan et al. 2018).

- The unfolding COVID-19 pandemic, which is a zoonotic disease according to all scientific evidence (Andersen et al 2020), will have an immense cost to the world economy. Recent estimates suggest costs in purely monetary terms will reach US$1-2 trillion and possibly more (UNCTAD 2020), with huge additional costs to human life, wellbeing, economic systems, security etc.

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 also found in numerous recent reviews of the topic (e.g. Patz et al. 2004, Karesh et al. 2012, Myers et al 2013, 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[8].

According to the literature reviewed in this section, the range of land-use changes[9] that are thought to elevate disease risk includes deforestation, forest degradation (e.g. through logging), fragmentation, expansion of infrastructure (e.g. roads, railways, powerlines, dams), changes in drainage, and hunting and capture (especially for trade). Risks are further multiplied by factors that include large movements of human populations, agricultural intensification near to natural areas, poor security, and climate change, among other factors (Gebreyes et al. 2014, Karesh et al. 2012). Marine and coastal systems also present zoonotic disease risk linked to levels of contact with marine mammals and fish, with humans typically as dead-end hosts in cases observed to date (Curtis et al. 1998, Tryland 2000, Waltzek et al. 2011, Pufall et al. 2012, Washington State University Institutional Animal Care and Use Committee 2016).

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 the inter-linked pressures of forest degradation, human encroachment on forests, and wildlife trade chains that connect biodiverse forests to markets:

1. **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, initial 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). As exemplified by SARS-CoV, 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.

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

[9] 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)

2. **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).

3. **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).

4. **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).

5. **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). It is hypothesized that ecological disturbances may alter patterns of bat movement and environmental shedding of Ebola virus in urine, feces, or saliva. Shared food resources may transmit Ebola virus to other mammals, including non-human primates and duikers, that then die and become human sources of infection (Leroy et al. 2005; Alexander et al. 2015). Outbreaks start in rural areas and are sometimes traced back to subsistence hunters and their families having direct contact with fruit bats or wildlife found dead (Leroy et al. 2004; Alexander et al. 2015).

6. **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).

7. **Malaria in Malaysia.** In Malaysian Borneo the main vector is *Anopheles leucosphyrus* and the malaria parasite is *Plasmodium knowlesi*, 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).

8. **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 multi-disease, 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 are believed to have been 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 spatially 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 little to no extinction risk and increasing populations (e.g. adaptable or 'weedy' species that thrive in heavily modified landscapes) are also significant carriers of zoonoses (Johnson et al. 2020, Keesing 2010, Salkeld et al. 2013). This indicates that the ongoing degradation of intact ecosystems along active frontiers is not the only source of high levels of wildlife-human transmission and that ecosystems that were extensively cleared and degraded in the past can also present significant continuing risk.

c) Theoretical modelling

Several recent modelling studies provide theoretical support to the plausibility of increased spillover risk being linked to ecosystem degradation, and highlight priorities for future work to increase the predictive power of the models that are available.

- Gortazar et al. (2014) develop a framework for analysis of the pathways linking the population sizes and interactions of pathogens, humans, and host or vector species to direct drivers of change in these elements (e.g. increased food for hosts or increased human migration) and ultimately, to the underlying, indirect drivers of change (such as intensified agriculture, change in natural habitats or changes in the human security situation), revealing many plausible pathways for such changes to occur and providing an agenda for further research.
- Wilkinson et al. (2018) model changes in human exposure to microbes through defined classes of habitat fragmentation and predict that increased fragmentation intrinsically increases the hazard from microbes for all modelled biological systems.
- Faust et al. (2018) develop a multi-host model for pathogen transmission between species inhabiting intact and converted habitat. In a range of scenarios, the highest spillover risk occurs at intermediate levels of habitat loss, whereas the largest, but rarest, epidemics

occur at extremes of land conversion. This framework provides insights into the mechanisms driving disease emergence and spillover during land conversion.

- Borremans et al. (2019) synthesize potentially important mechanisms affecting cross-species spillover of parasites across ecosystem boundaries (e.g., edge effects, patch size, and host/parasite movement temporality) as a step towards developing a general theory of spillover associated with ecosystem boundaries.

d) Mechanisms

Across these various lines of evidence, several 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 (Olson et al 2010, Vittor et al. 2006, 2009, Fornace et al. 2016; Brock et al. 2019). 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).

- Rapid evolution/mutation of pathogens due to novel conditions and novel hosts is also suspected to be a contributory factor, making some pathogens more infectious or virulent (Zohdy et al. 2019).

It is also possible that declines in the biodiversity within ecosystems (e.g. extinctions or local extirpations of some species) can increase or decrease the risk of diseases being transmitted among the remaining species ('dilution' and 'amplification' effects, respectively), although there is insufficient evidence to confirm how common these alternative patterns are (Keesing et al. 2009, Randolph & Dobson 2012). The dilution effect is well known for Lyme disease (see above) but has been looked for in other disease systems (e.g. 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 hypothesized to relate to the fact that forest-human associations in Africa are more long-standing, and do not so often 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 Senegal, dam construction degraded freshwater ecosystems and led to local extirpation of native prawns, but 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. 2015). Similar interventions to improve ecological integrity by restoring prawn populations affected by dams elsewhere are predicted to reduce schistosomiasis risk for roughly 90-190 million people (Sokolow et al. 2017).

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 five, 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 relate to, among others, 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 et al. (2019), Kilpatrick et al. (2017), and Whitmee et al. (2015).

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

SOLUTIONS AND RESPONSES

As described in the evidence review 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. These risks go well beyond those associated with the wildlife trade, although the two issues are inter-related. 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 as much as possible. Responses specific to the commercial wildlife trade and associated markets, for human consumption, are detailed in a separate WCS position paper[10]; below we outline the range of responses available in relation to the degradation of ecosystems.

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.

[10] https://www.wcs.org/get-involved/updates/a-primer-on-the-coronavirus

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[11] 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 recognizes 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 to minimize 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, be supported by additional science and take account of the security and conflict contexts in which they occur. 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 extractive uses (e.g. industrial logging, harvest of animal and plant products), not fragmenting areas with infrastructure, pastures and farmland, and not disrupting natural fire and flood regimes.
- Priority actions to maintain ecological integrity include multi-stakeholder spatial planning, the creation of effectively managed protected areas, support for management by Indigenous Peoples and local communities, and policies to reduce threats arising from specific economic sectors. Recommendations relating to the wildlife trade also apply in these areas.

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

- Since many of the most ecologically intact areas are inhabited by, and protected by, Indigenous Peoples and local communities, we must also strengthen health care infrastructure to meet the needs of these populations, enhance emerging infectious disease surveillance in collaboration with them (Munster et al. 2018), and better understand the patterns of exposure and immunity that they experience.

In shared landscapes many of the solutions noted above also apply. In addition, given the significant ongoing levels of contact between humans, wildlife, and livestock we should plan land-uses and zoning in ways that reduce the degree of contact and the extent of high-risk interfaces where possible. We should then mitigate the risks of contact where they remain, and be aware of factors (e.g. changing farm practices, further fragmentation of habitats) 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.[12] Solutions that benefit both human health and environmental targets have the advantage of contributing to multiple Sustainable Development Goals.

- Forest edges are an example of a potentially high-risk 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 an aspect of the landscape that it is not feasible to reduce, in which case the focus should be on mitigating the risks they present.[13]
- 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.

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

[13] 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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