TAKING A LANDSCAPE APPROACH TO REDUCE PANDEMIC RISKS

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Acknowledgements:
This white paper is funded in part by the Gordon and Betty Moore Foundation

January 2023

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Summary

The emergence of COVID-19 has heralded a cry to 'prevent pandemics at the source', with numerous funders, practitioners, researchers, and other stakeholders recognizing the need to coordinate their efforts around ecologically-based prevention goals. Land-use change and associated environmental degradation have significantly altered ecological systems, including the dynamics of pathogen transmission within and between species. As such, 'land-use induced spillover' is one major contributor to pathogenic risk, and increasing this risk is assumed to increase pandemic risk.

To reduce the risks associated with land-use induced spillover, we need to address the drivers and processes that create the conditions conducive to spillover. These include stressors to ecosystems that reduce landscape immunity (e.g., habitat fragmentation and degradation, changes to ecological structure and processes that impact resource availability, and the introduction of toxins and other pollutants), as well as dynamics that shape wildlife-to-human and human-to-human spillover and spread (e.g., the patterns of human and wildlife spatial and temporal proximity in general, more specific activities such as intensive livestock farming near forests and wildlife trade, as well as the capacities of public health systems and local communities to detect and contain disease spillovers when they do occur).

WCS has convened a group of experts to review how to reduce pandemic risks associated with land-use induced spillover through investments in targeted landscape-based interventions. These include:

- Averting harmful land-use and land-use change, for example by reducing conversion or degradation of ecosystems, and/or reducing intensive livestock farming in high-risk locations
- Eliminating high risk forms of wildlife trade, in particular commercial trade and sale of live or freshly killed wild birds or mammals for human consumption
- Human health and education programs aimed at minimizing the occurrence, severity, and spread of spillovers in local communities

Additional important interventions include wildlife and livestock health programs to reduce pathogen sharing, ecosystem restoration to reverse past damages and lower spillover risk, and a range of customized interventions for specific, high-risk interfaces between people and wildlife (e.g., skirting palm sap collection pots to prevent bat urine contamination). An individual program should address multiple landscape interventions as part of an integrated strategy, (e.g., developing wildlife and human health programs within an effort to support a protected area). All interventions should be tailored to specific landscape conditions based on how much ecosystem clearance and land degradation has already occurred, and should include the full consent and active participation of Indigenous Peoples and local communities.

Public and philanthropic investments are critical to advancing and integrating these interventions. Philanthropy has a unique role to play at the landscape level to support on-the-ground implementation in high-risk regions. Solutions that should be deployed now to address land-use induced risk factors include: conservation of tropical and subtropical biodiverse landscapes, elimination of high risk elements of the wildlife trade, provision of human health and education to bolster biosecurity, creation and strengthening of wildlife health programs, restoration of degraded landscapes in ways that reduce spillover threats, and context specific interventions that are win-wins for conservation and human infectious disease control. Importantly, philanthropy can help champion the integration of these solutions within any landscape strategy. Philanthropy also has a role to play

in creating the enabling environment for landscape level solutions (e.g., national legal frameworks and spatial planning processes, high-level intergovernmental advisory panels and new intergovernmental health and trade partnerships and applied research to close critical knowledge gaps, among many other areas).

1. Introduction and background

1.1. Aim of the review

The emergence of COVID-19 (the disease caused by SARS-CoV-2) has heralded a cry to 'prevent pandemics at the source', with numerous funders, practitioners, researchers and other stakeholders recognizing the need to coordinate their efforts around ecologically-based prevention goals. To minimize the likelihood of future pandemics that start with zoonotic spillover, as well as smaller-scale disease outbreaks, we need to address the drivers and processes that create the conditions conducive for spillover in the first place–the transmission of wildlife-originating pathogens into human populations. While not all spillover leads to pandemics, all pandemics with zoonotic origins have involved a spillover event.

Understanding of these conditions relies on a body of scientific evidence that describes how ecological processes and human activities contribute to spillover risk factors. Land-use change and associated environmental degradation have significantly altered ecological systems, including the dynamics of pathogen transmission within and between species. As such, 'land-use induced spillover' (LUIS) [1] is one major contributor to pathogenic risk, via a pathway of landscape-level processes that drive changes in transmission of wildlife pathogens (Reaser et al. 2022) and increasing this risk is widely assumed as a precursor to increased pandemic risk.

This white paper discusses how to reduce pandemic risks associated with LUIS through investments in targeted landscape-based interventions. It builds on a review of evidence developed by WCS in 2020 (Evans et al. 2020) updated with more recent literature, involving a wider range of external expert co-authors, and focussing more strongly on potential solutions and stronger evidence of their likely efficacy. Within the Quadripartite 2022-2026 Joint Plan of Action, these environment-focused interventions fall within Track 6, 'Integrating the Environment into One Health' (FAO 2022).

Reducing the anthropogenic factors that drive LUIS risk will not wholly eliminate novel pandemics, since pandemics are complex and not all have origins that include LUIS processes. It should, however, reduce their occurrence, by targeting factors that we know favour zoonotic spillover and contribute to novel viral emergence. In addition, the same actions that we propose here have many benefits to other sectors—including reversing biodiversity loss, restoring ecosystem services and addressing climate change—many of which also provide benefits to human and animal health. So success should therefore have large and substantial human health, societal, and economic benefits. By coupling LUIS interventions with improved public health responses, the risk of severe consequences from spillovers that *do* occur can also be minimized.

This paper makes several references to the broader One Health approach. One Health 'is an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems' (Adisasmito et al. 2022). In raising awareness of health inter-dependencies,

[1] Over the years the LUIS pathway has also gone by other names, including pathogenic landscapes (Lambin et al. 2010) and unhealthy landscapes (Patz et al. 2004).

One Health calls for developing intersectoral and integrative solutions, which encompass public health investments in conservation to address LUIS (Grützmacher et al. 2019).

1.2. Outline of the land-use induced spillover pathway

This high-level summary is provided as an introduction to LUIS, which is relevant to all ecosystem types including terrestrial, marine and freshwater environments, and we refer readers to the scientific literature for richer details (e.g., Plowright et al. 2021). LUIS is a conceptual model of the causal pathway (Fig. 1) for zoonotic spillover based on research on the barriers that pathogens have to overcome to cause epidemics and pandemics (Plowright et al. 2017).

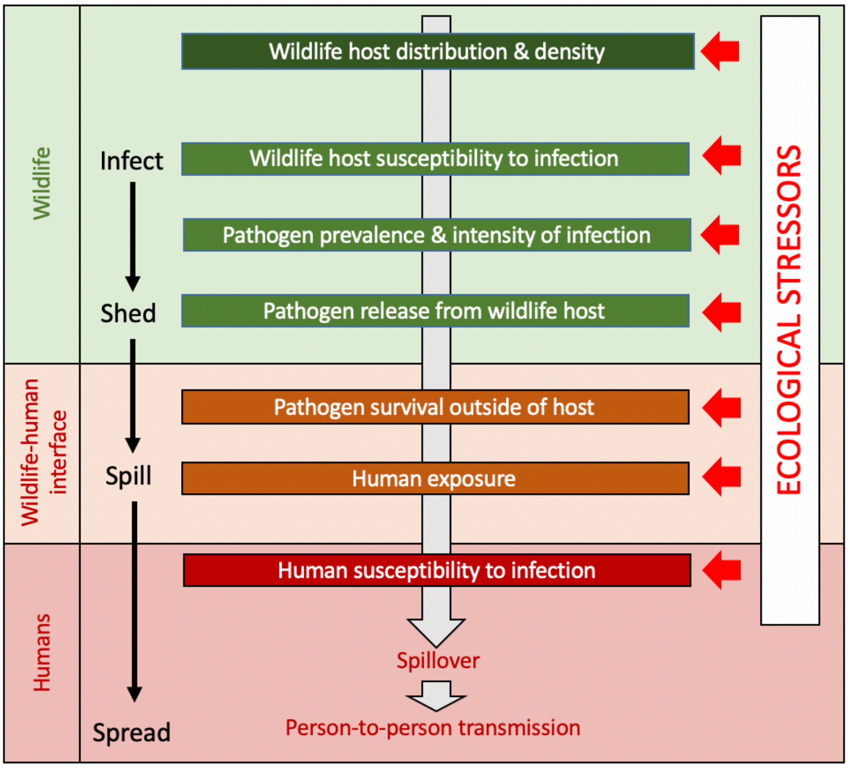

Figure 1. Pathway of spillover from wildlife to humans adapted from Plowright et al. 2021.

LUIS identifies two broad risk components that contribute to this 'infect-shed-spill(over)-spread' cascade: (i) landscape immunity (the first two stages) and (ii) the dynamics of human and wildlife proximity (the latter two).

> Landscape immunity (infect and shed). Landscape immunity (Reaser et al. 2022) is a relatively new scientific concept, building on similar earlier 'healthy landscapes' (Patz et al. 2004) and 'pathogenic landscapes' concepts (Lambin et al. 2010), that speaks to the ecological conditions affecting the risk that a wild species or set of species will harbour substantial prevalence of a pathogen in a population (infect) and will facilitate pathogen shedding (shed). In this model, low landscape immunity increases the risk of cross-species transmission, including some pathogen transmission to humans. Stressors and pressures known to reduce individual immune function are thought to reduce population immunity. For example, individual immunity underpins herd immunity, which is determined by the fraction of resistant hosts in the population above a

certain threshold. Maintenance of that threshold prevents ongoing pathogen transmission.[2] Landscape immunity is the same concept applied to species and populations within an ecosystem. Landscape immunity risk factors include changes that alter food webs, movement and clustering patterns of species, and species richness and abundance, all of which could increase pathogen prevalence and shedding due to stress and the degraded health of reservoir host individuals. While individual- and population-level responses to stressors are relatively well established, further research is needed to more fully characterize landscape-scale effects of stressors that affect the immunity of individuals within populations of species inside and across ecosystems (Becker et al. 2020).

Dynamics of proximity and contact (spill and spread). The patterns of human and wildlife proximity govern wildlife-to-human and human-to-human transmission of a pathogen. Wildlife-human proximity governs the likelihood of an initial pathogen jump from an animal into a person (spill), and human-human proximity governs onward transmission that causes an epidemic and possibly pandemic (spread). Contagious diseases like COVID-19 and flu are usually mediated by direct or aerosol transmission but proximity dynamics also encompass vector-mediated, environmental and other forms of transmission. Both wildlife and human spatial and temporal dynamics will determine the kind, amount, and frequency of transmission that occurs. Survival and persistence of the pathogen outside the host in the environment also influences transmission. Interfaces where animal-human contact occur (e.g., forest edges) are key standing risk factors for proximity dynamics. When new interfaces alter habitat and animal behaviour, landscape immunity components (infection and spilling) can be affected in addition to expansion of the proximity and contact zone.

Wildlife trade can form a special, highly condensed example of the same 'infect-shed-spill-spread' cascade. Because elements of the wildlife trade can be addressed efficiently as part of holistic landscape-level strategies we mention it here.

Many parts of the LUIS pathway are going to be accentuated by climate change, including both landscape immunity and the dynamics of proximity and contact. For example, climate change is a global stressor on species' physiology and ability to thrive and early research has established concomitant shifts in species range may lead to thousands of new cross-species transmission events, with unknown but worrying implications for spillover of zoonotic pathogens to humans (Carlson et al. 2022).

1.3 Theory of change

The Theory of Change we present (Fig. 2), which is consistent with most recent literature on this topic, focuses on the ultimate goal of reducing the frequency and severity of pandemics and epidemics (Column 1) by reducing the frequency and severity of those spillover events that originate in wild animals (Column 2) since these are known to be the source of a high proportion of emerging infectious diseases (Jones et al. 2008). To achieve this we believe it is possible to reduce the intensity of each of the major steps in the LUIS pathway (Column 3) by reducing a set of direct anthropogenic 'pressures' and other risk factors such as poor surveillance (Column 4, see Section 1.4). The heart of this paper is a set of recommended landscape-scale interventions (Column 5, see Section 2) that will reduce these pressures and risk factors. To be fully effective at scale many of these interventions

[2] This concept also underpins the fraction of a population requiring vaccination coverage and varies by the characteristics of the host as well as the pathogen.

may also require good enabling environments, or actions at the national and international level to put such enabling conditions in place (Column 6, see Annex).

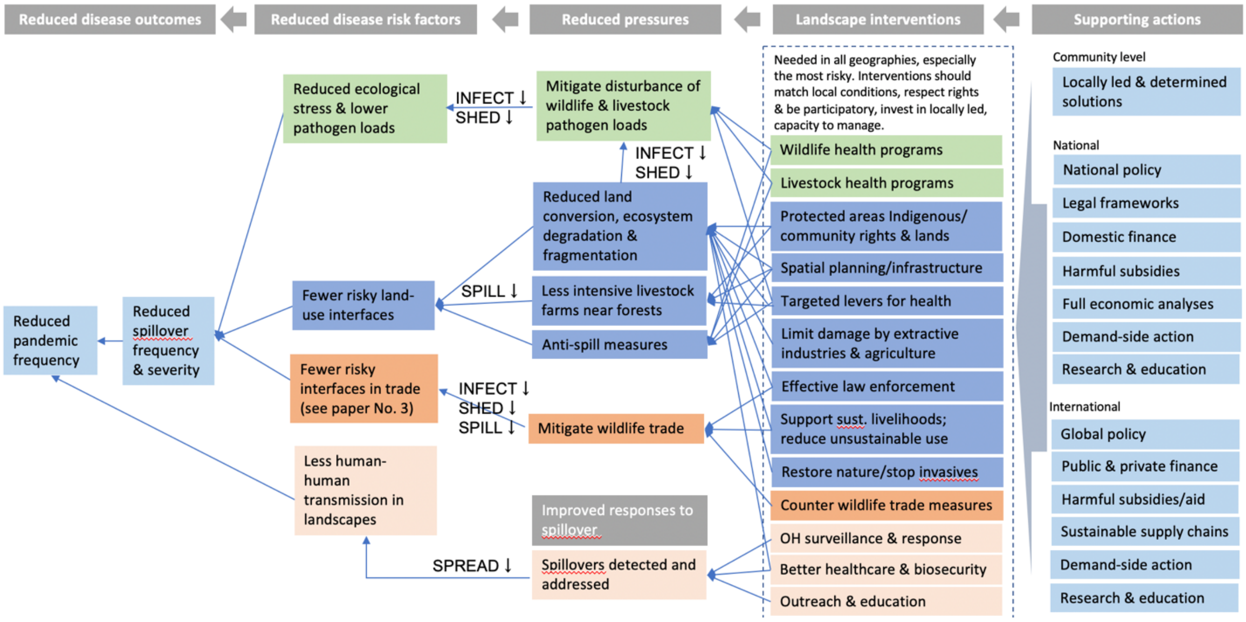

Figure 2. Theory of Change. Whilst there are many cross-connections between the boxes in the theory of change, the colour coding of boxes in columns 3-5 helps the reader to see the way they group into four main pathways for action [OH = One Health].

1.4 Pressures that worsen land-use induced spillover

The anthropogenic pressures driving LUIS result from environmental degradation that alters ecological systems. The Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) global synthesis report (IPBES 2019) clearly documents 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.

The key direct pressures that the literature indicates need to be reduced to lower LUIS risk factors are shown in the theory of change (Column 4) and illustrated with a selection of brief examples below. The scientific evidence base that identifies these LUIS risk factors includes case studies, regional and global analyses, theoretical modelling and investigation of specific mechanisms (see Evans et al. 2020 for a fuller discussion). Current understanding of the geographical areas where these risks are most significant are outlined in Box 1 (see also Practice 1 of Reaser et al. 2021a). Actions to address these pressures should be taken in parallel with further research[3] to refine our knowledge of the complex and interacting factors involved (see Practice 10 of Reaser et al. 2021a).

[3] Further research will be needed to understand the relative importance of different pressures on LUIS and how intensity and spatio-temporal dynamics of different pressures may interact with context-specific spillover processes. It should also assess potential research bias as scientists to date have primarily documented the increasing risks with less focus on the 'net' effect, i.e. by looking across diseases and acknowledging where there are

Disturbance of wildlife and livestock pathogen loads

Stress due to severe habitat changes or unnatural crowding can increase the quantity of pathogen(s) in circulation in wildlife and livestock populations beyond levels observed in non-disturbed landscapes. For example:

- American robins that are food stressed have higher viral titers of West Nile virus, increasing viral hazard in the environment (i.e., higher numbers of infected mosquito vectors; Owen et al. 2021);
- Bacterial transmission has increased between people, livestock, and nonhuman primates as the level of disturbance increased within forest fragments in western Uganda (Goldberg et al. 2008).

Offtake of wild animals can also lead to trophic disruption, potentially increasing pathogen loads elsewhere along food chains. For example:

- Removal of scavengers from food webs means carcasses and the pathogens they carry persist longer (see Sokolow et al. 2019 and references within for this and other examples);
- Range-wide loss of coyote and red fox, small mammal predators that prey on the main reservoir host species, were correlated with increase in Lyme disease (Levi et al. 2012).

Land conversion, ecosystem degradation and fragmentation

Land conversion causes a cascade of effects that influence spillover, including ecological disruptions that magnify infection and shedding risk, as well as increased extent of the contact zones that facilitate transmission, many of them in new locations where the likelihood of wholly novel pathogen spillovers is highest and host immunity is lowest. For example:

- In one modelling exercise, spillover risk was highest at intermediate levels of habitat loss, whereas the largest, but rarest, epidemics occurred at extremes of land conversion (Faust et al. 2018).
- In Australia, agricultural land conversion has reduced native nectar resources for flying foxes, causing nutritionally stressed bats to form sedentary colonies in urban areas (Plowright et al. 2015), driving increased shedding of Hendra virus and risks of spillover into nearby horse populations (Becker et al. 2022).

Ecosystem degradation and fragmentation, which can be much more extensive than outright land conversion, create stress that can drive infection and shedding risk, as well as altering the dynamics of proximity and contact. For example:

- A mechanistic model of landscape conversion showed that increased fragmentation also increased human exposure to pathogens (Wilkinson et al. 2018);
- Rhinolophid bat populations in China have undergone higher levels of forest fragmentation and live in a landscape with greater concentration of people and livestock than elsewhere in their range (Rulli et al. 2021). All else being equal this greater opportunity for contact between bats, livestock, and people is expected to increase sarbecovirus spillover risk.

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cases of reduced risk or no change in risk due to the same processes. Assessment of successful LUIS mitigation measures will need to adjust for preparedness and response interventions, e.g., pharmaceutical measures.

Intensive livestock farming near forests

Forest edges represent areas where newly arrived humans and livestock populations, especially those in intensive production systems, are exposed to novel pathogens for which they lack immunity, with exposure exacerbated 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, Parsons et al. 2014, da Silva-Nunes et al. 2008), e.g.:

- Pig facilities have amplified Nipah virus which can be shed to pigs by fruit bats feeding in trees above the pigs, with subsequent onward viral transmission from pigs to people (Chua 2000);
- Intensive poultry production has contributed to the global emergence of highly pathogenic avian influenza (Ramey et al. 2022).

Formation of especially high risk interfaces

Certain activities or processes can create spatially-restricted locations that have much higher risk of transmission than the broader landscapes that surround them and thus require specific attention. For example:

- caves heavily used by both bats and humans (Adjemian et al. 2011),
- specific human or domestic animal food sources that are permeable to wildlife pathogens (Chua et al. 2000; Pulliam et al. 2012; Khan et al. 2012)
- areas heavily dominated by invasive plant species or alien species that favour pathogen vectors and/or hosts (see Reaser et al. 2021b)
- restoration of trophic predators to wetlands whose ecology (vegetation, fauna, etc.) has been strongly modified by dams reduced transmission of human schistosomiasis (Sokolow et al. 2015)

Wildlife trade

The live wildlife trade can intensify all four steps of the LUIS pathway through the unnatural and often unsanitary environment it creates. Moving through the supply chain, animals' immune function can be compromised by the conditions inherent in the trade, leading to high prevalence, mixing, and shedding of pathogens (Baker et al. 2013, Huong et al. 2020, Wyatt et al. 2022, Nga et al. 2022). For live-traded species flowing into large commercial markets, hosts and the pathogens they carry are often moved into new geographies. Humans and wildlife are in close proximity from the point of capture to the point of sale or consumption (Greatorex et al. 2016).

- Within the wildlife trade, mixing of diverse species, crowding and poor hygiene practices have contributed to an increase in coronavirus detection to greater than 50% along supply chains from forest/field to fork in Vietnam rat trade (Huong et al. 2020).

Limited capacities to detect and respond to spillover events

It is unlikely that all spillovers can be prevented by minimizing risks in the early part of the LUIS chain, but in situations with strong public health systems and high levels of health awareness amongst community members, spillovers that do occur can often be rapidly detected and contained with minimal cost or health impact. These positive factors are absent or weakly developed in many areas of the world, especially in remote frontier areas of the tropics (see below); such lax conditions can allow more spillovers to become epidemics and more epidemics to become pandemics.

Box 1 Spatial patterns of pressure and risk

Whilst spillovers can occur in almost any context, current understanding of the available evidence from a range of sources is that the highest risks are associated with tropical and subtropical forests, in particular around frontiers of clearance and degradation and where human and or livestock populations are high or rapidly rising (Allen et al. 2017). These are also typically areas where wildlife trade chains originate, as new access points allow hunting of well-stocked, previously unaffected areas.

- Viral diversity and sharing among mammal species, a proxy of spillover potential, is highest in tropical areas, especially for rodents and bats (Albery et al. 2020)
- 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).
- Frequent human-animal interactions with low biosecurity in tropical biodiverse areas makes these areas prone to spillover risk (Li et al. 2019).

Observed pathogen spillover and emergence risk in areas outside tropical forested ecosystems is considerably lower (Keatts et al. 2021) but still a material risk in many contexts.

2. Landscape interventions

2.1 Overview

The main potential landscape[4] interventions are broadly grouped into categories focused on different types of pressure, as shown in Table 1 and discussed in sub-sections 2.3-2.7. The second column separates the categories between those we judge as having high importance and those with very high importance. The interventions are a precautionary principle approach and address all four parts of the infect-shed-spill-spread pathway. Human health responses may be seen by some as outside the scope of 'conservation' programs, but they are critical to lowering the likelihood of the 'spread' step of the pathway and they take place in the same landscapes as many of the actions

[4] The term 'landscape' is used here in a broad sense to refer to a large, contiguous area of land, well below the international or national scale, which has broadly similar socio-economic and ecological conditions. For our purposes, a landscape is an area where spillover risks can be addressed through the implementation of place-based actions relating to specific communities, companies, land management units, development projects, local government agencies, and NGOs. Landscapes are nested within and affected by subnational, national, and international governance frameworks.

designed to reduce pressures, often amongst the same human communities, so it is helpful to consider them here as part of a holistic approach.

Table 1. Elements of an integrated landscape intervention and the pressures they are designed to address.

Category of intervention	**Importance to addressing global pandemic risk**	**Aim**
Averting harmful land-use change and land-use [Section 2.3]	Very high – applicable in most geographies, especially in key tropical regions.	Preventing increased spillover risk that results from conversion of ecosystems, degradation of ecosystems, over-harvesting of valuable species and/or intensification of livestock farming in high risk locations
Counter wildlife trade measures	Very high – applicable in most geographies, especially in key tropical regions.	Mitigating risks associated with the wildlife trade
Human health and education programs [Section 2.4]	Very high – applicable in most geographies, especially in key tropical regions.	Minimizing occurrence, severity and spread of spillovers in local human populations
Wildlife and livestock health programs [Section 2.5]	High – applicable in specific, restricted locations.	Minimizing pathogen sharing between wildlife and livestock and the pathogen load of reservoir species
Restoration [Section 2.6]	High – applicable in specific, restricted locations.	Reversing past damage to ecosystems and species populations in ways that lower spillover risk
Customized solutions for specific, high-risk interfaces [Section 2.7]	High – applicable in specific, restricted locations.	Identifying and mitigating particular localized processes that increase transmission risk

Each landscape or program will require a variety of integrated interventions, ideally planned and delivered as a coherent program or strategy, e.g., developing wildlife and human health programs within an effort to support a protected area. To significantly reduce spillover risk, programs of landscape-level action need to be applied in as many as possible of the high-risk areas in a country, region, or (ideally) globally. The appropriate balance of actions differs widely between landscapes depending on the local context. One potentially useful framework for identifying the right mix of actions is outlined in Section 2.7.

2.2 The importance of land rights, sovereignty, and wellness of Indigenous Peoples and local communities

Whichever interventions are supported, it is important that they are planned and implemented in a way that respects human rights, social equity, and environmental justice. This includes respect for principles of free, prior, and informed consent, legal and customary rights (including land tenure and harvest rights and the right to good health), and due consideration for marginalized groups (including women, young people, the elderly, disabled and ethnic minorities, among others) (Fellows et al. 2021).

In most cases, interventions planned in a way that fully respects peoples' rights and involves a high degree of participation will also probably be more effective and more sustainable. For example, the presence of Indigenous Peoples and local communities (IP&LCs) in forests is a major deterrent to land encroachment and conversion through strong social and cultural institutions, traditional land governance, direct defence of land, and political activism. Indigenous communities of the Amazon have been shown to be remarkably effective buffers against forest loss, protecting their territories from destructive actors such as gold-miners, loggers, and agribusinesses (Walker et al. 2020; Garnett et al. 2018). This is a major opportunity, because whilst Indigenous Peoples make up only 6% of the world's population, they manage or have tenure rights to more than 38 million km^2 on all inhabited continents, adding up to more than a quarter of the earth's land surface (FAO 2021). Areas managed by Indigenous Peoples intersect with 40% of all terrestrial protected areas and ecologically-intact landscapes (Garnett et al. 2018).

2.3 Averting conversion and degradation of ecosystems

Key solutions

- *Protected areas and Indigenous or local community lands*
- *Spatial and infrastructure planning*
- *Limit damage by extractive industries and agriculture*
- *Effective law enforcement*
- *Support sustainable livelihoods and reduce unsustainable use*

These interventions are needed to slow or halt conversion of ecosystems (especially forest) to other land-uses (typically agriculture, pasture, or tree plantations); degradation and fragmentation of ecosystems (especially forest) through harvest of timber and other plant products; over-hunting of animal species; creation of roads or other infrastructure; changes in fire or flood regimes; and spread of invasive species, etc.

Since these damaging processes also impact many other environmental (such as biodiversity and carbon storage) and social justice (e.g., local rights holders) values, the interventions needed to halt them have been a principal focus of conservation programs worldwide for many years—there is an extensive 'how-to' literature—and they bring many benefits besides reduced spillover risk. In any given landscape a combination of the actions listed below will be required, depending on local context.

Protective designations for areas of natural ecosystems should be central to a landscape strategy to minimize spillover risk in many or most cases. There is growing consensus that *at least* 30% of the global land surface should be maintained as natural ecosystems in protected areas or other designations with similar conservation benefits, located to be representative of the full range of biodiversity and managed to ensure their full effectiveness in preventing threats to ecosystems and the species they support. This approach, now often referred to as '30x30' in recognition that it should be achieved by 2030, would make a major contribution to reducing many of the drivers of increased LUIS risk identified above (Reaser et al. 2021, Practice 3), is supported by many statements in the literature and has become a key element of the Global Biodiversity Framework 2020-2050, under the Convention on Biological Diversity, endorsed in December 2022 by most of the world's governments. Some scientific authorities suggest up to 50% of the land surface should be placed in protective designations (representing well over 50% of the remaining natural ecosystems). In the

Amazon areas with relevant designations together already cover around 50% of remaining forest, and there are costed proposals to increase this to over 80%.

Some of these designated areas should be protected areas, where biodiversity conservation is the primary stated management goal, but there is now general acceptance that there are many other forms of effective area-based management, including many types of management or ownership by Indigenous Peoples or local communities. Landscape approaches to minimizing spillover risk should aim for a mixture of these designation types, based on the local social conditions and the views of local rights holders.

Spatial planning (e.g. 'zoning') can reinforce the effectiveness of protective designations by affirming to other stakeholders their importance, or by establishing umbrella designations such as conservation mosaics. It can also prioritize new areas where protective designations should be made and/or traditional land tenure should be formally recognized, and play a key role in ensuring the long-term security of areas not formally designated for protection. For instance, it can guide the siting of infrastructure or other damaging activities away from vulnerable locations, or ensure that any development that does take place does so in such a way as to minimize fragmentation (and hence the extent of high spillover risk edge zones) and keeps intensive livestock production separate from areas of greatest spillover risk. It can also enable the maintenance of landscape-wide connectivity (Reaser et al. 2021a, Practice 5) and be designed in a way to optimize benefits across landscapes while minimizing costs and managing trade-offs.

Spatial planning is most effective when led or endorsed by local/national government authorities (which may essentially give it force of law) but it can have some impact (especially on their own actions) when conducted by companies or communities without government endorsement. Existing good practices should be followed to involve stakeholders effectively in planning processes, and a range of software tools exists to help develop technically optimal plans.

Limit damage to ecosystems by extractive industries and agriculture. Expansion of agriculture, especially for commodity production, is responsible for the great majority of deforestation in the tropics, whilst new infrastructure (e.g., for mineral extraction) and the expansion of timber extraction are among the key drivers of degradation and fragmentation in intact forests worldwide. Interventions to limit damage by particular sectors can thus play an important role, complementing site-based protection and spatial planning. These interventions may be led by companies and government agencies charged with development who themselves take on sustainability goals, or by other stakeholders (e.g., government environmental agencies, civil society, local communities) pushing for specific kinds of damage to be avoided. Familiar examples could include a company adopting a zero deforestation approach to increasing production in a given landscape, or a network of community groups lobbying against the construction of an illegal or harmful mine in a remote forest area.

Effective law enforcement. Worldwide, many good existing environmental laws are poorly enforced, so enhanced enforcement could result in reduced ecological damage in landscapes at high risk of spillover. Pathways include building high level political will, capacity-building for enforcement staff, and increased transparency that enables watchdog organizations to raise awareness about ongoing breaches of the law and so catalyse state action. Law enforcement is relevant to many pressures driving LUIS risk, including ecosystem conversion and damage, pollution events, and illegal harvesting or transportation of wildlife products.

Support sustainable livelihoods and reduce unsustainable use. A focus on making the use of ecosystems sustainable can have benefits in its own right (e.g., reducing avoidable ecosystem damage or promoting recovery), and also reinforces many of the other interventions, especially where it results in economic improvements (e.g., a durable resource base, better incomes) for key stakeholder groups whose active support or legal compliance is required with broader landscape management efforts (such as reductions in future clearance). Some interventions address use of natural ecosystems, including a wide variety of community harvesting systems as well as commercial use (e.g., timber harvesting operations). Others relate to farms and plantations, with a focus on minimizing damage in-field as well as reducing the wider impacts through agrochemical use and attrition of residual patches of native vegetation.

The two standard elements of a sustainable use intervention are to reduce levels of pressure to within the recovery abilities of the system, and to improve economic outcomes (e.g., through value-add processing, business planning, loan facilities, or better marketing). A diverse toolkit of options exists for each of these two elements. For example, damage can be reduced by changes in laws and regulations, membership of voluntary schemes (such as certification), or by raising awareness among producers of attractive improved techniques. Economic outcomes can be improved through investments in new crops/technologies/alternative livelihoods, raising prices for produce (e.g., premiums for environmentally responsible goods), improving access to markets, etc.

2.4 Human health and education programs

Programs to increase health education and access to healthcare in remote settings are of course recognized as a major human development imperative, and they can often also be expected to have significant impacts on the intensity of the LUIS pathway by, for example, lowering the overall susceptibility of marginalized communities to disease, improving general surveillance and response systems and improving peoples' understanding of health issues (Munster et al. 2018). It is unlikely that directing the small amounts of available conservation finance to these very large-scale programs would have much incremental impact. However, there are more targeted landscape-level human health and education programs that could deliver more perceptible biosecurity benefits. For example, outreach and education programs focussed on wildlife-associated disease threats can benefit both community wellbeing and efforts to conduct surveillance on wildlife mortality events, leading to earlier detection and response (Kuisma et al. 2019, Denstedt et al. 2021) or increase awareness of potential risks (Martinez et al. In Press, Reaser et al. 2021a Practices 2 and 9).

Some health programs can also be seen as interventions addressing other pressures. For example, under the Health in Harmony model, accessible and affordable healthcare can offer an additional pathway to prevent spillover from taking place through meeting the needs of rural communities, reducing deforestation, and providing access to healthcare that does not require livelihoods that put people in contact with wildlife or into risky environments such as forests (Jones et al. 2020). By providing access to health care in rural Borneo along with other Health in Harmony programming, deforestation was reduced by 70% over 10 years (Jones et al. 2020).

2.5 Wildlife and livestock health programs

Wildlife health programs and networks are critical to establish baseline information on the prevalence and intensity of zoonotic pathogens in wildlife in intact and degraded habitats and to understand how these habitat changes affect overall health (e.g., immune defense). Robust surveillance practices can help identify pragmatic targets for limiting zoonotic pathogen spillover, such as avoidance of certain caves during periods of known high virus shedding in bat hosts (e.g., Amman et al. 2012), limiting contact between tourists and macaques in south and southeast Asia due to possible spillover of herpesviruses and influenzaviruses (Engel et al. 2002, Karlsson et al. 2012), and immunization of wildlife (Slate et al. 2009).

Implementation efforts like WildHealthNet[5] are early efforts that build on existing frameworks and guidelines to establish national wildlife health surveillance systems (Pruvot et al. 2022; OIE 2021; Stephen et al. 2021). Much more needs to be done - a review of Convention on Biological Diversity National Biodiversity Strategies and Action Plans found just 8% (10/125) of countries contained 'wildlife health and/or zoonotic content' and only 6% (8/125) had 'wildlife health or programmes and activities related to zoonotic diseases' (Machalaba et al. 2021).

Best practices using targeted sampling designs are needed to appropriately sample wildlife over both space and time to identify where and when zoonotic infections are most common as well as the conditions that facilitate active infections and the interventions that can prevent them (Plowright et al. 2019, Becker et al. 2020, Giles et al. 2021).

Unlike wildlife health, livestock health, livestock surveillance, and livestock biosecurity measures are usually well codified and practised by both international and national bodies (e.g., FAO, WOAH, and national agencies), but the scale, depth and integration of programs is often insufficient, especially in high risk remote tropical frontier locations. Innovative anti-spillover approaches include expanded diagnostic testing for novel pathogens (Bird & Mazet 2018), use of technology to reach backyard and small-scale producers, and participatory surveillance to understand interfaces between livestock and wildlife (Yano et al. 2018, Denstedt et al. 2021).

2.6 Restoration

Restoration can include practices such as revegetation, rebuilding the productivity of working lands, creation of ecological corridors and green infrastructure, 'greening' of cities and reintroduction programs. Some approaches to restoration are referred to as rewilding.

In principle, restoration of degraded ecosystems evidently has the potential to minimize or even reverse negative impacts of past land conversion and degradation on the prevalence and intensity of zoonotic pathogens in their wildlife hosts as well as reducing opportunities for risky contact between wildlife and humans (Reaser et al. 2021b, Reaser et al. 2022). However, whilst documented examples of restoration projects that reduce disease transmission do exist, and many more are likely to be found, empirical assessments of this aspect of restoration programs are generally rare, thus much more research is needed to clarify the conditions where they are beneficial. Neutral or even negative impacts may conceivably occur in some cases (e.g., increased contact between humans and wildlife in restoration areas near to settlements).

Whatever the situation with regard to spillover risk, restoration has many other clearly established benefits and so is growing rapidly in scale in many regions, driven in part by very ambitious national pledges made under for example, the Bonn Challenge. Such programs should be implemented with appropriate conditions (e.g., dietary and space use requirements) in mind for target ecosystems and/or species to avoid unintended negative consequences (e.g., Blanco et al. 2011) and be used as opportunities to study the impacts on disease transmission.

[5] https://oneworldonehealth.wcs.org/Initiatives/WildHealthNet.aspx

2.7 Customized solutions for specific, high-risk interfaces

A recent extensive literature review identified 46 solutions that are win-wins for human health and the conservation of living things. The authors then characterized them (e.g., by geography, IUCN threat classes affected, pathogen taxa) and assessed them for viability, feasibility, and acceptability (Hopkins et al. 2022). Six of the solutions directly address pathogen spillover to people, two relating to wildlife trade and four highlighted here:

1) use poultry biosecurity to reduce influenza spillover and wild bird conflicts;
2) educate people about living safely with bats to reduce spillover and conserve bats;
3) use skirts on sap pots to reduce Nipah virus spillover and conserve bats; and
4) restore bat habitat to reduce Hendra virus spillover.

We highlight these examples for readers to learn more about landscape interventions for specific systems and their evidence base (see Hopkins et al. 2022, and https://ecohealthsolutions.stanford.edu/research/win-win-solutions- people-and-nature). Actions to manage human activities such as recreation within forests, and to avoid attracting wildlife to people (Reaser et al. 2021a) are also relevant here. Further research is likely to reveal many other targeted, localized, high impact interventions of this kind.

2.8 Tailoring interventions to specific landscapes or landscape conditions

The interventions outlined above are relatively complex and potentially costly. Although modelling suggests that the societal benefits of large-scale delivery of such interventions from the reduced burden of pandemics will greatly outweigh their costs (Dobson et al. 2020; Bernstein et al. 2022) we should nonetheless aim to implement them in the most cost-effective way possible, for example by careful targeting. Targeting programs towards the landscapes with highest spillover risk is described in Section 1.4. It is also essential to select and target interventions cost-effectively *within* priority landscapes. The evidence base on how to do so with respect to spillover risk is less precise than is the case for some other environmental values, so recommendations are, of necessity, broad. In specific landscapes, One Health risk assessments can help identify important interfaces for spillover and potential interventions (IUCN 2022). Looking ahead, it would be valuable to monitor systematically the health outcomes of a sample of conservation investments so as to generate the evidence base for more precise targeting of future investments (McKinnon et al. 2016).

The choice of interventions should be placed in the context of how much ecosystem clearance and land degradation has already occurred in an area. The ‘three conditions for conservation’ 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 (see map in Locke et al. 2019):

- 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. They are divided into 'broad conservation guidance' which would deliver benefits for securing a wide range of environmental values and 'additional One Health considerations' - actions whose main benefit is in relation to spillover prevention. There is great potential to integrate the latter more fully with the former.

In large, intact, mostly natural areas

Broad conservation guidance:

- Retain ecosystem integrity to the greatest extent possible, which in practice means avoiding the expansion of intensive extractive uses (e.g. industrial logging, harvest of animal and plant products), not fragmenting areas with infrastructure[6], pastures and farmland, and not disrupting natural fire and flood regimes. Remove and restore anomalies resulting from historical damage, where possible;
- Establish large, effectively managed protected areas, titled Indigenous and community lands, and Indigenous and community conserved areas. Secure Indigenous knowledge and livelihoods;
- Ensure multi-stakeholder spatial planning and policies to reduce threats arising from specific economic sectors;
- Address the commercial wildlife trade where it begins to emerge.

Additional One Health considerations:

- Strengthen health care infrastructure to meet the needs of IP&LCs, enhance emerging infectious disease surveillance in collaboration with them and better understand the patterns of exposure and immunity that they experience at wildlife interfaces;
- Implement or grow wildlife health surveillance in and around natural areas with information designed to flow to human health and domestic animal health sectors and stakeholders;
- Support access to health care and treatment, as well as outreach and education on local human health issues and veterinary care for livestock and domestic animals.

In shared landscapes

Broad conservation guidance:

- Avoid further degradation and fragmentation of natural ecosystems;
- Establish 'ecologically representative and well-connected systems of protected areas' with a focus on key biodiversity areas (KBAs); restore and maintain ecological processes and viable populations of native species (ensure area protected is in the range of 25–75% per ecoregion);
- Where communal management systems remain, secure Indigenous and community tenure;
- Across landscapes integrate sustainable natural resource extraction and activities such as tourism, grazing, and use of wildlife (where appropriate and sustainable) with Indigenous knowledge and protected area networks;

[6] It is important to recognize that the disturbance effect of the first phase of linear infrastructure development is disproportionately higher in more intact landscapes.

- Ensure multi-stakeholder spatial planning and policies to reduce threats arising from specific economic sectors. Integrate ecological and human health impact assessments for development projects;
- Address the wildlife trade.

Additional One Health considerations:

- Given the significant ongoing levels of contact between humans, wildlife, and livestock, plan land-uses, zoning (and restoration) in ways that reduce the degree of contact and the extent of high-risk interfaces (e.g., minimize edges, restrict usage, and create buffer zones) where possible;
- 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 levels of risk;
- Implement or grow wildlife health surveillance in and around natural areas with information designed to flow to human and domestic animal sectors and stakeholders;
- Engage communities in human health and education programs that are linked to conservation outcomes.

In areas dominated by cities and farms

Broad conservation guidance:

- Increase conservation efforts to secure endangered species and protect all remaining primary ecosystem fragments;
- Mainstream sustainable practices such as protecting good farmland, practising productive regenerative agriculture, and keeping nitrogen out of freshwater;
- Maintain pollinators and support strategic ecological restoration;
- ‘Green’ cities to reduce carbon emissions, prevent urban sprawl, and provide access to nature for urban dwellers’ health and well-being. Plan cities using a One Health approach to enhance liveability and wellbeing, minimize spillover risks but also buffer against extreme weather events.

Additional One Health considerations:

- 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;
- Manage farms to limit the emergence and spread of antimicrobial resistance;
- Raise social awareness about the intersection of climate change, biodiversity loss, pandemic risk and global food systems to support policy change (Wegner et al. 2022);
- Whilst public health, biosecurity and disease surveillance, and response systems tend to be more robust for known pathogens in these places, defences should nonetheless be strengthened for new, emerging pathogens (e.g., in urban wildlife markets or human-wildlife interfaces). Recognize international airports are nodes in global movement of people, wildlife products, and pathogens they may be carrying.

Annex: Action at global and national level

Whilst this white paper focuses on action at the landscape level, broader measures will also be required, both to ensure that landscape action can be delivered at the necessary scale and also to address drivers that originate elsewhere in the global socio-economic system, such as demand for forest risk commodities.

The points outlined below are drawn (with minor edits) from the results of a key workshop organized by the IPBES (2020), with the addition of two points highlighted through consultations on the present paper, marked *. Most points apply at both national and international levels and while our report has focused on LUIS, climate change action is also important at these levels to address synergistic effects with LUIS. For a complementary list, with more emphasis on guiding principles and enabling conditions, the 2017 synthesis by the Convention on Biological Diversity (CBD 2017) and the underlying principles of One Health (Adisasmito et al. 2022) are useful resources.

Develop enabling mechanisms

Launch a high-level intergovernmental panel on pandemic prevention (e.g., the One Health High Level Expert Panel (OHHLEP), the Scientific Advisory Group on the Origins of Novel Pathogens (SAGO) and the WHO Intergovernmental Negotiating Body[7] now drafting a Pandemic Treaty).

Institutionalize One Health in national governments to build pandemic preparedness, enhance prevention programs and investigate and control outbreaks (e.g., the One Health Joint Plan of Action of the Quadripartite[8]).

Integrate ('mainstream') the economic cost of pandemics into consumption, production and government policies and budgets.

Generate new green corporate or sovereign bonds (*and strengthen existing development assistance and payment for environmental services programs) to mobilize resources for biodiversity conservation and pandemic risk reduction.

Design a green economic recovery from COVID-19 as an insurance against future outbreaks.

Implement policies to reduce the role of land-use change and climate change in pandemic emergence

*Ensure that national legal frameworks and spatial planning processes provide a framework to support appropriate action.

Develop and incorporate pandemic and emerging disease risk health assessments into major development and land-use projects.

Reform financial aid for land-use so that benefits and risks to biodiversity and health are recognized and explicitly targeted.

Develop scalable, evidence-based programs for effective habitat conservation measures, including protected areas, communal land-tenure systems and restoration programs, that can minimize spillover risks.

[7] https://apps.who.int/gb/inb/pdf_files/inb1/A_INB1_8-en.pdf
[8] https://apps.who.int/gb/MSPI/pdf_files/2022/03/Item3_31-03.pdf

Enable transformative change to reduce the types of consumption, globalized agricultural expansion and trade that increase pandemic risk.

Implement policies to reduce pandemic emergence related to the wildlife trade

Build a new intergovernmental health and trade partnership to reduce zoonotic disease risks in international wildlife trade.

Educate communities from all sectors regarding health risks associated with wildlife use and trade.

Reduce or remove species in wildlife trade that are identified as high risk[9] of disease emergence, coupled with enhanced disease surveillance.

Foster a role for all sectors of society to engage in reducing risk of pandemics

Educate and communicate with all sectors of society about the origins of pandemics.

Identify and label high pandemic-risk consumption patterns.

Increase sustainability in agriculture to meet food requirements from currently available land.

Promote a transition to healthier and more sustainable and diverse diets, potentially including taxes or levies on meat.

Promote sustainable mechanisms to achieve greater food security and reduce consumption of wildlife.

Ensure sustainability incentives for companies to avoid high pandemic-risk land-use change, agriculture, and use of products derived from high pandemic risk trade or wildlife farming.

Conduct applied research to close critical knowledge gaps[10].

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[9] The WCS position is that according to the precautionary principle all trade and sale of live or freshly killed wild birds and mammals for human consumption, in particular to urban venues, whether supplied from wildlife farms or wild-caught, should be stopped because of the high risks.

[10] The IPBES (2020) report lists nine key gaps under this heading.

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