Reducing land use induced-spillover risk by fostering landscape immunity: policy priorities for conservation practitioners

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Abstract

Anthropogenic land use change is the major driver of zoonotic pathogen spillover from wildlife to humans. In response to the global spread of the SARS-CoV-2 virus (the agent of COVID-19 disease), there have been renewed calls for landscape conservation as a disease preventive measure. While protected areas are a vital conservation tool for wildlands, more than 50% of habitable land is now human-modified and thus requires strategic, site-based measures to prevent land use-induced spillover, especially by managing landscape immunity and the dynamics of animal-human proximity. Crisis is a conversation starter for reimagining and recommitting ourselves to what is most vital and generative. Here we provide a brief overview of zoonotic spillover concepts and dynamics from a conservation practitioner perspective and outline a landscape-oriented policy agenda to minimize the risk of future large-scale zoonoses outbreaks. Among other things, we need to recognize human health as a vital ecological service, ensure ecological resilience, and facilitate public investment in biosecurity to sustain economic viability and human well-being. Landscape management approaches to spillover risk reduction are part of a toolkit that includes ecological, veterinary, and medical interventions, disease surveillance, and wildlife trade policy measures.

1 | INTRODUCTION

> *"Make no mistake, they are connected, these disease outbreaks coming one after another. And they are not simply happening to us; they represent the unintended results of things we are doing*."

~ David Quammen, Spillover: Animal Infections and the Next Pandemic

Pathogens and parasites are vital components of biodiversity that drive ecosystem processes and services through their influences on host species population dynamics (Hudson et al. 2006) and may warrant greater conservation attention as native biota (Gómez & Nicholas 2013). However, anthropogenic ecosystem disruption can inadvertently turn "good guys" into "bad guys" by altering the relational contexts—physical and ecological—in which organisms exist (Mooney & Hobbs 2000; Reaser *et al.* 2020b). Recent increases in the frequency, scale, and severity of zoonotic disease outbreaks evidence such phenomena; anthropogenic land use change is the major driver of zoonotic pathogen spillover (transmission) from wildlife to humans (Patz *et al.* 2004; Brearley *et al*. 2013). Considering 'land use change' broadly as anthropogenically-induced ecosystem change, we provide examples of spillover events associated with land use change in a supplemental table (Table S1). Hereafter, we refer to cases in which land use change has triggered the inter-specific transmission of pathogens (further discussed below) as 'land use-induced spillover' (after Plowright *et al*. 2020).

Although the land use factors leading to the transmission of SARS-CoV-2 (the agent of COVID-19 disease) from its evolutionary origins in *Rhinolophus* bats (Boni *et al.* 2020) to humans is currently unknown, recognition of the connection between land use change and zoonotic disease emergence has led to renewed calls for ecosystem protection as a disease preventive measure (e.g., Andrade *et al*. 2020, Dobson *et al.* 2020). Plowright *et al.* (2020) call on the scientific community to urgently form interdisciplinary investigations into mechanisms driving land use-induced spillover *in situ*. Here we complement their proposal by providing a brief overview of zoonotic spillover concepts and dynamics from a conservation practitioner perspective and outline a landscape-oriented priority action agenda to be implemented by conservation practitioners to minimize the risk of future large-scale zoonoses outbreaks. Fundamentally, landscape management approaches to spillover risk reduction should be regarded as elements of an integrated toolkit that includes ecological, veterinary, and medical interventions (e.g., Sokolow *et al.* 2019 review ecological/veterinary interventions), disease surveillance, wildlife trade policy, and other social-economic measures (see priority actions herein).

Effective land use policy and management decision making are predicated on the existence, accessibility, and spatio-temporal applicability of relevant scientific data (Reaser et al., 2020). In the context of zoonotic disease prevention, the available science has enabled us to establish first principles for landscape conservation that include maintaining intact ecosystems while minimizing habitat penetration, fragmentation, and wildlife-human interaction ('dynamics of proximity') in already disrupted environments (Sokolow *et al*. 2019; Johnson *et al*. 2020). Protected and conserved areas are the land-use designations widely used around the world to prioritize maintaining intact ecosystems and associated traditional patterns of human-wildlife interaction (Hockings *et al.* 2020).

However, while the aspiration to protect and restore intact ecosystems is a worthy goal for the sake of all life on Earth, more than 50% of habitable land is now human-modified (Field 2020). Due to a lack of policy prioritization, we do not have the base of knowledge, nor technical, logistical, or financial capacity to return the vast majority of these ecosystems to a "pristine" state. The conservation community must accept responsibility for the world as we find it and then act in a restorative manner. Locke *et al.* (2019) have identified three broad classifications for landscape conditions globally: "shared lands" (</= 50% human-modified) now cover 56% of the terrestrial landscape, the last remaining large wild areas account for 26% land cover, and heavily human-modified landscapes (urban and agriculture landscapes) constitute 18% of land cover.

Under such circumstances, a precautionary approach to minimizing zoonotic outbreaks by protecting wildlands (intact landscapes outside and within human-modified environments) is a primary goal. However, in human-modified landscapes other place-based strategies are required to prevent or mitigate zoonotic disease emergence. In these contexts, the relationships between land use change and wildlife disease are rarely consistent; the issue is highly variable, typically reflecting such factors as host and pathogen species, pathogen transmission scenario (directly to humans, via intermediate vertebrate host, or arthropod vectored), animal-human dynamics of proximity, and land use (current and historical)(reviewed by Brearley *et al.* 2013; Plowright *et al.* 2020, Table 2).

Through a recent literature synthesis, Johnson *et al.* (2020) found that the number of zoonotic viruses detected in mammalian species scales positively with global species abundance, suggesting that virus transmission risk has been highest from animal species that have increased in abundance and even expanded their range by adapting to human-dominated landscapes. A broader analysis of vertebrates by Gibb *et al.* (2020) revealed that known wildlife hosts of human-shared pathogens and parasites (particularly rodents, bats, and passerine birds) overall comprise a greater proportion of local species richness (18-72% higher) and total abundance (21-144% higher) in sites under substantial human use (secondary, agricultural and urban landscapes) compared with nearby undisturbed habitats, indicating greater need to investigate the drivers of wildlife-human proximity. In effect, biodiversity buffers disease risk. Clearly, in order for the conservation community to help prevent future large-scale outbreaks of zoonotic disease, science needs to be brought to bear within the context of the human enterprise, at the margins of and within disturbed landscapes matrixes, which are subject to a high degree of spatio-temporal variation.

2 | LANDSCAPE IMMUNITY: A CONSERVATION PRACTIONER’S PERSPECTIVE

In general terms, three potentially inter-related linkages between land use and wildlife disease dynamics are clear: 1) ecological patterns across the landscape determine the distribution and abundance of biota, buffering wildlife disease dynamics, 2) environmental stress affects wildlife susceptibility to pathogen *infection*, as well as the likelihood of wildlife *shedding* pathogens in a manner that increases exposure of other animals (including humans), and 3) human-altered landscapes bring wildlife into closer proximity to domestic animals and humans, thus increasing the likelihood that shed pathogens will *spill over* into populations of other species (ultimately, humans) where they may *spread* further. For SARS-CoV-2 to reach epidemic or pandemic scales of spread, we know that a wild animal was infected with a zoonotic pathogen and then shed the pathogen in sufficient quantities to infect susceptible people either directly or through intermediate animals (other wildlife and/or domestic species)(Plowright *et al.* 2017). Plowright *et al.* (2020) refer to this process as the ‘infect-shed-spill-spread cascade’ or simply, land use-induced spillover (Figures 1 and 2 therein).

A detailed knowledge of what and how land use-induced environmental stressors initiate the infect-shed-spill-spread chain of events is needed to enable landscape managers to strategically intervene to arrest the specific trigger(s). Metaphorically, this is akin to garnering a thorough understanding of the factors that influence the first dominos to fall and subsequently to cause others to fall. Plowright *et al.* (2020) point to the need for investigation into the specific mechanisms by which land use change operates *in situ* at local to regional scales to facilitate zoonotic spillover. Closing these knowledge gaps is fundamental to reducing spillover risk. They propose ‘landscape immunity’ as a topic for place-based interdisciplinary research into land use-induced spillover, defining it as the ecological conditions that, in combination, maintain and strengthen the immune function of wild species within a particular ecosystem and prevent periods and places of high prevalence and pathogen shedding. In principle, a high degree of landscape immunity enables wildlife to resist pathogen infection, lower prevalence, minimize shedding, or reduce their spread *in situ*, thus preventing the chain of events necessary for spillover to humans. Landscape immunity thus governs the dynamics of the infect-shed-spill-spread cascade. In Figure 1, we use falling dominos to depict landscape immunity as an operationalized land management principle and practice.

All organisms are physiologically-influenced by chemical, physical, and biological conditions (hereafter 'environmental conditions') and have innate, generally taxa-specific, physiological parameters by which they thrive or are limited (Seiler *et al.* 2020). Characterizing landscape immunity parameters will require an understanding of how specific land uses impact the proximal environmental conditions that act as stressors: a) causing an animal's immune system to weaken to the extent that it is pathogen-vulnerable and b) triggering the physiological processes that result in pathogen shedding (Beldomenico & Begon 2016 review stress-host-parasite interactions). The environmental stressors driving susceptibility to infection may be different from those that invoke shedding and thus it is possible that, ultimately, different land uses may be acting in concert to drive the infect-shed-spill-spread cascade. For at least some species, research indicates that a wild animal's resistance to infection and shedding is influenced by growth, aging, reproduction, and movement patterns, thus delineating a variable, but potentially predictable, physiological baseline (Plowright *et al.* 2017).

Landscape conservation practitioners can readily demonstrate that certain land uses in specific contexts cause wildlife injury and mortality. For example, there is substantial evidence that roads lead to wildlife being injured or killed by traffic, large plate glass windows increase bird strikes, plastic waste can kill animals that consume it, and chemical spills into waterbodies can cause the mass mortality of aquatic and terrestrial species (see Fey *et al*. 2015 review). Environmental impact assessments have long been used to document and foresee variations in environmental conditions (as a proxy for specific stressors) and new quantitative tools may enable evaluation of ecosystem vulnerability at various scales (Zip *et al*. 2017). Biologists have also identified a relatively small number of species with moderate, predictable, tolerances in environmental variability that can serve as bioindicators, species or species assemblages whose function, populations, or status qualitatively reflect environmental condition . In instances in which community assemblages can serve as bioindicators, "biotic indexes" or other "multimetric" approaches are used to score environmental condition (Burger 2015). These bodies of work may help us generate hypotheses regarding: a) the array of land uses potentially impacting wildlife physiology in a specific spatio-temporal context and b) relative site condition, yet more specific immunological diagnostics are needed to establish the causal linkages cascading from land use to environmental condition to physiological responses governing infection (see Becker *et al.* 2020 for review). While it may seem like a daunting task, field-based investigations of the associations between land use and zoonotic pathogen dynamics are feasible where there is sufficient data on pathogen and host occurrence, land use, and spillover event patterns. In Table S1 we provide a taxonomically- and geographically-broad set of examples of studies that empirically-associate land use change with one or more components of land use-induced spillover. Land use-induced changes in host population size and density appear to have a strong influence in pathogen infection and shedding, while increasing wildlife-human proximity is a key factor in spillover.

Protecting and building landscape immunity provides a means of operationalizing ecosystem resilience concepts (Chambers *et al.* 2019). Our tenet is that even if more intact ecosystems are rich in pathogens, the relatively low intensity of ecological stressors to trigger the infect-shed-spill-spread cascade and low wildlife-human proximity translates into low spillover risk when compared to human-dominated landscapes. Landscape immunity goals complement and could amplify the outcomes of other ecological resilience goals, such as preventing adverse impacts of climate change and biological invasion (of which zoonotic pathogen and host translocation is a component). In transformed ecosystems worldwide, restoration ecology principles and practices will need to be brought to bear to secure landscape immunity. Aronson *et al.* (2016) review the needs and opportunities for restoration ecology to serve public health goals.

Based on our current correlative understanding of land use change and zoonotic disease outbreaks, ecologically-based policy and management approaches are being aptly posed as priority measures to prevent future pandemics (e.g., Dobson *et al.* 2020). Application of the scientific knowledge resulting from investigations into landscape immunity is urgently needed to apply these broad concepts in specific spatio-temporal contexts, ideally by making land use decisions that minimize the risk of wildlife becoming susceptible to pathogen infection; if the first “domino” in the infect-shed-spill-spread causal chain of events doesn’t fall, the other “dominos” remain standing. Highly-targeted land use interventions designed to minimize the risk of zoonotic pathogen spillover by arresting one or more of the environmental stressors that trigger land use-induced spillover could serve as ‘ecological countermeasures’ that can be more sustainable and cost-efficient in the long term while complementing reactive response measures, such as vaccination (Reaser *et al.* 2020a).

3 | PRIORITY POLICY ACTIONS FOR PREVENTING LAND USE-INDUCED SPILLOVER

Building on the recommendations of Patz *et al.* (2004), we outline an 8-point policy agenda by which conservation scientists and landscape managers can help secure and restore landscape immunity, foster landscape immunity studies in specific contexts, and consider ecological countermeasures where the dynamics of animal-human proximity create a high-risk for spillover. See also Plowright *et al.* (2020) regarding interdisciplinary collaboration and diagnostic toolkit needs, as well as Plowright *et al.* (2020) and Reaser *et al.* (2020b) for information system considerations.

1. **Recognize human health as an ecological service**. Highly-influential institutions such as the World Health Organization acknowledge that “human health ultimately depends upon ecosystem products and services (such as availability of fresh water, food and fuel sources) which are requisite for good human health and productive livelihoods” (https://www.who.int/globalchange/ecosystems; accessed 15 October 2020). However, there is still considerable work to be done for governments, donor agencies, conservation organizations, and others to formally recognize the protection of human health as an ecosystem service (e.g., Keesing *et al.* 2010). Doing so requires, for example, that environmental impact assessments consider human health implications. This could help reduce the zoonoses risk of land use projects (see also #4) and increase the data available to link land use change to spillover events, thereby helping to inform predictive models and identify risk mitigation options.

2. **Enact comprehensive biosecurity**. There is an urgent need for governments to recognize that national security needs extend well beyond military activity; environmental and human health issues are fundamental to protecting national assets and human well-being (National Academy of Sciences 2017). Landscape management, such as the use of ecological countermeasures to restore landscape immunity, should thus be considered within biosecurity frameworks (e.g., Meyerson *et al.* 2009). Conservation policy practitioners need to seek out opportunities to create and support inter-ministerial bodies, laws, and policies that take a comprehensive approach to biosecurity—one that is not limited to points of jurisdictional entry, but also addresses national security risks that emerge within landscape matrices.

3. **Protect and restore ecosystems**. Locke *et al.* (2019) provides guidance for enacting three global conditions for biodiversity conservation and sustainable use. In order to secure landscape immunity, these conditions need to put into force from local to global levels through relevant legal and policy frameworks and adopted as social norms. Implementation of the expanded Aichi Biodiversity Targets (https://www.cbd.int/sp/, accessed 26 September 2020) provides an opportunity for operationalizing

landscape immunity principles and practices. See also Hockings *et al.* (2020) for a perspectives on protected areas and COVID-19.

4. **Institutionalize a One Health/Planetary Health as a foundational approach.** Although One Health and Planetary Health approaches are progressing with conceptual bridge-building and catalyzing collaborations among scientists (see Plowright *et al.* 2020), academic and research institutions, non-governmental organizations, government agencies, and scientific grant making bodies have not yet demonstrated a strong inclination to break down silo walls and put these principles into practice. For example, although the World Bank has a One Health Operational Framework (World Bank 2018), it doesn't recognize the protection of human health as an ecosystem service within the Environment and Social Standards Framework (World Bank 2016) that guides borrower's projects. If it did, the human health implications of Bank-supported projects that impact ecosystem services, such as dam construction, would need to be considered with regard to landscape immunity constructs (see also # 1).

5. **Establish land use impacts indices**. An open-access clearinghouse of data on the relationship between land use and resulting environmental conditions across space and time would help facilitate empirical studies of the stressors triggering land use-induced spillover, enabling better informed decision-making. The Convention on Biological Diversity is in the process of developing indicators for Post 2020 Strategic Plan for Biodiversity which will identify relevant databases (https://www.cbd.int/conferences/post2020; accessed 25 September 2020).

6. **Foster mechanistic studies**. There is an urgent need to expand the number of empirical studies of landscape immunity for comparative purposes, as well as to identify risk management options in specific contexts. Plowright *et al.* (2020; Supplementary Material) and Becker *et al.* (2020) review data gaps and provide examples of inquiry needs to advance such studies, discussing how such studies could best examine wildlife disease dynamics and immunity *in situ*. Much of this work needs to be accomplished by interdisciplinary teams of landscape ecologists, wildlife epidemiologists, wildlife immunologists, microbiologists, and social scientists.

7. **Address dynamics of proximity in land use planning**. The dynamics of wildlife-human proximity influence zoonotic spillover risk from taxonomic and contextual perspectives (e.g., Gibb *et al.* 2020). Land use planners can help prevent land use-induced spillover by collaborating with biologists, social scientists, and policy experts to design human-dominated landscapes so as to limit human exposure to wildlife-originating pathogens. Human intrusion into wildlife habitats, wild animal-domestic animal contact, and wildlife attraction into human environments need to be considered.

8. **Employ ecological countermeasures**. For example, evaluate and further develop tree planting projects with zoonoses prevention services in mind. In order to meet biodiversity conservation, carbon sequestration, and other sustainable development goals, large-scale tree planting initiatives are being undertaken throughout the world (e.g., https://www.trilliontrees.org/, accessed 25 September 2020). These projects have the potential to influence landscape immunity by shifting the population dynamics of zoonotic pathogen hosts, including by drawing hosts toward or away from human habitation, as well as pathogen susceptibility and shedding by altering conditions that impact wildlife immune systems. Ideally, large scale tree planting projects would be strategically harnessed as ecological countermeasures to facilitate landscape immunity by reducing the environmental stressors that trigger spillover.

4 | CONCLUSION

Crisis is a conversation starter for reimagining and recommitting ourselves to what is most vital and generative. In the case of COVID-19, this means expanding the conservation mindset to include maintenance of human health as a vital ecological service. It means mobilizing conservation practitioners to become even more committed to protecting and restoring landscapes in order to ensure the biological resilience of their inhabitants and processes. It means facilitating public understanding and investment in prevention, in biosecurity, as a prevailing societal paradigm to sustain economic viability and human well-being. It means fostering landscape immunity so the dominos don't fall.

ACKNOWLEGEMENTS

RKP and PJH was supported by NSF DEB-1716698, DARPA PREEMPT D18AC00031, and RKP by the USDA NIFA Hatch 1015891. HL was supported by a Gordon and Betty Moore Foundation grant to the Yellowstone to Yukon Conservation Initiative which sponsors the IUCN World Commission on Protected Areas Beyond the Aichi Targets Task Force. We thank Robyn Egloff for finalizing the figure.

AUTHOR CONTRIBUTIONS

JKR led manuscript and figure drafting with substantial input from RKP. BH and MRA prepared the table with substantial input from JKR, RKP, DB, and PH. All others participated in concept development and contributed their expertise to manuscript drafts.

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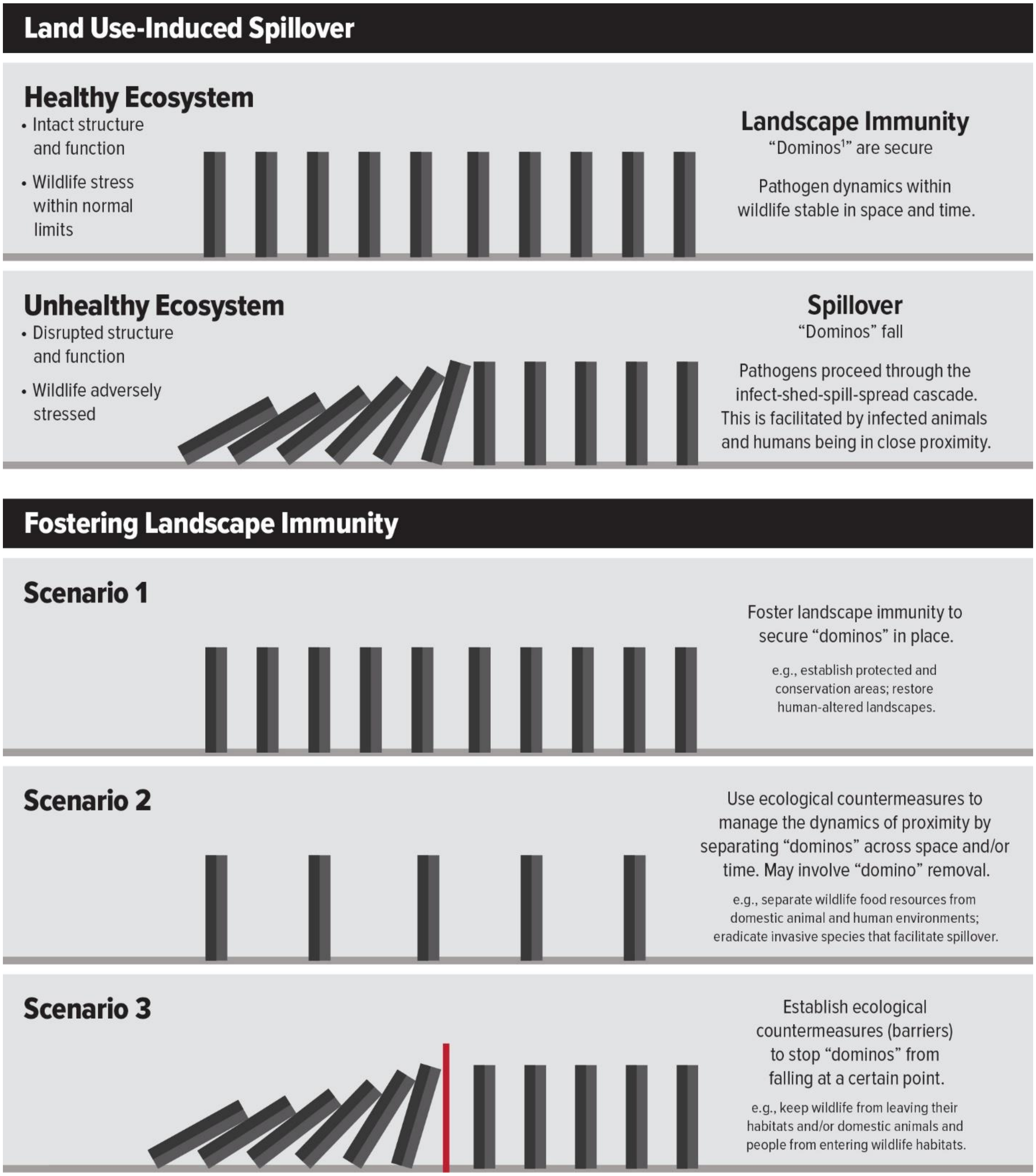
Figure 1. Land use-induced spillover: the dominos management metaphor.



Dominos represent components of the zoonotic pathogen infection, shed, spillover, and spread chain of events triggered by land use-induced environmental stressors. We term this ecological process, 'land use-induced spillover'. The goal of the "game" is to keep any of the dominos from falling by protecting and restoring landscape immunity, an aspect of ecological resilience.

Ecological countermeasures are highly-targeted land use interventions designed to minimize the risk of zoonotic pathogen spillover by arresting one or more of the environmental stressors that trigger land use-induced spillover.

Scenarios 1-3 are presented independently for clarity. At any location, more than one scenario may be appropriate, enacted simultaneously or sequentially.

Table S1. Examples of land use-induced spillover studies in which specific changes in environmental condition have been empirically associated with one or more components of the infect-shed-spill cascade.

We provide a taxonomically- and geographically-broad set of examples of studies that empirically-associate land use change with one or more components of land use-induced spillover. Land use-induced changes in host population size and density appear to have a strong influence in pathogen infection and shedding, while increasing wildlife-human proximity is a key factor in spillover.

See EcoEvoRxiv link to supplemental material.