Land use-induced spillover: a call to action to safeguard environmental, animal, and human health

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The rapid global spread and human health impacts of SARS-CoV-2, the virus that causes COVID-19, show humanity's vulnerability to zoonotic disease pandemics. Although anthropogenic land use change is known to be the major driver of zoonotic pathogen spillover from wildlife to human populations, the scientific underpinnings of land use-induced zoonotic spillover have rarely been investigated from the landscape perspective. We call for interdisciplinary collaborations to advance knowledge on land use implications for zoonotic disease emergence with a view toward informing the decisions needed to protect human health. In particular, we urge a mechanistic focus on the zoonotic pathogen infect–shed–spill–spread cascade to enable protection of landscape immunity—the ecological conditions that reduce the risk of pathogen spillover from reservoir hosts—as a conservation and biosecurity priority. Results are urgently needed to formulate an integrated, holistic set of science-based policy and management measures that effectively and cost-efficiently minimise zoonotic disease risk. We consider opportunities to better institute the necessary scientific collaboration, address primary technical challenges, and advance policy and management issues that warrant particular attention to effectively address health security from local to global scales.

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Introduction

The rapid global spread and human health impacts of SARS-CoV-2, the virus that causes COVID-19, have led to calls for greater control of wildlife commerce and consumption. Although warranted in high-risk situations, these measures should be complementary to regulatory reforms to address land use change—the primary driver of pathogen transmission from wildlife to humans[1,2]—a process known as zoonotic spillover.[3] When political and financial capital are wisely invested in measures to protect the health of ecosystems and their wildlife inhabitants, human health is a return on investment.

Land use change—which we regard as anthropogenically-induced ecosystem change—operates through various mechanisms from local to regional scales and can induce environmental stressors that determine the abundance and distribution of wildlife, shape the dynamics of wildlife exposure and susceptibility to pathogen infection, drive pathogen shedding or excretion from wildlife (panel), and create novel contact opportunities facilitating pathogen spread between species (spillover), ultimately leading to human infection and further spread.[1,11] When land use change drives this infect–shed–spill–spread cascade, we refer to this process as land use-induced spillover (figure 1).

The linkages between land use and wildlife disease dynamics are well recognised in concept; however, the scientific underpinnings have rarely been investigated from a mechanistic, landscape-scale perspective. As a result, there is no philosophy of managing land use to minimise zoonotic disease emergence, or sufficient data to advance such a practice. An interdisciplinary applied research effort focused at the interface of landscape ecology, wildlife immunology, and disease ecology is required to develop an operational understanding of land use consequences for wildlife and human health. The results of this work are urgently needed to formulate an integrated holistic set of science-based policy and management measures, as shown by the COVID-19 pandemic and other epidemics, that effectively and cost-efficiently minimise zoonotic disease risk by preventing or mitigating the ecological conditions that trigger events leading to zoonotic pathogen spillover.

We call on colleagues across the fields of environmental, wildlife, and human health to forge the collaborations urgently needed to advance our knowledge of how land use change drives zoonotic disease emergence. We call for a well integrated, mechanistic focus on the zoonotic pathogen infect–shed–spill–spread cascade across multiple scales—from the molecular interactions of a wild animal's immune system to the influence of environmental change on pathogen spread among species. We elucidate biases and information gaps in knowledge of land use-induced spillover, consider opportunities to better institute the necessary collaborations, and address the primary technical challenges to progress. We conclude by discussing applications for policy and management decision making, noting issues that warrant particular attention for conservation and global health security.

Land use-induced spillover

A person's risk of acquiring a pathogen from wildlife depends on the degree and distribution of zoonotic infection in wildlife, the extent to which wildlife is shedding the pathogen, and the patterns of human–wildlife interaction.[3] Understanding land use as a primary driver of the infect–shed–spill–spread cascade is fundamental to assessing this risk.[3] However, most studies intended to better inform spillover prevention—despite their importance—do not directly address these mechanisms. The major research investments in spillover prevention have focused on pathogen discovery in wildlife and surveillance where there is likely to be

Panel: Key definitions

Pathogens

Pathogens are disease-causing microbes—including viruses, bacteria, and parasites—associated with specific higher taxa, known as hosts (which help to sustain the pathogens) or vectors (which help to transmit the pathogens). Natural systems are interacting, dynamic assemblages of species and ecological processes. Microbes are an integral part of these systems, playing crucial roles in the biology of other organisms, and contributing to overall system regulation.[4] We use the term pathogen to describe microbes that cause disease in humans. Host–pathogen and vector–pathogen relationships are dynamic, fluctuating, and adaptive, changing in response to various biotic and abiotic conditions. Change in land use is one such factor that can alter the distribution of hosts, vectors, and pathogens across the landscape; magnify and intensify pathogen dynamics; and contribute to the emergence of new adaptive traits, sometimes distinct pathogens. The risk of pathogen transmission from wildlife to people, known as zoonotic spillover, is driven by an interaction of these ecological factors and human behaviour.[3]

Infection

Infection does not always result in disease and wildlife reservoir hosts frequently tolerate infection without exhibiting clinical signs.[5] This benign relationship between microbe and host often results from a long coevolutionary history. However, a new host infected with the same microbe might have a different reaction to pathogen exposure, ranging from infection resistance to severe disease manifestation or death.[3,5]

Land use-induced spillover

Land use-induced spillover is the process by which land use change drives the transmission of pathogens from wildlife to humans. Spillover proceeds through a series of events: pathogen infection in wildlife, shedding of the pathogen from wildlife, transmission of the pathogen to people (sometimes through other animals that act as intermediate pathogen hosts), and further spread of the pathogen by person-to-person transmission. We refer to these dynamics simply as the infect–shed–spill–spread cascade. Land use-induced spillover is influenced by landscape immunity and the dynamics of wildlife–human proximity.

Landscape immunity

Landscape immunity arises from the ecological conditions that, in combination, maintain and strengthen the immune function of wild species within a particular ecosystem while preventing the conditions that lead to high pathogen prevalence and shedding. Intact ecosystems characterised by the structure and function associated with high species diversity should have greater landscape immunity than systems acute or chronically degraded by land use changes—which might range from readily evident habitat destruction to more subtle factors, including biological invasion, pollution (chemical, light, sound), and recreation. Landscape immunity might be improved through provision of adequate resources for wildlife, support for normal behaviour and group size, and prevention of high abundance of hosts that harbour more zoonotic pathogens.[6] Moreover, high biodiversity can reduce pathogen prevalence by diluting infectious contacts among pathogen reservoirs and can reduce human exposure by buffering human contact with the pathogen.[7]

Pathogen shedding

The term shed, generally refers to the release or excretion of a pathogen into the environment; we use this term broadly to indicate the release of pathogen from the host in a manner that facilitates exposure of another individual (eg, shedding into saliva that could come into contact with a human or other animal through a bite wound or release of pathogen following slaughter).[3] Host infection is controlled by immune function of the reservoir host; however, when immune function is compromised, there might be increased pathogen replication and shedding as observed in bat populations that shed more coronavirus when body condition (and presumably immune function) is low,[8] and bank voles that shed higher titres of *Puumala hantavirus* during the acute phase of infection.[9]

Pathogen pressure

Pathogen pressure is the amount of a pathogen available to infect humans at a given point in time and space (eg, number of virus particles or bacterial cells in animal faeces) and is governed by the number of infected animals (prevalence), the intensity of infection (pathogen load), and the excretion of pathogen from infected animals (shedding).[3] Pathogen pressure is highly variable and sensitive to changing system conditions. Land use changes that cause even small increases in pathogen pressure can have large effects on spillover risk, because many of the interactions necessary for cross-species transmission are not straightforward (eg, pathogen dose–response relationships are non-linear).[10]

contact between wildlife hosts and people.[12,13] Although understanding the diversity of wildlife pathogens in natural environments and making improvements in disease detection in high-risk human communities is essential, these approaches are insufficient to prevent spillover events.[14,15]

We propose land use-induced spillover—the process by which land use change drives the infect–shed–spill–spread cascade—as a priority area for interdisciplinary focus to mobilise existing data, fill information gaps, and guide spillover prevention measures. In particular, we call for timely, innovative investigations into land use influences on the biology and dynamics of zoonotic pathogens with the aim of preventing spillover into human populations by fostering landscape immunity. We define landscape immunity as the ecological conditions that maintain and strengthen the immune function of wild species within a particular ecosystem, prevent high pathogen prevalence and shedding, and buffer human exposure to infection through the effects of biodiversity

(panel). The crux of this work is inquiry into the complex interactions between land use and disease dynamics. What are the ecological conditions that lead to high prevalence of zoonotic pathogens in wildlife populations, wildlife shedding pathogens, spillover of these pathogens into other species (ultimately humans), and further pathogen spread through the human population? This paradigm recognises that the mechanisms by which zoonotic pathogens cause human disease are far more complex than the mere act of human contact with infected animals in nature, under propagation (eg, food and fur farms) or in commerce (eg, distribution facilities, wildlife markets).[3] Our call for scientific inquiry is based on the premise that we can identify and foster the ecosystem conditions that are within control and can reduce the risk of zoonotic spillover.

Land use variables that affect human health have been broadly conceptualised,[1,16,17] but seldom robustly investigated.[18] We provide a conceptual framework to guide inquiries into land use-induced spillover (figure 2). We illustrate land use-induced spillover using examples of bat-borne zoonoses; bats have been identified at the beginning of the infect–shed–spill–spread sequence of several zoonotic pathogens, including coronaviruses, Ebola virus, rabies virus, Nipah virus, and Hendra virus. However, the processes we describe in bats are broadly applicable across other wildlife that can serve as zoonotic pathogen reservoirs, including primates, rodents, ungulates, carnivores, and a diverse range of birds (table).

First, bat distribution, abundance, and density are determined by resource availability, mainly food and the availability of mates and roosting sites. The destruction and fragmentation of bat habitat reduces key resources. Thus, bats might be forced to change behavioural norms, for example shifting from feeding in native forests to feeding in human-dominated landscapes (eg, agricultural and ornamental plants) and roosting in urban parks or anthropogenic structures.[45,46] Accordingly, the likelihood and intensity of bat infection changes with the host population distribution, as bats that are nutritionally or physiologically stressed (eg, when food is scarce, animals are crowded around resources, or during reproduction) are more likely to become infected.[41]

Second, bats are more likely to shed pathogens into the environment during periods of stress.[8,47] For example, in Australia, acute nutrient deprivation is thought to reduce the ability of pteropodid bats to control pathogens; nutritional stress might precipitate extreme, brief, and spatially restricted pulses of viral shedding during which multiple zoonotic viruses are shed.[42,48] However, there is a paucity of research on bat immune function during shedding in response to stressors. The parsimonious theory is that bats are persistently infected with zoonotic viruses, such as henipaviruses, but shed these viruses only when immunocompromised, similarly to humans shedding the herpes simplex virus through cold sores when stressed.[48]

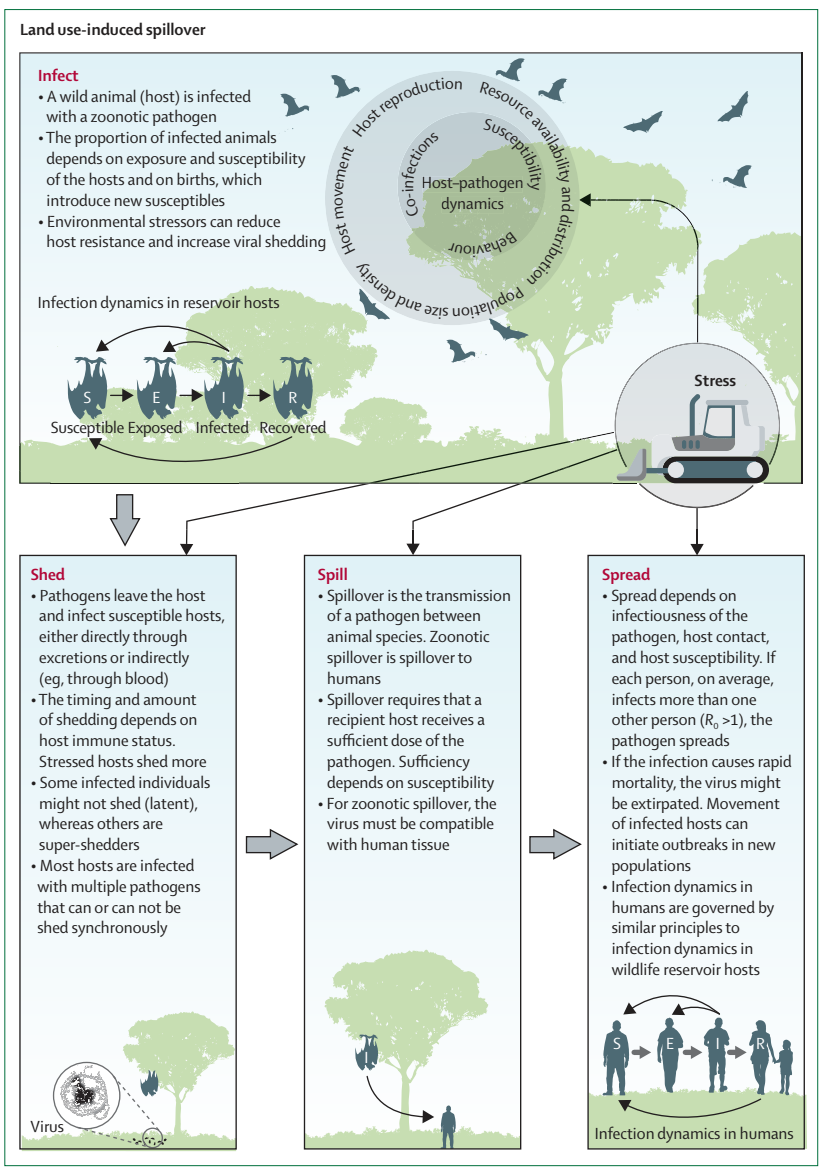

Figure 1: **Land use-induced spillover**

Third, wildlife–human contact is a key determinant of spillover. If a bat sheds virus in a remote wilderness, no human will be infected. If that same bat sheds virus while foraging on fruit trees in a village or being slaughtered for human consumption, human exposure is more likely.[11] Many other factors also determine the likelihood of a pathogen establishing in a new host, including pathogen dose (influenced by pathogen pressure; panel), route of infection, and molecular compatability.[3] The factors driving susceptibility in a new host mirror the factors driving susceptibility in a wildlife reservoir and might be shaped by environmental and internal stressors (eg, nutritional and physiological stress; figure 2).

Finally, multiple factors affect the likelihood of onward transmission, including pathogen biology, human

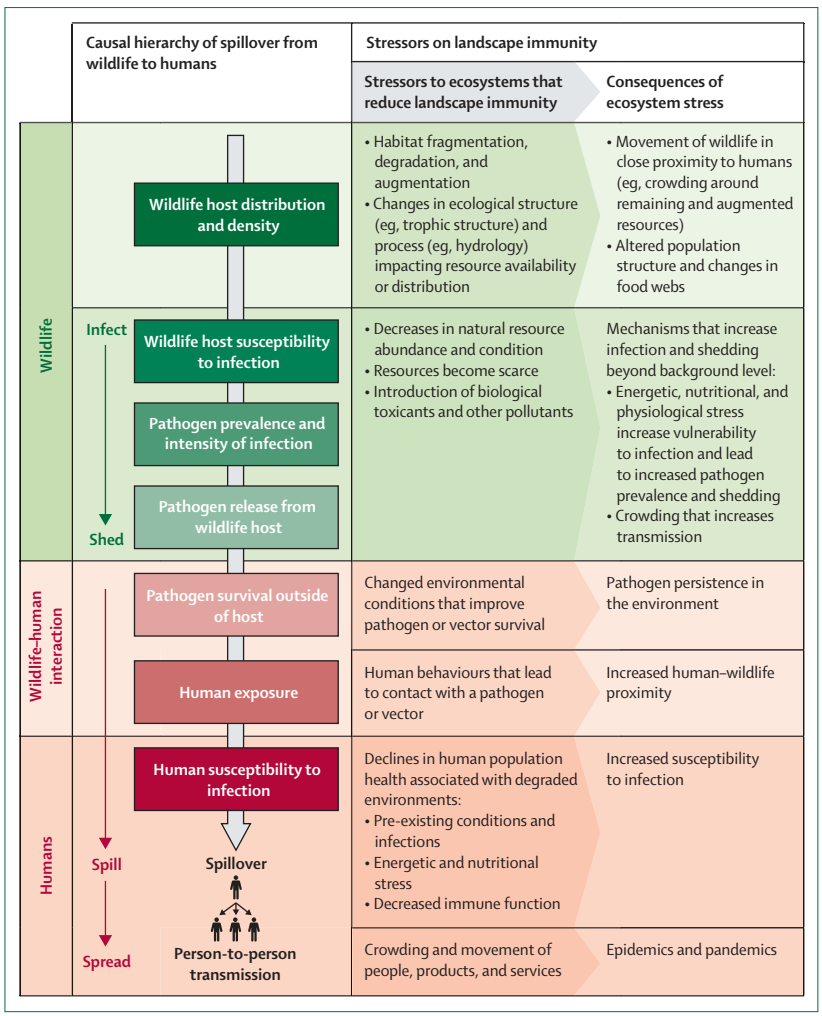

Figure 2: **The zoonoses spillover cascade: loss of landscape immunity as the pandemic trigger**

See Online for appendix

population size, and human population connectivity (figures 1, 2),[49,50] with the largest epidemics predicted to occur at extremes of land conversion.[11] Global spread of infectious diseases is increasing over time; HIV took 56 years to reach the USA in 1970, Ebola took 4 months to reach the USA in 2014, and SARS-CoV-2 took 2 months to reach the USA in 2020.

Over the past three decades, viruses such as the Ebola virus, influenza A (pandemic H1N1, H7N9) virus, Middle East respiratory syndrome coronavirus, Hendra virus, and Nipah virus[3,45,49] have aptly showed the interdependence of human, animal, and ecosystem health and that local land use decisions can have large scale socioeconomic consequences. Integrative concepts such as One Health emerged to address the human and animal health connections inherent in zoonotic disease.[51] Our proposal for an interdisciplinary focus on the infect–shed–spill–spread cascade fits within and complements dimensions of the One Health concept by, for example, including wildlife health as an essential component of global disease prevention and employing transdisciplinary approaches to investigate animal-to-human transmission.[18,52] To clarify the relatedness of One Health principles and practices to the proposed area of inquiry, we provided definitions (appendix pp 2–4), which can serve as the foundation for a shared vocabulary. Studies to quantify the causal links between habitat change, physiological stress, susceptibility, and pathogen shedding are rare (table), largely from the physiological rather than landscape science perspective, and are limited in their spatial replication, range of possible immune assays, and insights into whether immune phenotypes are protective.

Our call to action seeks to catalyse collaborative research among scientific, human health, and conservation institutions. Such partnerships should focus on fundamental information gaps and help to address limiting factors to understand land use-induced spillover; a scarcity in rigorous studies that delineate causal associations between land use and disease emergence, limited spatiotemporal replication, and use of a narrow range of scientific tools (table). Observational and correlational studies almost entirely define knowledge on the effects of land use on infectious diseases.[2] There is a clear need for combined experimental, field, and modelling studies that provide mechanistic and causal inference.[53] Field studies need to be replicated because host–pathogen interactions in natural systems are highly dynamic and complex.[18,54,55] Similarly to the calls for a Global Immunology Observatory for humans,[56] an analogous approach to the study of wildlife reservoirs of zoonotic pathogens could aid international collaboration for large scale, long-term studies that characterise landscape influences on infection. A major information gap is how the land use change affects reservoir host immune function. The host immune system is an interface between the environment and the pathogen and helps to determine how land use changes influence infection and shedding. A scarcity of tools makes it difficult to study wildlife immune function at a meaningful scale to delineate the effect of land use change on disease dynamics. Many current tools that measure wildlife immune status are difficult to apply and interpret, and are impractical for large sample sizes that are expected in field-based, spatiotemporal monitoring.[18,22] Investment is needed in, reagents such as monoclonal antibodies to assess immunity in non-model species,[57] experiments to validate biomarkers of susceptibility and shedding in high-risk host–pathogen systems,[58] and application of omics approaches (eg, transcriptomics, proteomics, metabolomics) to develop new immunological tools.[27,58] Moreover, tools need to be integrated—eg, serological with genomic studies and metabolomic studies—requiring interdisciplinary collaboration and novel statistical approaches including machine learning.

Research funding for interdisciplinary studies is scarce.[59,60] Nevertheless, programmes such as the

Data challenge	Crucial need and limitations
Studies examining mechanistic links among habitat change, physiological stress, immunity, and infection outcomes in wildlife studies[19–21] are rare, especially for reservoir host species	Measures of stress response (glucocorticoid hormones) and immunity, and infection state and shedding intensity are needed across habitat gradients in reservoir hosts such as bats
Although many ecoimmunology studies sample multiple wildlife populations, few address anthropogenic drivers and most have low spatial replication, especially when sampling wildlife over large spatial extents[18]	Spatial and temporal studies that sample reservoir hosts across different environmental conditions to statistically link environmental stressors with immune changes, likelihood of infection, and intensity of pathogen shedding
Ecoimmunology studies often measure only one or few metrics, but single, general immune measures cannot provide insight into whether metrics correlate with protection[22]	Determining protective immune measures (those that decrease susceptibility and shedding) requires temporal and spatial replication or experimental manipulations[22]
Ecoimmunology studies are limited by a scarcity of reagents to measure immune components in non-model species, although some reagents can be adapted from domestic animals[23]	Genomics and transcriptomics can allow the design of primers to quantify expression of immune genes relevant to key pathogens.[24,25] Sequencing and bioinformatics are costly and gene expression does not always correlate with functional signalling proteins
A heightened immune state of wild animals can indicate a strong immune response or a recent (or active) infection, and data in field systems are typically difficult to interpret without robust measurements of both[26]	Experimental validations can help to develop immunity biomarkers for field studies. This captive approach was used for house sparrows, in which expression of key cytokines indicated a high West Nile virus resistance[27]
Ecological integrity and susceptibility to infection, examples	
Urban habituation of wildlife is associated with immune impairment[28]	Only a few urban studies link immunity and susceptibility
Mercury exposure in wildlife is linked with a weaker immune response[29,30]	Functional measures, but specific to one pathogen or antigen
Wildlife at the latitudinal limits of the geographical range might have increased susceptibility[31–35]	Sampling is often temporally asynchronised and spatial replication is generally low
Primates with nutritional stress had higher cortisol and were more likely to be infected[36]	No habitat gradient, and immunity is not quantified
A meta-analysis[37] suggested that deforestation is generally associated with more physiological stress, weaker immunity, and greater infection prevalence	Immune measures are general and restricted to leucocytes
Ecological integrity and pathogen shedding, examples	
Spatial patterns in immunoglobulins predicted spatial intensity of nematode shedding in red deer[38]	Fine-scale sampling, but across a small spatial extent
Habitat fragmentation is associated with poor condition, few leucocytes, high chronic stress, and higher chances of astrovirus shedding from bats[39,40]	Usually a small spatial scale, and immune measures are general
Bats with nutritional stress and in poor condition during a food shortage had a higher prevalence of Hendra virus antibodies[41]	No habitat gradient, no spatial or temporal replication, and immunity was not quantified
Multiple viruses were shed by bats in an extreme and synchronised shedding pulse[42]	Environmental stress was hypothesised as the underlying driver, but physiological and immunological data were not collected
Wild ungulates with nutritional stress were in poor body condition and shed more parasites[43]	No habitat gradient, and immunity not quantified
Experimental increases in glucocorticoid hormones amplify viraemia and the infectious periods in birds[44]	Captive experiment, not linked to habitat

Table: **Land use-induced spillover data challenges, needs, cases studies, and limitations on the inference**

National Science Foundation's Dynamics of Coupled Natural and Human Systems and Ecology and Evolution of Infectious Diseases are increasing feasibility for multifacted infectious disease studies. Investments in studies addressing the infect–shed–spill–spread cascade would magnify the value of investments already made in programmes such as the Emerging Pandemic Threats PREDICT programme, which aimed to identify and map wildlife pathogens with zoonotic potential.[61] Also, although surveillance of human pathogens is essential for detection and control once an outbreak has occurred, human infection comes late in the chain of zoonotic disease emergence; broader prevention is possible by addressing the upstream stressors from ecological disruption that set the wildlife disease process in motion.

Studies of land use-induced zoonotic spillover should explore whether zoonotic disease emergence needs to be considered unpredictable because of data shortfalls or whether sufficient risk analyses can be developed to manage capacities for host–viral systems in specific contexts. As for all biodiversity studies, the proposed work is hampered by the scarcity of baseline data on wildlife and associated pathogens in native and introduced ranges. Organisms are in constant interplay with other species and their environment. Therefore, when species occurrence and biological data are available, they need to be considered with respect to a chain of land use consequences such as impacts on geophysical parameters which influence resource type and abundance, which in turn have implications for species diversity, abundance, and density at the population level; and animal nutrition and physiology, which regulate immune function and within-host processes at the individual level.[48] A further challenge is the ability of

scientists to access and integrate relevant data across disciplines and information platforms. Big data and artificial intelligence are promising tools to identify patterns for risk assessment and actions.

The justified call to action

Consideration of land use-induced zoonotic spillover as an interdisciplinary priority is justified from the technical perspective, and strategic pragmatism. Although there are existing fields focused on landscape ecology, and the immunology and epidemiology of infections, the specific area of interface that relates to the mechanics of spillover from wildlife to humans has yet to be conceptualised and is largely under-resourced. Recognising the proposed work as an explicit field for scientific inquiry will enable the rapid synthesis of ideas and approaches across disparate areas of technical investigation and practice. By exploring beyond disciplinary boundaries scientists can develop questions and tools to discover what has not yet garnered their attention.

We hope that the proposed work will not only address an unoccupied inquiry niche that needs to be filled to make urgently needed scientific findings available for land use policy and management decisions, but also it will provide a framework for immediate action. Worldwide, epidemics of zoonotic disease—eg, COVID-19—have awakened policy makers and land use managers to the scarcity of information available to guide decision making aimed at protecting human health from wildlife-based zoonoses, a key aspect of global health security. The crucial need for science-based information that unpacks the causal mechanisms linking environmental stressors to zoonotic pathogen spillover has been recognised, and demands for action-informing data are being voiced globally by various policy, research, and funding entities, including the Convention on Biological Diversity's Subsidiary Body on Scientific, Technical and Technological Advice, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, and the US Agency for International Development.

All these initiatives, and those that will be added in the future, require the knowledge derived from a better understanding of the zoonotic pathogen infect–shed–spill–spread cascade to direct well informed and cost-efficient decisions for human, animal, and environmental health. Preventing future pandemics requires substantial, highly-focused investments in the proposed work from intellectual, technical, and policy perspectives that can only be driven by a call to fill a crucial scientific niche.

Research findings applied

Policy considerations

A comprehensive approach to biosecurity considers the risks that potentially harmful organisms pose to a wide range of assets, including the environment and human health.[62] A growing number of countries such as Australia and New Zealand are developing broad biosecurity frameworks that integrate across environmental, agriculture, and human health sectors.[63] Fostering landscape immunity should be regarded as a biosecurity imperative and actions need to be taken to maintain and enhance landscape immunity as part of the national and global security agenda.

Increasingly, risk evaluation is mandated by international, national, and subnational policies to improve measures to prevent potentially harmful organisms from entry across jurisdictional borders or introduction into novel ecosystems, or both.[64,65] To minimise the risk of future zoonotic epidemics and pandemics, research is urgently needed to deepen our understanding of which land use practices are associated with low, medium, and high risk of zoonotic pathogen infection, shedding, spillover, and spreading in a specific context; what are the land use management options to minimise risk; and how can these risk management options be communicated in a manner that institutes the lowest risk land use practices fit to context. Since these options will include various actions to reduce human–wildlife interaction, careful consideration needs to be made to promote biophilia rather than biophobia. Risk communication that instills disrespect or fear of wildlife could facilitate even greater human–wildlife conflict. For example, COVID-19 has greatly increased fear of bats worldwide, resulting in mass culling events and a subsequent outcry by conservation organisations to focus on the societal drivers of the pandemic rather than the wildlife hosts.[66]

Advances in the study of land use factors that influence the infect–shed–spill–spread cascade will help to understand and show how investments in landscape conservation provide returns for human health, climate change, international trade, sustainable development, environmental justice, and other policy issues associated with human wellbeing. The proposed work can help to operationalise land use planning and place protected area initiatives in the biosecurity context. However, unless new biosecurity initiatives are coordinated through a comprehensive policy strategy, the transfer of research findings into practical measures to prevent zoonotic spillover will be slow and largely fortuitous. In 2002, Reaser and colleagues[67] recommended a broad set of US policy measures focused on wildlife disease prevention that have not yet been institutionalised. In 2019, WHO, Food and Agriculture Organization, and the World Organization for Animal Health collaborated to develop a guide for addressing zoonotic disease at the national level.[68] The guide does not raise awareness of or provide a framework for addressing land use policy and management as a fundamental aspect of zoonosis prevention.

Management considerations

Even though human transformation of nature has reached unprecedented levels,[69] we can reduce the risk of future pandemics by addressing the land use stressors

that influence the zoonotic infect–shed–spill–spread cascade. In practice, landscape immunity corresponds to ecological integrity.[70] Landscapes with high ecological integrity such as structural intactness and connectivity, biotic diversity and abundance, and generative trophic system relatedness and function, provide biosecurity. Any land use practice that reduces ecological integrity and resilience erodes the barriers to zoonotic spillover (figure 2). Ideally, a focus on the cascade will help to identify practical, context-specific land use metrics and measures to enhance landscape immunity, and thus reduce the risk of zoonotic pathogen spillover to humans.

Minimising anthropogenic habitat fragmentation and penetration, and the perimeter of habitat edges, should be one of the first principles in landscape management to reduce wildlife zoonoses risk.[71] Regarding the type and extent of human impact, the risk of pathogen spillover varies considerably by landscape condition.[52,72] Penetrating the world's large wild areas creates a set of risks, landscapes that are semi-wild with strong edge effects create a different set of risks,[11] and intensely transformed landscapes with high human population density present even greater risks.[73] Thus, a practical approach is required to organise conservation and distancing measures aimed at sustaining landscape immunity using the Three Global Conditions for Biodiversity Conservation and Sustainable Use framework.[74]

Because interaction and connectivity among species and the environment define the essence of all life, promoting ecological connectivity is a conservation priority at the local and global scale.[75] Conservation policy and practice need to holistically navigate the fact that intact and connected nature is crucial for health of the biosphere and that human livelihood is derived from social contact (commerce, travel, and sociocultural traditions). A challenge for land managers is navigating this connectivity paradox. Land use decision makers need to simultaneously consider how to maintain and enhance landscape immunity while meeting the increasing demand for infrastructure expansion. Practices for maintaining landscape immunity and reducing wildlife–human contact have considered land use-induced spillover in the protected and conserved area context.[76] Notably, there is potential to identify and deploy ecological countermeasures once the mechanism driving land use-induced spillover are understood.[77]

Conclusion

COVID-19 has taught us that humanity is highly vulnerable to zoonotic disease pandemics. Fragmented landscapes and fragmented solutions increase this vulnerability. As the planet faces various cumulative stressors on ecological systems, the infect–shed–spill–spread cascade and associated studies of landscape immunity can serve as a new integrative path forward to safeguard natural systems and human health as a biosecurity priority. Investigations of this cascade can identify the factors that reduce landscape immunity and inform policy and management decisions that need to be taken to protect public health by proactively minimising spillover risk. Scientists have a moral obligation to prioritise inquiry that serves the public good and, as necessary, challenge long held disciplinary boundaries. At this time, the relevant institutions must mobilise political, cultural, and financial encouragement.

Contributors

All authors contributed to the conceptualisation of ideas. RKP, JKR, and GMT wrote the first draft of the manuscript. RKP, JKR, and GMT designed the figures with input from all coauthors. RKP, JKR, and DJB compiled the tables. All authors wrote, edited, and revised the manuscript.

Declaration of interests

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