Ecological Countermeasures for Pandemic Prevention: When Ecological Restoration is a Human Health Imperative

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Ecological restoration should be regarded as a public health service. Unfortunately, the lack of quantitative linkages between environmental and human health has limited recognition of this principle. Advent of COVID-19 pandemic provides the impetus for the further discussion. We propose ecological countermeasures as highly targeted, landscape-based interventions to arrest the drivers of land use-induced zoonotic spillover. We provide examples of ecological restoration activities that reduce zoonotic disease risk and a five-point action plan at the human-ecosystem health nexus. In conclusion, we make the case that ecological countermeasures are a tenent of restoration ecology with human health goals.

Key words: ecological countermeasures, invasive alien species, landscape immunity, land use-induced spillover, restoration ecology, zoonotic disease

Implications for Practice:

- Ecosystem health directly affects human health and ecological restoration should, therefore, be regarded as a public health service.
- Ecological countermeasures can be employed to prevent land use-induced zoonotic spillover by fostering landscape immunity and reducing the risk of human exposure to wildlife-transmitted pathogens.
- Invasive species removal and the reintroduction of native plants are ecological countermeasures when undertaken to address zoonotic disease risks.
- Interdisciplinary collaboration, mechanistic studies of land use-induced spillover, the integration of ecological and health targets in policy frameworks, increases in zoonotic pathogen surveillance, and community engagement will help advance ecological countermeasures.
- Restoration ecologists can promote the linkages between ecological and human health within the One Health and Planetary Health frameworks.

Introduction

"Extreme remedies are appropriate for extreme diseases…"

Hippocrates (460-370 B.C.)

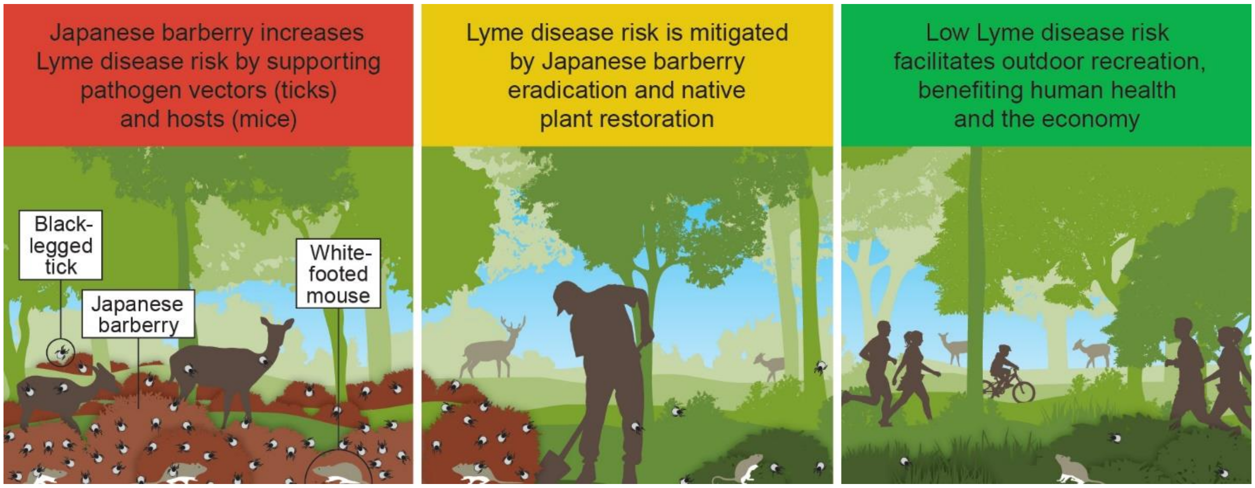
Ecosystem health directly affects human health (Patz et al. 2004; Andrade et al. 2020) and should, therefore, serve as a powerful incentive for ecological restoration (Aronson et al. 2016). A growing interest in One Health (Gibbs 2014) and Planetary Health (Seltenrich 2018) initiatives demonstrates that scientists and policy makers increasingly recognize that human and environmental condition are co-regulators. Considerable work remains, however, before human health is fully regarded as an ecological service (Patz et al. 2004; Reaser et al. 2020a). Breed et al. (2020) identify the lack of quantitative linkages between environmental and human health as a principal knowledge gap that limits understanding of ecological restoration as a public health service. They propose a five-point action plan (outlined later) to elucidate ecological-human health links and firmly establish the ecological restoration-human health nexus.

Advent of the COVID-19 pandemic (SARS-CoV-2 virus) provides impetus for further discussion and operationalization of ecological approaches to protecting human health. This realization inspired Plowright et al. (2020) to call on scientists to investigate the mechanisms by which land use change drives zoonotic spillover into human populations (termed 'land use-induced spillover'), Reaser et al. (2020a) to propose fostering landscape immunity (the ecological conditions that, in combination, keep pathogen populations in check and foster the immunological defenses of wild species within a particular ecosystem) as an approach to reducing spillover risk, and Reaser et al. (2020b) to recommend priority actions for employing protected areas to safeguard human populations from future pandemics. Here we expand on this new body of work by focusing on 'ecological countermeasures' as a novel concept and technical approach to addressing land use-induced spillover.

Countermeasures are generally regarded as actions taken to counteract a threat (Dictionary.com). In the military context, countermeasures involve the employment of devices and/or techniques to impair the operational effectiveness of enemy activity (DOD 2020). Medical countermeasures constitute life-saving medicines and medical supplies used to diagnose, prevent, or treat conditions associated with chemical, biological, radiological, or nuclear (CBRN) threats, emerging infectious diseases, or natural disasters (https://www.cdc.gov/cpr/readiness/mcm.html). From an environmental perspective, countermeasure typically refer to site remediation and restoration activities undertaken to address contaminants (e.g., Fesenko and Howard 2012; Shuangchen et al. 2017).

For zoonotic disease outbreaks, countermeasures have largely focused on medical and veterinary interventions (Sokolow et al. 2019). We define ecological countermeasures as highly targeted, landscape-based interventions to arrest one or more of the elements of land use-induced spillover, particularly the environmental stressors that: 1) trigger increased susceptibility of wildlife to pathogen infection; 2) cause these animal hosts to shed viable pathogens in sufficient quantity to spill over to (infect) other susceptible hosts, including humans; and 3) then spread through the human population ('the infect-shed-spill-spread' cascade; Plowright et al. 2020; Figures 1 and 2 therein). Ideally, ecological countermeasures would be used to restore landscape immunity and/or reduce human exposure to wildlife-transmitted pathogens (Figure 1; see contextual overview in Reaser et al. 2020b).

Figure 1. Ecological Countermeasure for Lyme Disease



We provide a short list of geographically and taxonomically diverse examples of ecological restoration activities that reduce zoonotic disease risk and apply ecological countermeasure principles and practices to Breed et al.'s (2020) five-point action plan. The case studies presented include measures to: a) remove or otherwise control invasive alien plants and animals that magnify spillover risks and b) reintroduce or increase populations of native species to re-establish habitat resources and trophic structure, thereby controlling pathogen prevalence and distribution.

Case Studies

Invasive alien plants may provide optimal habitat for zoonotic pathogens, hosts, and vectors; they tend to have long flowering durations, vigorous growth, and increase biomass as they spread, particularly in disturbed sites (Stone et al. 2018). The large-scale removal of invasive alien plants that facilitate zoonotic spillover (e.g., via microclimate or trophic changes) can function as ecological countermeasure when the goal is disease risk mitigation. In aquatic environments, there is a clear link between invasive alien plants, water stagnation, and the prevalence of mosquito-borne diseases. Upon reviewing relevant literature, Stone et al. (2018) concluded that the control of invasive alien plants in aquatic environments could contribute to malaria risk mitigation. They highlight research priorities to integrate vector and invasive alien plant management in a synergistic fashion.

Similar opportunities are being identified for terrestrial environments, especially for tick-borne disease management. Japanese barberry (*Berberis thunbergii*), a woody understory shrub, was introduced to the United States from Asia in 1875 for ornamental landscaping. It now invades a wide range of natural areas throughout the much of the United States and eastern Canada (USDA 2020). Japanese barberry benefits at least two species that contribute to Lyme disease (*Borrelia* *burgdorferi*) spillover. Barberry infestations foster microclimates favorable to the proliferation of blacklegged ticks (*Ixodes scapularis*), a species known to transmit several zoonotic pathogens (Williams and Ward 2010) and nesting areas for white-footed mice (*Peromyscus leucopus*), as well as other rodents that host *B. burgdorferi* (Linske et al. 2018). In barberry removal experiments, Williams and Ward (2010) found that intact barberry stands had 280 ± 51 adult blacklegged ticks/ha, which was significantly higher than for controlled (121 ± 17/ha) and no barberry (30 ± 10/ha) areas. Linske et al. (2018) found that management of barberry stands reduced contact opportunities between blacklegged ticks and white-footed mice. They encouraged the eradication and control of the invasive shrub to reduce the number of *B. burgdorferi*-infected blacklegged ticks.

Numerous animals that host or vector zoonotic pathogens have become widespread invasive alien species. Of these, various rodent species are among the highest risk invasive hosts, while several species of mosquitoes and ticks pose the greatest concern as invasive vectors capable of facilitating large-scale disease outbreaks (Chinchio et al. 2020). However, lessor-known animal species can also facilitate disease outbreaks of epidemic and pandemic proportions. Schistosomiasis is an infestation of parasitic flatworms (*Schistosoma* spp.) via aquatic snail hosts (e.g., invasive *Biomphalaria straminea*) that causes life-threatening health conditions (e.g. anemia, liver failure, bladder cancer, and lasting cognitive impairment) in more than 250 million people, with nearly 800 more at risk, in Africa, Asia, and South America (Sokolow et al. 2016). In Africa's Senegal River Basin, Sokolow et al. (2015) demonstrated that re-introduction of river prawns indigenous to the west coast of Africa (*Macrobrachium vollenhovenii*) where dam construction blocked their annual migration could offer a sustainable, low cost form of snail control; when used in synergy with existing drug distribution campaigns, the prawns were able to reduce or locally eliminate the parasite. Re-establishing trophic structure by restoring river prawns within these river systems could serve as a novel ecological countermeasure.

In addition to eradicating or controlling biota that act as spillover risk amplifiers, ecological countermeasures could be employed to augment key habitat resources under conditions of scarcity that stress wildlife hosts and/or drive them into human occupied areas for supplementation. In Bangladesh, bats (*Pteropus medius*) visit silver date palm trees (*Phoenix sylvestris*) tapped for sap collection. Bats lick the shaved area of the tree or urinate or defecate in the collection pots, sometimes contaminating the sap with Nipah virus (Luby et al. 2006, McKee et al. 2020). Although covering sap containers has reduced disease risk (Nahar 2013), the ideal solution would be an ecological countermeasure that draws bat populations to food resources not shared with people (Mckee et al. 2020). In Australia, work is underway to develop such a "population distancing" ecological countermeasure where bat (*Pteropus alecto*) habitat destruction triggers a cascade of factors that ultimately lead to Hendra virus spillover from bats (*Pteropus alecto*) to horses, and subsequently humans. When nutrient stressed due to loss of winter nectar resources, bat populations fragment, increase viral shedding, shift from natural landscapes into agro-urban areas occupied by people and domestic animals (Plowright et al. 2016; Edson et al. 2019; Eby et al. In Review). Regeneration of winter flowering habitat via native tree planting as an ecological countermeasure could potentially reverse these processes and reduce spillover events.

Large-scale tree planting has been popularized to meet biodiversity conservation, carbon sequestration, and other sustainable development goals (Bastin et al. 2019; Domke et al. 2020), although not without controversy (Veldman et al. 2019). We caution that such projects, when conducted in human occupied areas, might attract pathogen-hosting wildlife to new food and habitat resources, thereby increasing the risk of human exposure to zoonotic pathogens. Under some circumstances, the societal costs of these large-scale tree projects may outweigh the benefits. Reaser et al. (2020a,b) call for donor agencies and other relevant institutions to proactively evaluate and further develop tree planting projects with zoonoses prevention services in mind. Ideally, these projects would be strategically harnessed as ecological countermeasures to prevent land use-induced spillover.

Beyond tree planting, we foresee using various other types of natural resource augmentation scenarios to complement and/or serve as an interim step in implementing countermeasures within a broad ecological restoration framework. Could the strategic use of feeding stations, artificial water sources, bird nest boxes, coverboards, sound and light features, electromagnetic fields, scented objects, or other introduced landscape features that attract or deter wildlife populations become part of the ecological countermeasures arsenal? Becker et al. (2018), summarizing the findings of a collection of scientific papers that investigate the influence of anthropogenic resources subsidies on host-pathogen dynamics in wildlife, conclude that public education and adaptive management can contribute to 'win–win' scenarios for feeding wildlife that optimize benefits for conservation, wildlife disease management, and human health. For example, in the Greater Yellowstone Ecosystem of the western United States, Cotterill et al. (2018) explore the possibility of using strategic, spatially-dynamic food provisioning to manage the proximity of elk (*Cervus canadensis*) and cattle while minimizing elk exposure to *Brucella abortis* (the pathogen responsible for brucellosis). Nest boxes have been used to increase and expand populations of native barn owls (*Tyto alba*) in order to control non-native rodent populations in agricultural and urban environments (Saufi et al. 2020). In Vermont, private landowners constructed more than 400 houses to attract native tree swallows (*Tachycineta bicolor*) for mosquito control. The Bird House Forest has not only greatly increased the swallow population, it has become a tourist destination drawing economic resources to the local community (https://www.atlasobscura.com/places/birdhouse-forest).

Action Plan

Building on the five-point action plan proposed by Breed et al. (2020), we provide an overview of needs and opportunities for further elucidating land use-induced spillover and establishing ecological countermeasures as a component of ecological restoration:

1. *Collaborations and conversations*. As One Health and Planetary Health collaborations become better institutionalized, opportunities will increase to advance ecological countermeasures in concept and practice. Plowright et al. (2020) emphasize that studies of land use-induced zoonotic spillover as an interdisciplinary priority is justified from technical perspectives, as well as strategic pragmatism. Gaps in our knowledge of land use influences on the infect-shed-spill-spread cascade need to be addressed *in situ* in order to inform ecological countermeasures. Proactive partnerships between epidemiologists, immunologists, and ecologists will enable the

rapid synthesis of ideas and approaches across disparate areas of technical investigation and practice (see Becker et al. 2020). Only by initiating conversations at the margins of these disciplinary boundaries can scientists develop the fit-to-context, restorative solutions urgently needed to prevent future pandemics.

2. *Education and learning*. Scientific understanding of land use-induced spillover is in its infancy. Plowright et al. (2020) summarize information gaps for the factors driving the infect-shed-spill-spread cascade. White and Razgour (2020) point out that, at least for mammals, the majority of published studies regarding anthropogenic land use change influences on zoonotic pathogen dynamics are reviews rather than primary empirical studies. These and other authors (e.g., Halliday et al. 2017) identify geographic, taxonomic, and additional biases in our current knowledge of zoonotic disease, while Watsa (2020) warns of the insufficient number and distribution of pathogen reference libraries. Although there has been an increase in investments for zoonotic pathogen discovery in understudied species and regions (e.g., PREDICT; https://www.ecohealthalliance.org/program/predict), the need remains to educate policy makers, funding agencies, and early career scientists on these information gaps in order to inspire the resources and sizable body of researchers needed to identify and employ ecological countermeasures. Ideally, an appropriate educational institution and donor will step forward to curate the emerging knowledge in an open-access, interoperable database established and managed with rapid peer-learning goals (also see Action 4).

3. *Defining the causal links*. Ultimately, untangling the causal relationships between land use change and zoonotic spillover will require the coupling of field-based empirical studies that identify the parsimonious links with large-scale experiments and dynamic mechanistic models. Advances are being made across a wide range of taxa and contexts. For example, Süld et al. (2014) elucidate the complexity involved in identifying causal linkages between land use and zoonotic pathogen dynamics, tying the supplementary feeding sites of wild boar (*Sus scrofa*) in Northern Europe to the spread of several zoonotic diseases (including alveolar echinococcosis, trichinellosis, rabies, and sarcoptic mange) via the invasive raccoon dog (*Nyctereutes procyonoides*). In the St. Louis region of Missouri (U.S.A), Allan et al. (2010) demonstrated that Amur honeysuckle (*Lonicera maackii*), which is invasive in much of North America, increases human risk of exposure to ehrlichiosis, an emerging infectious disease caused by bacterial pathogens transmitted by the lone star tick (*Amblyomma americanum*). They observed that white-tailed deer (*Odocoileus virginianus*), a preeminent tick host and pathogen reservoir, preferentially-used areas invaded by honeysuckle, consequently leading to a considerably greater numbers of ticks infected with pathogens in honeysuckle-invaded areas relative to adjacent honeysuckle-uninvaded areas. They proposed honeysuckle eradication as tick-borne disease intervention. Reaser et al. (2020a; Supplemental Table 1) provide additional examples of research that mechanistically links land use to at least one component of the infect-shed-spill-spread cascade. They call on scientists to expand the number of empirical studies of land use-induced spillover for comparative purposes, as well as to identify ecological countermeasure 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.

4. *Monitoring restoration and health outcomes*. There are timely opportunities to include "ecological restoration for human health" targets within ecological policy and management frameworks, such as those being negotiated under the Convention on Biological Diversity toward a 2050 benchmark (https://www.cbd.int/conferences/post2020#). With regard to land use-induced spillover, targets should prioritize zoonotic pathogens surveillance and monitoring, especially given pending shifts in species' geography due to globalization and climate change. Although pathogen surveillance is often viewed as relevant to the biodiverse tropics, the need is valid for temperate and polar regions as well. For example, in Ireland, Nally et al. (2016) discovered a novel serovar of pathogenic *Leptospira* associated with the invasive greater white-toothed shrew (*Crocidura russula*). As a complement to decentralized zoonotic pathogen libraries, Watsa (2020) proposes a publicly accessible, centralized, curated system for monitoring zoonotic pathogens. Although she presents the GISAID (global initiative on sharing all influenza data) EpiFlu repository (https://www.gisaid.org/) as an example of a disease-focused public database that could be expanded to include other zoonoses, we would prefer to see zoonotic pathogen data directly or inter-operably incorporated into GBIF (Global Biodiversity Information Facility; http://gbif.org) to allow for co-analysis with pathogen host and vector distributions, geographic mapping tools, and land use data (see Reaser et al. 2020c for a relevant discussion). In combination, this information would enhance our capacity to generate ecological countermeasures, thereby mitigating zoonotic disease risk. In order to facilitate adaptive management, the monitoring and evaluation of ecological countermeasures should be standard practice.

5. *Community ownership and stewardship*. Halliday et al. (2020) observe that public health interventions often fail due to a lack of attention to their social, cultural, and historical contexts and poor engagement of the people they are designed to benefit. They note that effective community participation has been crucial for successful control of Ebola in West Africa, rinderpest eradication, and the success of many neglected tropical disease programs. Due to land use and ethical sensitivities, community engagement is key to ecological countermeasure development and acceptance. Island Conservation has effectively supported the Floreana Island community to their efforts to eradicate rodents and cats that pose public health risks and are barriers to ecological restoration (Island Conservation 2013). The large-scale tree planting effort in progress in southern Australia as an ecological countermeasure for Hendra virus mitigation is community-based (Plowright, pers. obs.). Gaddy (2020) provides insights into the application of local knowledge in emerging infectious disease research that is applicable to ecological countermeasures. Where relevant, traditional ecological knowledge should be included in these initiatives. Ultimately, community understanding and acceptance is fundamental to mitigating the environmental stressors that drive land use-induced spillover—currently and into the future—so that public health goals are achieved.

Conclusion

We believe that, as a tenant of ecological restoration, ecological countermeasures could become standard operating procedures for zoonotic disease prevention and response. Since land use-induced spillover scenarios are contextually unique, there is a need for a large, diverse, adaptable toolkit to mitigate zoonotic disease emergence and transmission. To date, efforts to mitigate zoonotic disease risk have largely focused on the control of specific pathogen, host, and vector species, including pathways of pathogen spread. This has proven inadequate under many scenarios; the scale of the problem substantially outsizes response willingness and capacity. Ecological countermeasures can serve as "extreme remedies for extreme diseases".

Although ecological restoration does not always provide direct, quantifiable benefits to human health, it would do so under the rubric of ecological countermeasures. The application of ecological countermeasures could be particularly valuable when there is a need to improve cost-efficiencies and efficacy; where, for example, highly vulnerable human populations live in poverty and there are few resources, coordinating mechanisms, and adequately trained professionals to apply large-scale medical and veterinary interventions in perpetuity. Such situations may also be prone to a lack of public trust in personally-oriented government interventions but acceptable of landscape-oriented approaches. Overall, ecological countermeasures may be more "public friendly" and provide substantial returns on investment for projects explicitly focused on zoonotic disease mitigation, while magnifying the returns on investment for natural resources projects with other primary goals (e.g., climate change mitigation). We welcome social scientists to collaborate on site-specific analyses of community attitudes regarding ecological countermeasure, cost-benefits, and economic efficiencies.

Further, we agree with Meyerson et al. (2009) that there is a need for a comprehensive approach to biosecurity that considers ecological perspectives. Since zoonotic pathogens may be moved intentionally as well as unintentionally, we propose that ecological countermeasures are viewed, prioritized, and institutionalized as landscape scale interventions to safeguard civil society. The United Nations Decade on Ecosystem Restoration (https://www.decadeonrestoration.org/) provides a timely platform for furthering these concepts and prioritizing the necessary work ahead through multi-lateral agreements and national policies.

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