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CLIMATE CHANGE AND COMMUNICABLE DISEASES

Ecosystem perspectives are needed to manage zoonotic risks in a changing climate

Better understanding of how environmental changes affect pathogens, hosts, and disease vectors can help prevent and respond to zoonoses, write Rory Gibb and colleagues

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Climate change and biodiversity loss are among this century's greatest threats to human health and are exposing people worldwide to increasing food and water insecurity, extreme weather, pollution, and infectious disease threats.[1 2] Zoonotic infectious diseases are situated at this nexus between environmental change, ecosystems, and health. Zoonotic pathogens and parasites are maintained in an animal reservoir and regularly or sporadically spill over to cause disease in humans,[3] sometimes leading to sustained human-to-human or vectorborne epidemics (eg, severe acute respiratory syndrome coronaviruses (SARS-CoV), Ebola, plague) but more commonly to endemic or sporadic disease (eg, leptospirosis, helminthiases, Lyme disease, hantavirus diseases).

Glossary of terms

- *Ecology*—Study of the relationships between organisms and their environment
- *Exposure*—The likelihood or frequency of contact and infection with a zoonotic agent
- *Host*—An organism that can be infected by an infectious agent under natural conditions
- *Reservoir host*—A host in which an infectious agent can be maintained and from which infection is transmitted to a target population
- *Spillover*—Process in which an infectious agent is transmitted into a novel host species
- *Trade-offs (in ecosystem functions)*—When one function responds negatively to a change of another function
- *Vector*—An organism, typically invertebrate, acting as intermediary in the transmission of an infectious agent from a reservoir to a target population
- *Vulnerability*—Possibility of a given exposure to hazard resulting in harm (eg, zoonotic disease outbreak) to a human target population
- *Zoonosis*—Disease that can be transmitted between humans and animals
- *Zoonotic pathogen/parasite*—Pathogen or parasite (eg, bacteria, virus, fungi, helminth, protozoan) that is maintained in a non-human animal reservoir and is capable of infecting and causing disease in humans
- *Zoonotic hazard*—Relative number of available zoonotic infectious agents at a given space and time acting as potential sources of harm (eg, zoonotic disease outbreak) to a human target population.

Animal-to-human transmission (spillover) is influenced by environmental and socioeconomic processes that reshape reservoir host communities and bring people and livestock into contact with wildlife, such as shifts in land use and food systems, deforestation, and climate change. As these pressures have escalated worldwide in the past half century, zoonoses from wildlife have been emerging at an increasing rate.[4]

Indeed, 2020 will be remembered for several zoonotic crises, including the global pandemic of SARS-CoV-2, two concurrent Ebola outbreaks in the Democratic Republic of the Congo, and the highest ever Lassa fever surge in Nigeria. Severe outbreaks like these profoundly affect public health, societies, and economies, which is why zoonoses are often viewed through the lens of pandemic preparedness.

However, such high profile events occur against a backdrop of a substantial burden of endemic disease that has long term effects on structurally vulnerable communities in low and middle income countries.[5] Many of these communities are also disproportionately exposed to hazards associated with rapid environmental change (eg, deforestation, urbanization, extreme weather).[6 7] Since global climate mitigation efforts currently seem unlikely to prevent significant warming,[8] regional and national adaptation strategies will be crucial to protect public health and build resilience to future zoonotic risks. Perspectives from ecology can inform efforts to prevent and respond to specific diseases and support disease management within a broader ecosystems context.

Socioecological challenges

Managing the risks of disease transmission from wildlife is fundamentally a socioecological challenge (fig 1). Zoonotic pathogens and parasites typically circulate unobserved in nature among reservoir communities of wildlife host species, often with biting arthropods (such as mosquitoes and ticks) acting as vectors of infection.[3] Human infections occur through exposure to reservoirs—for example, direct contact with wildlife or livestock hosts, bites from infectious vectors, or contaminated materials (eg, food, water, soil, surfaces).

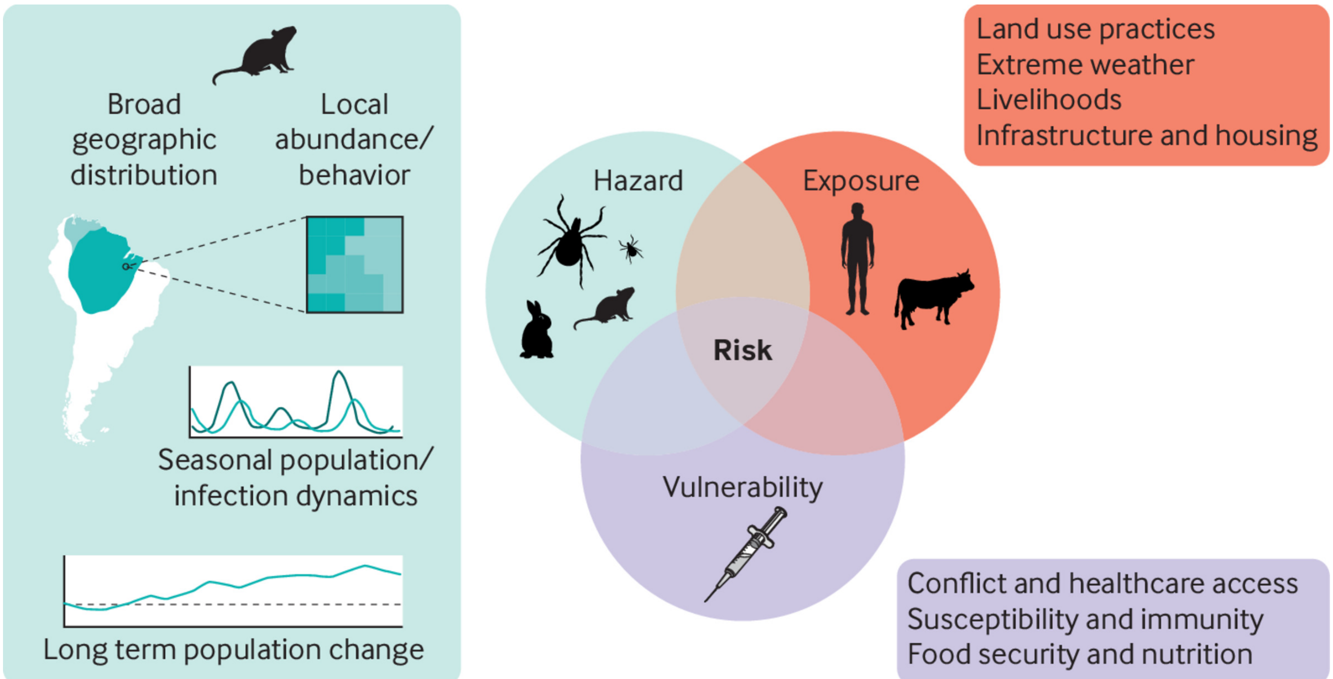

Fig 1 | Effects of global environmental change on zoonotic disease hazards and risks. Inset boxes highlight key socioecological processes through which climate and land use changes can affect hazard, exposure, and vulnerability. For example, zoonotic hazard (underlying potential for pathogen spillover) is a consequence of changes in reservoir host and vector distributions, abundance, and host-pathogen dynamics (example shown for a hypothetical rodent species)

Risky interfaces between people and reservoir communities are complex, dynamic, and pathogen specific (table 1), with interactions among hosts, vectors, pathogens, and environments driving geographic and seasonal trends in the potential for spillover to people. Understanding these trends is crucial to predicting where and when human infections are likely to occur. However, the degree to which hazards become realized risks also depends on factors that drive human exposure (eg, land use practices, hunting, housing and sanitation, extreme weather) and vulnerability to infection (either individually or at population level—eg, nutrition, access to healthcare).[6]

Table 1 | Zoonoses of known public health significance likely to be affected by future climatic and land use changes

Disease	Reservoir host/vector	Pathogen	Main transmission route to humans	Annual global incidence (estimated cases)	Socioecological context and current trends	Potential sensitivity to climate and land change
Lassa fever	Rodent (single species)	Lassa arenavirus	Contact with rodent contaminated food and surfaces	100 000-300 000	Seasonally endemic in rural west Africa, where rodent reservoir host is common around fields and villages. Reported cases have steadily increased over past twodecades	Increasing rainfall and agricultural expansion across much of west Africa may expand suitable habitat for reservoir host. Future shifts in rainfall seasonality may affect reservoir host population cycles and seasonality of human risk
Leptospirosis	Rodents (numerous species)	*Leptospira* spp	Contact with rodent contaminated environment (water, soil)	~1 million	Found in rodents globally, but human exposures and burden are highest in poor communities in the tropics[9] (eg, subsistence farms, informal urban areas). Flooding after extreme weather events can lead to large human outbreaks	Climate change is increasing the frequency and intensity of extreme weather events. Agricultural expansion and unplanned urbanization can increase both rodent-human contact and susceptibility to flooding
Lyme borreliosis	Wild vertebrates (numerous species), ticks	*Borrelia burgdorferi* spp	Tick bite	Unknown but ~30 000 in US alone	Maintained in forested areas across Palaearctic in complex, multispecies transmission cycles. Disease in humans arises through infectious tick bites. Reported incidence increasing	Forest degradation and fragmentation often favors more competent host communities, increasing hazard for humans.[10] Geographic distributions of tick vectors are likely to shift as climates change
Zoonotic malaria	Primates, *Anopheles* mosquitoes	*Plasmodium knowlesi*	Mosquito bite	Unknown; seems to be increasing	Maintained among macaques and mosquitoes in forests of South East Asia. Spillover to humans occurs through infectious mosquito bites, in forests and around forest edges. Human incidence rising in recent decades	Ongoing rapid deforestation and forest fragmentation in South East Asia is increasing human exposure[11]
Rift Valley fever	Mosquitoes (several genera), ruminant livestock	Rift Valley fever phlebovirus	Mosquito bite, infected livestock body fluids	Variable; occurs in sporadic outbreaks	Maintained and transmitted by mosquitoes in Africa and Arabian peninsula. Periodic, explosive outbreaks occur in ruminant livestock (eg, cattle) and in humans through mosquito bites and contact with infectious livestock fluids (eg, through slaughtering)	Seasonal temperature and water availability shape mosquito populations and virus persistence.[12] Future climate and land changes may affect hydrology, mosquito-virus interactions, and human/livestock exposure, which may increase the frequency, intensity, and geographic distribution of outbreaks
Ebola virus disease	Bat reservoir (species unknown), primate and duiker intermediate hosts	Zaire ebolavirus	Contact with infectious body fluids (wildlife or people)	Variable; occurs in sporadic outbreaks	Ebola reservoir not definitively identified but most likely bat populations in central and west Africa. Following initial spillover event(s), epidemics driven by extended human-to-human transmission chains, with high case fatality rates	Warmer and wetter climates in Africa, forest fragmentation and expansion of plantation ecosystems, may increase habitat suitability for reservoir hosts and facilitate human-bat contact[13]

For instance, although rodents worldwide carry *Leptospira* bacteria, most human leptospirosis occurs in poor agricultural and urban communities with high exposure to rodent contaminated environments.[9] The One Health framework has conceptualized these links between human, animal, and ecosystem health, but most research has focused on human-animal (especially human-livestock) interactions in relatively localized settings.[14] Scaling up the results of such localized studies to inform national and regional policy to prevent or respond to zoonotic outbreaks is challenging because of the socio-ecological complexity of zoonoses and histories of sporadic detection of many diseases.

Even when long term systematic case surveillance data exist for neglected and emerging zoonoses, their observational nature and geographic biases make it difficult to disentangle the relative influence of ecological and socioeconomic changes on disease incidence. For example, there have only been about 25 confirmed human Ebola virus spillover events since 1976; such a small sample makes it difficult to infer drivers and risks of future spillovers from human epidemiologic data alone. Framing the ecological aspects of zoonotic disease systems (eg, reservoir host and vector population responses to environment) as natural hazards[7] can help overcome this difficulty. Existing data sources on host and pathogen biology, ecology, and biogeography can be used to inform the assessment of current and future risks. Modeling approaches that incorporate ecological processes are gaining traction in vectorborne disease and climate change research[15,16] and can improve our understanding of how global change will affect zoonoses more broadly.

Ecological perspectives for public health decisions

Ecological theory and approaches are already embedded in epidemiologic and public health understanding of many zoonoses. They have been instrumental in many disease control programs, such as the eradication of rabies in wildlife in Western Europe[17] and management of leptospirosis and dengue in urban areas.[18,19] Under future climate change, ecological knowledge will be increasingly important to support both short term health policy (eg, forecasting for prevention and prioritizing clinical resources) and long term decisions (eg, strengthening health systems and diagnostic capacities, and targeting vaccinations).

One potential application is to predict seasonal risk of zoonoses from environmentally linked demographic and infection dynamics among reservoir species.[20] For example, surveillance of yellow fever in non-human primates has already been used to inform human vaccination strategies in Brazil, leading to fewer cases in municipalities using this early warning system.[21] Models that integrate ecological or biological knowledge of important reservoir or vector species with near realtime climate and earth observation data can inform forecasts of certain zoonotic hazards weeks or months in advance. Seasonal variations in temperature and water availability (which affect persistence of mosquito host populations) have been used to predict outbreaks of Rift Valley fever in east Africa and facilitate mitigation activities.[22] Similarly, human surges in rodent borne hantavirus disease in China[23] and Europe[24] follow predictable host population cycles linked to rainfall and vegetation.

In future, climate change trends and extremes may disrupt natural seasonal changes to ecosystems,[25] with potential for unexpected effects on reservoir hosts and infection hazards. Integrating ecological forecast models into health planning could support preparedness for such surges in risk, including for high burden zoonoses such as Lassa fever in west Africa (table 1). Indeed, climate based early warning systems already support prevention strategies and health planning for well monitored vectorborne infections such as dengue.[26]

In the longer term, the coming decades will see huge worldwide changes in biodiversity as changing climates and pervasive human transformations of natural landscapes (eg, agricultural expansion, urbanization) restructure and homogenize wildlife communities.[27] Changes in reservoir and vector distributions can move diseases into new areas. For example, the geographic expansion of *Ambylomma americanum* ticks between 1993 and 2013 was correlated with increasing incidence of tickborne rickettsiosis in the US.[28] Such responses of reservoir, vector, and host-pathogen biology to environmental pressures will vary among species, leading to complex effects on future hazards that may differ widely among diseases and locations.[29]

For instance, by 2070 some geographic areas (often temperate regions) are expected to become more climatically suitable for mosquito transmission of dengue and chikungunya and other areas (especially in the tropics) less suitable.[15] Crucially, these changes will often intersect with existing or emerging climate related vulnerabilities to spillover and epidemics (eg, food and water insecurity, extreme weather; table 1).

Scenario based evaluation of future geographic changes in hazard for multiple zoonoses, and analysis of uncertainty between different future climate, land use, and disease models,[30] could support long term strategic planning in health and environmental sectors (see examples in table 2). Recent advances in combined ecological-epidemiological models show promise not only for projecting zoonotic risk responses to future environments (based on multimodel climate forecasts) but also for testing the effects of interventions on spillover and epidemic thresholds.[12,13,31] Similar approaches are increasingly used in biodiversity planning—for example, the design of spatial conservation programs that account for future climate change uncertainty.[32] More immediately, improving systematic and community based disease surveillance, especially in areas with rapid changes in land use or climate, will be vital to early detection and response for known and novel infections.[33]

Table 2 | Policy areas where ecosystem perspectives could assist in reducing zoonotic disease risk driven by climate change

Policy sector	Ecological contributions to policy	Examples of ecosystem based approaches to managing zoonotic risks
Urban planning	Understanding the ecology of urban adapted reservoir/vector species (eg, brown rat, *Aedes aegypti*) can inform better design of housing and sanitation to exclude them—eg, improving water drainage, food, and water storage and waste management to reduce vector breeding sites and food for rats	Future urban planning could aim for co-benefits of climate adaptation and disease reduction. Increasing the density of drainage networks and the provision of piped water can mitigate increased flooding and water shortage risks while also reducing reservoir or vector habitat. Green spaces can help to reduce urban heat island effects, which would otherwise provide warmer microclimates for vector breeding, and reduce heat stress for people
Agricultural (arable)	Evaluating how animal reservoir or vector populations respond to expansions of agriculture and to climate changes in human managed landscapes can identify high risk emerging interfaces for zoonotic transmission	Agricultural landscapes and practices could be designed to naturally regulate populations of synanthropic reservoir hosts (eg, rodents) or vectors, reduce pathogen or parasite transmission (eg, by reducing standing water), and regulate local microclimates. This could also help to benefit food security by reducing crop losses
Agricultural (pastoral)	Climate and land use change will influence occurrence and abundance of reservoir and vector species that can transmit pathogens to livestock and people, as well as influencing environmental suitability for livestock husbandry. Understanding how these interfaces will change can identify high risk areas for future outbreaks	Adopting methods from higher yield farming systems could enable more efficient use of land and reduce human-wildlife-livestock interfaces. Agricultural landscapes can be designed to reduce contact between livestock and wildlife reservoir species (eg, bat hosts of henipaviruses), lowering risks of livestock epizootics and spillover to humans
Public health and clinical planning	Early warning surveillance systems (eg, monitoring sentinel wildlife populations) or mapping and forecast models of reservoir populations, can inform targeted prevention and outbreak response for specific zoonoses	Modeling approaches can evaluate how future climate and land change scenarios may affect geographic trends in zoonotic hazard for multiple zoonoses. The outcomes from these models can inform targeted strengthening of national health systems and health information management, as well as long term planning for prevention and response
Habitat loss and degradation	Understanding and mapping habitat use by known or predicted hosts of priority pathogens (eg, betacoronaviruses, filoviruses), under present and future environmental conditions, can identify regions that may pose a high hazard of zoonotic emergence and outbreaks	Much deforestation and agricultural expansion is driven by upstream factors, including global trade. Identifying and addressing upstream drivers could reduce human exposure risks to emerging zoonoses while preserving biodiversity and other ecosystem functions
Wildlife trade and hunting	People hunting and trading in wild animal species can increase risks of exposure to zoonotic pathogens. Understanding and mitigating the environmental drivers (eg, climate, land use) that increase pathogen prevalence in reservoir species could help to reduce hazards. Policy interventions to protect species could in some cases reduce exposures	Hunting and wildlife trade are often driven by nutritional and financial needs, and bans would not eliminate these needs. Investment to increase opportunities for profitable alternative livelihoods that are resilient to future climate change could reduce reliance on wild animal products while benefiting food security and biodiversity conservation

Toward ecosystem based approaches

A challenge to integrating ecological knowledge into decision support is the lack of understanding and data on key biological, ecological, social, and geographic features of many zoonoses and their reservoir hosts (including for priority diseases such as viral hemorrhagic fevers). Tackling this requires integration of knowledge, evidence, and research programs across ecological, social, and health domains.[33 34] The development of open access platforms to bring together data that already exist (eg, wildlife, livestock, and human serological surveys) could support analyses of future zoonotic disease responses to environmental change.

More broadly, including ecological expertise in public health research and design of policy—and vice versa—could fill gaps in data and improve programs to prevent and control infectious disease.[35] Multidisease, socioecological, and health based studies of reservoir communities, vectors, and human infection rates along landscape and climatic gradients (eg, from natural to agricultural and urbanized systems) can provide models for how future environmental changes will simultaneously reshape zoonotic hazards, exposures, and vulnerabilities.[36] Ongoing transdisciplinary research into zoonotic malaria in Malaysia (table 1), for example, shows how such approaches can identify communities, livelihoods, and locations at greatest risk, particularly for understudied diseases.[11]

The covid-19 pandemic has again focused attention on the drivers of the emergence of new zoonoses and has triggered calls for broadbrush interventions such as bans on hunting or wildlife trade to curb the risks of spillover. Yet such blanket proposals risk ignoring the complexities and local contexts of zoonotic disease systems, and the many direct and indirect ways that ecosystems contribute to health (and, in turn, susceptibility to disease; fig 1). The "nature's contributions to people" model in ecology[2] and health based frameworks such as Planetary Health,[37] recognize that zoonotic hazards are part of a broader environment-health nexus alongside other crucial ecosystem outputs (such as food and water security). Understood in this way, zoonoses are concerns not only for health policy but environmental policy more generally (table 2).

The future presents difficult challenges for decision makers, especially, but not only, in economically marginalized regions where many communities depend directly on wildlife and ecosystems for their wellbeing. How should landscapes be best managed to balance trade-offs between food production and natural regulation of zoonotic hazards (eg, reservoir host and vector populations), while supporting sustainable, healthy livelihoods that maximize resilience to the effects of climate change? Questions of this kind are rarely considered for zoonoses, even though analyses of such trade-offs are common in ecological science[2]—for example, between crop production and carbon sequestration.

This is changing. Promising recent work has shown that restoring river prawns in riverine ecosystems in Senegal can reduce human schistosomiasis prevalence (by regulating snail host populations) while also potentially benefiting local food security.[38] Similarly, land use policy decisions could affect existing disease control efforts, as suggested by recent evidence that global demand for commodities linked to deforestation can affect malaria burden in the tropics.[39] Importantly, such environmental trade-offs will also occur between different diseases—for example, agricultural expansion may simultaneously favor increased populations of some reservoir hosts (eg, rodents) and declines in others (eg, primates).[40]

These complexities highlight the need for more adaptive, ecosystem based interventions to help manage zoonotic hazards and risks across multiple areas of policy (table 2).[33] Single disciplinary interventions are unlikely to be able to deal with the dynamic, moving target nature of zoonotic systems under global environmental change.[33] Such a perspective is concordant with the increasing recognition in biodiversity sciences, emphasized last year by several authors from the Intergovernmental Panel on Biodiversity and Ecosystem Services, that tackling economic inequality while preserving ecosystem functions on which human wellbeing depends will require "transformative change" away from the current extractive global economy toward more sustainable relations to nature.[2]

Integrating ecological perspectives on zoonoses into national and regional public health action plans, as well as other policy sectors dealing with climate adaptation (eg, agricultural policy) would be a step toward reducing the global burden of zoonoses while building broader health resilience to the effects of climate change.

Key recommendations

- Climate and land use change are likely to significantly influence hazards of many zoonoses
- How these translate to changes in risk will be determined by socioecological and economic contexts that shape human exposure and vulnerability
- Policy makers should incorporate ecological understandings of zoonotic disease into health and environmental planning to help evaluate disease-risk trade-offs, prioritize interventions, and build wider health resilience to climate change
- Integration of research design across health, social, and ecological disciplines can provide clearer understanding of how environmental changes are reshaping zoonotic risks and inform forecasting

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