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Climate change and communicable diseases

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CLIMATE CHANGE AND COMMUNICABLE DISEASES

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Strengthening the global response to climate change and infectious disease threats

Climate change is emerging as an important driver of disease incidence, and a wait and see approach invites unnecessary risk, write **Jeremy Hess and colleagues.** Governments, funders, researchers, and practitioners must act now

Global health leaders have identified climate change as the greatest health challenge of the 21st century.[1] Impacts on infectious disease are a particular concern: there is growing evidence that some of the greatest health impacts of climate change are, and will continue to be, on the emergence, re-emergence, and spread of infectious diseases.[2] For at least two decades, global assessments have highlighted the need to reduce greenhouse gas emissions[3 4] and to invest more substantially in climate and health, including surveillance, preparedness, and response.[5-7]

The global health response has largely been characterized by scepticism and watchful inaction. The world's largest global health funders, including the US National Institutes of Health (NIH)[8] and the Bill and Melinda Gates Foundation (BMGF), still lack specific climate and health programming, let alone programming focused on climate change and infectious diseases. Climate change remains a vanishingly small element of the portfolio of funders like the European Commission and the Wellcome Trust that have stepped into the breach. Funding for training, research, and practice related to climate change and infectious disease has been limited accordingly.

This is partly because the evidence is difficult to parse.[9] The rationale for an association between climate change and infectious disease is clear, and mosquito-borne pathogens, particularly malaria and dengue, are of particular concern[10 11] given established climate sensitivities of vector populations.[12 13] But evidence of major impacts of climate change on communicable disease has been somewhat limited. The relative importance of climate variability and change has been difficult to evaluate among drivers of disease incidence such as globalization, urbanization, migration, land use changes, poverty, vector-pathogen characteristics, and control measures.[14] In recent years, the world has seen substantial declines in many prevalent infectious diseases, including malaria, yellow fever, lymphatic filariasis, schistosomiasis, onchocerciasis, Chagas disease, and African trypanosomiasis,[15] indicating that other drivers have obscured any climate change contribution to disease incidence.

KEY MESSAGES

- Prioritize decarbonization in the health sector and global health practice
- Increase funding for climate and health research and practice
- Encourage a transdisciplinary approach and support interdisciplinary activity
- Incorporate environmental information into public health practice and assessments
- Invest in decision support modeling tools and communication
- Build human capacity in data management, integrated surveillance, and leadership

Gaps in the evidence base

Ruling out climate change as a key driver of infectious disease risk is premature, however, for several reasons. First, our evidentiary database is incomplete. Some areas that have experienced substantial shifts in climate (such as areas of Africa and the Middle East) are under-represented in the evidence base, which limits conclusions about climatic influences in certain regions.[16] Second, there is limited research on the role of interannual climate variability, which is important for many infectious diseases with a marked seasonal component. Third, insufficient attention has been paid to the effects of increasingly frequent and severe extreme weather events, which have a known association with infectious disease outbreaks.[17 18] A precautionary approach would argue for more research, at a minimum, to settle any remaining doubts.

In addition, interactions between climate change and other infectious disease drivers seem to be accelerating. Over two thirds of human infectious diseases are zoonotic, causing widespread morbidity and mortality.[19] Zoonotic disease spillover is determined by interactions between humans and natural systems.[20] Increasingly widespread disruption of landscapes and biodiversity, through deforestation and agricultural development, changes socio-ecological systems and forces humans, vectors, livestock, and pathogens into increasingly closer contact.[21] For example, land use and land cover changes, in parallel with temperature increase, may contribute to the spread of leishmaniasis by moderating vector activity.[22 23] This, combined with unplanned and precarious urbanization, increasing global connectivity via international travel and trade, and climate variability, can allow invasive vectors and novel pathogens to spread widely, with the potential for transcontinental pandemics with devastating public health, social, and economic consequences.[24]

Tipping towards action

The detection and attribution of climate change effects on infectious diseases is challenging,[25] but substantial progress has been made. Climate change is emerging as an important driver in several cases. Dengue incidence, for example, has risen sharply over recent decades, and prior consensus has held that climate change is just one of many contributing factors.[26] But recent analyses indicate that climate change has had a more decisive role[27] and that climate change could have similar effects on other mosquito-borne diseases in some regions.[28] Other analyses have implicated climate change in the increasing incidence of diseases like Lyme and tick-borne encephalitis.[29 30] Notably, this evidence has arisen from groups based in regions with more access to climate change and health research funds.

Other signs of increasing effects of climate change on infectious disease are emerging. For example, malaria incidence is increasing in the highlands of Colombia and Ethiopia,[31] Lyme disease is expanding its range northward as the climate warms,[29 32] and arboviral diseases are extending from the tropics into temperate regions globally.[33] In Europe, climate change has facilitated the spread and establishment of West Nile virus in new regions.[34] There are also signs that the autochthonous spread of some infectious diseases may be facilitated by climatic changes increasing ecological suitability (the availability of niches suitable for vectors and pathogens)[35] and vectorial capacity (the ability of the vector to transmit the disease) in multiple settings.[36 37] Emerging evidence reinforces concern for the future due to projected warming, urbanization, and global connectivity,[38] including large parts of Europe and Eurasia.[39]

The steady acceleration of climate change emphasizes the need for a more active posture to take advantage of response options while they are still available. Climate change is accelerating and ecosystems are nearing dangerous tipping points,[40-42] promoting infectious disease transmission through multiple pathways. One common pathway is increased transmission of zoonotic diseases between wildlife and domesticated animals.[43] Other pathways involve ecosystem changes. In wetland ecosystems, for example, heat and drought conditions may lead to water bodies shrinking and organic matter becoming more concentrated (eutrophication). Such conditions favour *Culex pipiens*, the main vector of West Nile virus.[44] The acceleration of these trends has the potential to constrain the range of response options we have at our disposal.[45]

Finally, climate change is likely to worsen infectious disease impacts by increasing sequelae and complicating control efforts. Climate change is expected to worsen food security and nutritional status,[46] limiting host ability to recover from infectious diseases and worsening sequelae. Migration, in response to increasingly scarce resources—such as water and arable land—and to sea levels rising,[47] is also likely to create fertile conditions for infectious disease outbreaks that confound conventional control strategies.

Increasing resilience in global infectious disease practice

A wait and see approach to climate change and health is short sighted and invites unnecessary risk. Based on the weight of the evidence and established calls for specific actions, we recommend key, "low regrets" strategies to reduce health risks associated with climate change by improving the ability to anticipate and engage infectious disease risks effectively.

Reduce carbon footprint

Globally, the health sector emits 4% of the world's greenhouse gases, more than aviation or shipping,[48] sectors that have been scrutinized for their climate change contributions. To limit warming to 1.5°C without carbon removal from the atmosphere, emissions from all sectors need to decline to zero by 2050,[49] moving well beyond commitments made in the Paris Agreement. Health sector emissions are driven principally by domestic energy system intensity, the carbon intensity of the domestic economy, and demand for health services.[48] Major reductions in the health sector are feasible and consistent not only with maintaining but also advancing population health. The UK National Health Service is working to reduce its greenhouse gas emissions by 80% from a 1990 baseline by 2050. Strong advocacy from the health sector to reduce carbon emissions is thus one of the more important levers for reducing its own carbon footprint, as is investment in energy efficiency in procurement and operations.[50 51] These investments are consistent with the sector's mission: Mitigation activities have well established benefits for health,[52 53] including reduced pollution exposure and less obesity through healthier diets and more walking and cycling. Other efforts are needed, as well. The health sector has been slow to divest from fossil fuels and should lead by example.[3 54 55] Climate change mitigation in healthcare systems must be adopted universally to achieve collectively endorsed mitigation targets, and help for poorer countries for greening their health sectors should be part of this commitment. A by-product of responses to the covid-19 pandemic has been reduced emissions of greenhouse gases and other harmful co-pollutants.[56] While they hold the world's attention, health systems can work to leverage these temporary reductions through the mechanisms mentioned above and seize the opportunity to promote further greening during recovery efforts.[57]

Increase funding for climate and health

Nations should acknowledge and invest in strategies to further elucidate links and tackle climate related health risks. The discipline of climate and health has been systematically deprived of funding for training, research, and other activities, including development and testing of interventions.[8] There is a conspicuous lack of investment in climate and health from major global health funders including the BMGF and the NIH. Although funders such as the Wellcome Trust have tentatively engaged climate and health programming, their investments have been relatively timid in ambition and limited in scope. The Belmont Forum has recently prioritized climate and health, but direct funding from health agencies is limited, and funds cannot be spent in the countries most affected despite their lack of contribution to the underlying problem and need for capacity.[58]

Recent years have seen some positive developments, including investments from the European Union and other international agencies in the Caribbean region for climate and health initiatives. This was spurred by regional advocacy and recognition of the high vulnerability of health systems in Caribbean small island developing states, particularly to climate related disasters. Nevertheless, investment is directed principally towards infectious disease diagnostics and therapeutics to tackle negative health outcomes. Investigating and tackling climate change health effects and greening global health practice are afterthoughts, despite the potential for climate change to undermine the global health gains of recent years.

Frame the problem with a transdisciplinary lens

Framing is important to characterizing problems and identifying response options. Several interdisciplinary and intersectoral concepts have been proposed to offer a more proactive and holistic framework for tackling global health threats, such as ecohealth, one health, planetary health, planetary epidemiology, and planetary wellbeing.[59 60]

These concepts share the notion that the health of humans, plants, and animals and the planet is inextricably linked. Other frameworks have identified the central importance of social determinants of health.[61 62] All of these frameworks reflect the fundamental importance of multiple sectors and disciplines coming together to improve health and wellbeing and the potential for working at cross-purposes when sectors do not work together.

These concepts have been embraced but not fully realized, as noted elsewhere in this collection. Transdisciplinary teams can learn to design more robust surveillance systems, develop innovative methodologies (such as quantifying and communicating model uncertainty and performing forecast verification) and effective communication strategies for target audiences on international, national, and city levels. Such teams could also bring in climate scientists and meteorologists to satisfy the longstanding suggestion for a merged community of practice.[63 64]

A broader frame could also lead to coupled action: efforts to reduce infectious disease effects such as mosquito net distribution could be linked with efforts to electrify villages, facilitating climate change mitigation and reducing population susceptibility to multiple hazards at the same time.

Incorporate environmental information into public health practice

The global response to climate change and its effects needs better information to support decision making. The past decade has seen progress towards integrating climatic data into the surveillance of infectious diseases. The Global Framework for Climate Services provides guidance on how to bring climate information into the mainstream of health sector activities.

Because this has not been broadly adopted in public health practice, however, many shortfalls still exist, including the lack of harmonization in the collection of climate and health data needed to inform climate adaptive responses. Integrating Earth observations (from satellites, weather stations, or drones, for example) and local environmental observations (such as from citizen science initiatives) into burden of disease estimates and disease surveillance activities could allow for the early detection of anomalies and facilitate pre-emptive actions.

Recognising the utility of the Global Burden of Disease (GBD) study and leveraging experience from that effort, the global health community could come together to pursue a major synthesis in environmental and health data, for example an effort to link GBD data with data on ecosystem health and services. The *Lancet's* Countdown on Health and Climate Change gestures towards such an analysis,[54] but there is potential for more substantial interdisciplinary collaborations, including interactions with policy makers. Leaders from the health community, including those from the GBD study, have emphasised the importance of such expanded efforts.[65]

These initiatives will need to quantify and characterise exposure, vulnerability, and risk for populations and health systems, identify and track key effects on population health over time, and attempt to identify the climate change components of infectious disease systems, among other health risks resulting from the changing climate, to help inform adaptation, mitigation, and surveillance strategies. These efforts will need to be well crafted, because effective transdisciplinary approaches rely on early, strong partnerships among diverse scientific experts and stakeholders (including policy makers, the private sector, and civil society) to ensure that the outcomes are relevant in guiding and informing actions. Relevant examples of successful efforts include several assessments of national vulnerability and adaptation, national adaptation plans for health, assessments of city climate risk, and projects using available adaptation funding. The Middle East Consortium on Infectious Disease Surveillance, for example, highlights the potential for regional collaborations.

Invest in decision support modeling tools and communication

Established effective global health practices should be retained but need to be integrated with other strategies to support management decisions. Computational models can help disentangle and quantify the role of multiple infectious disease transmission risk factors, including climatic and environmental factors, human mobility, socioeconomic status, asymptomatic infections, and background immunity.

Predictive modeling has the potential to help decision makers understand where infections will emerge or spread or when future epidemics might occur. Outbreak predictions that use seasonal climate forecasts can prepare public health systems months in advance of a period of heightened risk of disease outbreaks, particularly in areas sensitive to large scale climate phenomena, such as the El Niño Southern Oscillation.[18 54]

Combining novel data streams, including seasonal forecasts and local seroprevalence data, in early warning systems could improve predictions of the timing and magnitude of outbreaks of multiple diseases.[65] Modeling approaches and processes for evaluating future climate change effects on infectious disease must be co-designed in partnerships involving public health climate practitioners and aligned with local priorities and capacities to identify the most appropriate spatial resolution and tackle cross scale problems.[13]

Supporting uptake of findings from these efforts is also important. A key component of effective model communication is the provision of user friendly interfaces to openly share and visualize results and to provide access to modeling architecture to allow for scrutiny and reproducibility.[63] Educating policy makers and other stakeholders regarding modeling processes and interpretation of findings is also essential.[55 64] Challenges related to interpreting modeling results have been apparent in the covid-19 response, with software engineers, decision makers, and the public calling for more transparent sharing of evidence used to inform vital decisions, and policy makers struggling to interpret seemingly disparate recommendations based on different model outputs. Looking forward, funders need to consider data science and software engineering as key components of any scientific tool kit and transdisciplinary epidemiological taskforce.

Build human capacity in data management, integrated surveillance, and leadership

Additional investment for incorporating climate considerations into global health practice, if and when it comes, should support training to maximize the effectiveness of programmatic investments. Although the discipline has continued to make halting progress, awareness remains low among the public health community of climate related epidemiological and assessment tools.[35] We recommend updated and expanded health professional educational programming. Sustained funding is essential for risk assessment, intervention development, programme evaluation, and implementation; for training the next generation of climate and health leaders to facilitate the requisite interdisciplinary collaborations; for maintaining longer term projects for sustained impact and learning about implementation strategies.

In addition, funders should prioritize support for surveillance that incorporates environmental information and skills training for interdisciplinary practice.[66] For example, easy to implement, low cost actions might include integrating weather data collection with malaria surveillance.[52] A recent study in the Caribbean[67] found that technical expertise in statistics, data science, and geographic information systems in the health sector needed to be strengthened to interpret basic climatic information and integrate this information into a health early warning system. At the same time, climate practitioners need a better understanding about the decision priorities and needs of the health sector to be able to provide relevant bespoke and useful climate indicators. An early warning system requires an integrated approach that cuts across research, health and climate operations, data and knowledge sharing platforms, outreach and education, and in country response activities. There are challenges to interdisciplinary design and work of this sort, including the need to develop shared language, perspective, and methods,[64] and future funding should recognise these concerns. Such climate resilience actions should leverage and engage with other global health innovations that aim to reduce the burden of infectious diseases such as the development of rapid, accurate, low cost diagnostics; novel therapeutics and vaccines; innovative vector control and surveillance tools; and community education and social mobilization via social media.

Call to action in global health practice

Global health has been defined as "an area for study, research, and practice that places a priority on improving health and achieving equity in health for all people worldwide . . . [that] emphasises transnational health issues, determinants, and solutions; involves many disciplines within and beyond the health sciences and promotes inter-disciplinary collaboration; and is a synthesis of population-based prevention with individual-level clinical care."[68]

The global health community has many actors that pursue this common agenda, including multilateral organizations; funders, including governments and foundations; non-governmental organizations; researchers; and practitioners. Action on climate and health, called out as an increasingly urgent priority by the World Health Organization (WHO), the Intergovernmental Panel on Climate Change (IPCC), and 197 signatories to the Paris Agreement, is squarely in the domain of global health, including its primary funders, organizations, and partners. Yet the calls of these multilateral organizations and governments have, in most cases, been met with a tepid response by global health funders and practitioners.

The covid-19 pandemic has taught us the consequences of unheeded warnings, and similar effects, drawn out over a much longer timeframe, are increasingly likely as a result of years of inaction on climate and health. There is now increased attention on the importance of core public health systems and the global conditions that lead to disease emergence and pandemic spread. This is an opportunity for the global health community, particularly its funders, researchers, and practitioners, to better align with WHO and IPCC in their calls for action on climate and health and usher in a new age in global health practice. The climate is changing rapidly, time is short, and options are increasingly limited: strong action must be taken now.

The global health community of governments, particularly the G20, and funders, particularly leaders including the NIH, the BMGF, and the Wellcome Trust, must seize the moment and take up the recommendations from WHO, the IPCC, and increasingly vocal members of the global health research and practice communities to prioritize equity, efficiency, and sustainability,[53] including vigorous action on climate change and infectious disease. To protect hard won gains, the global health community needs to recognize its shortcomings, broaden and expand its perspective, assume a proactive posture, and intensify its activity. Our vision is for a sustainable, proactive new age in global health, in which it expands its frame, leads by example, works with partners from other disciplines, invests in new skill development and interventions, and is resilient to extreme events, shocks, and large population movements.

A reorientation of global health practice requires input and engagement from all of its actors. Development and health agencies need to incorporate recommendations for changing priorities and practice. Funders—particularly the BMGF, which has a disproportionate effect on information flow and priority setting through its support of the GBD study—have an important role to play in framing the problem, promoting transdisciplinary approaches, and increasing transparency and accountability. Opportunities to expand current efforts to incorporate climate action abound. Assessments of action on the sustainable development goals (SDGs) and their health impacts,[69 70] for example, could easily expand to incorporate climate action. Both governments and funders have important roles in prioritizing decarbonization in global health programming, practice, and research, including efforts to green global health supply chains and reduce health sector carbon intensity. Practitioners have a role to play as well, by demanding that investment in transdisciplinary training and data integration become routine and creating pathways for career development in climate and health.

Health organizations including ministries and large non-governmental actors should engage with scientists from various disciplines (such as climatology, ecology, social sciences, biology, modeling) to design and prioritize policy oriented research, including strengthening and evaluating adaptation of the health systems. This involves greening our own practice; investing in substantial, durable interdisciplinary activities and effective data sharing; breaking down informational and disciplinary silos; wrestling with complex issues beyond diagnostics and therapeutics; and supporting decisions that reduce health risks across multiple sectors. This will take substantial, sustained investment; development of new training pathways; support of new data streams; and commitment to working with stakeholders, including communities and policy makers.

Global health needs to think more holistically and act more comprehensively. We know what challenges climate change brings and how to respond. Now we need the will.

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Infographic: Climate change and infectious disease

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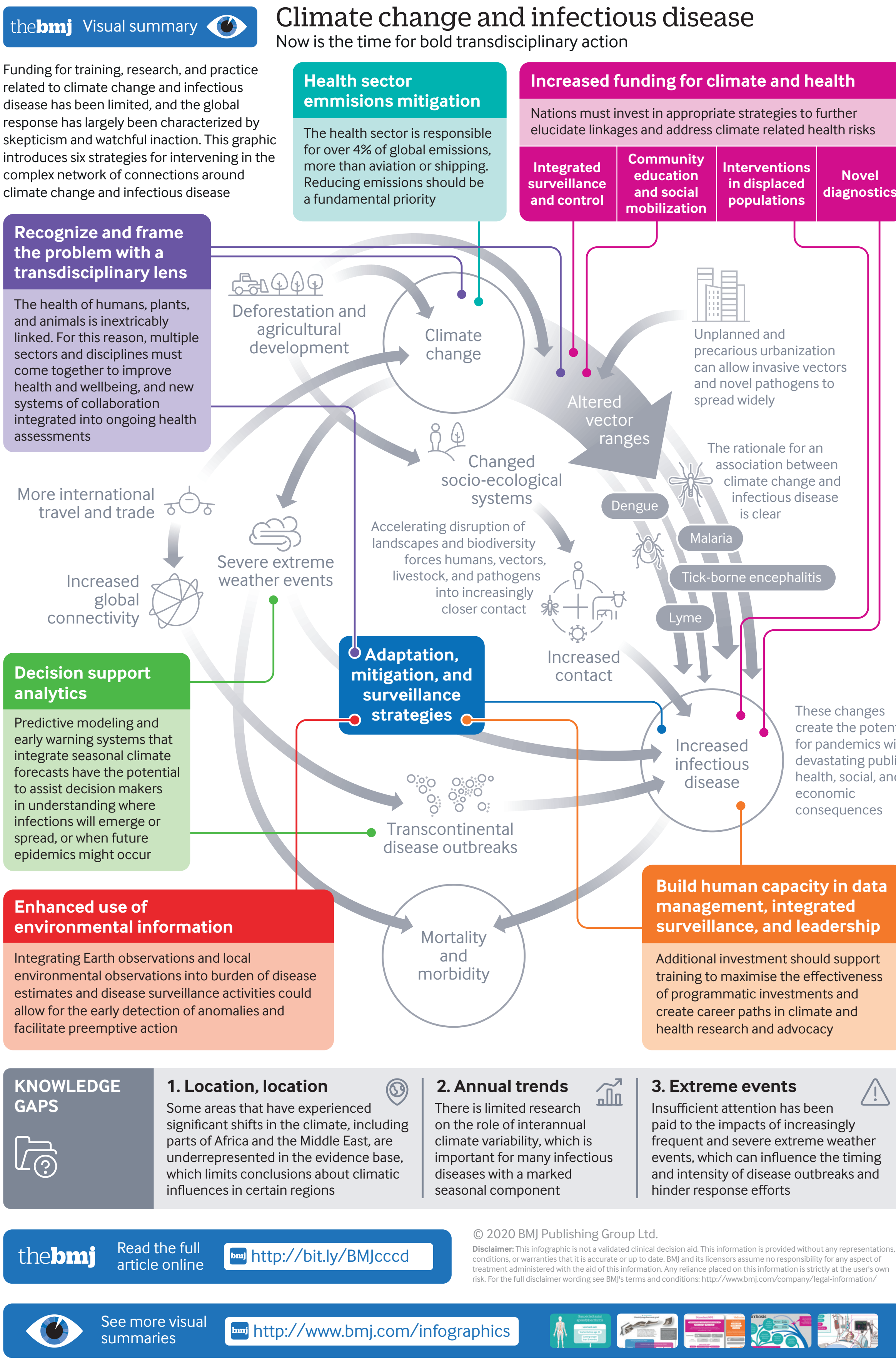
thebmj Visual summary
Climate change and infectious disease
Now is the time for bold transdisciplinary action
Funding for training, research, and practice related to climate change and infectious disease has been limited, and the global response has largely been characterized by skepticism and watchful inaction. This graphic introduces six strategies for intervening in the complex network of connections around climate change and infectious disease
Health sector emmisions mitigation
The health sector is responsible for over 4% of global emissions, more than aviation or shipping. Reducing emissions should be a fundamental priority
Increased funding for climate and health
Nations must invest in appropriate strategies to further elucidate linkages and address climate related health risks
Integrated surveillance and control
Community education and social mobilization
Interventions in displaced populations
Novel diagnostics
Recognize and frame the problem with a transdisciplinary lens
The health of humans, plants, and animals is inextricably linked. For this reason, multiple sectors and disciplines must come together to improve health and wellbeing, and new systems of collaboration integrated into ongoing health assessments
Deforestation and agricultural development
Climate change
Altered vector ranges
Unplanned and precarious urbanization can allow invasive vectors and novel pathogens to spread widely
Changed socio-ecological systems
The rationale for an association between climate change and infectious disease is clear
Dengue
Malaria
Tick-borne encephalitis
Lyme
More international travel and trade
Increased global connectivity
Severe extreme weather events
Accelerating disruption of landscapes and biodiversity forces humans, vectors, livestock, and pathogens into increasingly closer contact
Increased contact
Decision support analytics
Predictive modeling and early warning systems that integrate seasonal climate forecasts have the potential to assist decision makers in understanding where infections will emerge or spread, or when future epidemics might occur
Adaptation, mitigation, and surveillance strategies
Increased infectious disease
These changes create the potential for pandemics with devastating public health, social, and economic consequences
Transcontinental disease outbreaks
Enhanced use of environmental information
Integrating Earth observations and local environmental observations into burden of disease estimates and disease surveillance activities could allow for the early detection of anomalies and facilitate preemptive action
Mortality and morbidity
Build human capacity in data management, integrated surveillance, and leadership
Additional investment should support training to maximise the effectiveness of programmatic investments and create career paths in climate and health research and advocacy
KNOWLEDGE GAPS
1. Location, location
Some areas that have experienced significant shifts in the climate, including parts of Africa and the Middle East, are underrepresented in the evidence base, which limits conclusions about climatic influences in certain regions
2. Annual trends
There is limited research on the role of interannual climate variability, which is important for many infectious diseases with a marked seasonal component
3. Extreme events
Insufficient attention has been paid to the impacts of increasingly frequent and severe extreme weather events, which can influence the timing and intensity of disease outbreaks and hinder response efforts
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Tracking infectious diseases in a warming world

Using infectious diseases sensitive to climate as indicators of climate change helps stimulate and inform public health responses, write **Kris A Murray and colleagues**

In one of the first articles published by *The BMJ* on climate change, Haines in 1991 wrote: "Eight of the hottest 10 years this century have occurred since 1980."[1] Noting the influence of temperature on the life cycles of several vectors, hosts, and pathogens, Haines went on to question the implications of predicted climate change for many infectious diseases. It is discomforting that today, three decades later, circumstances have hardly changed, and that early forecasts have begun to ring true.[2,3] Eight of the 10 hottest years on record have now occurred since 2010[4]; associations between climate change and the burden, transmission, or distribution of many infectious diseases (principally caused by protozoan, helminth, vectorborne, foodborne, soilborne, and waterborne pathogens) are increasingly being reported[5]; the European Centre for Disease Prevention and Control (ECDC) now ranks climate among the most frequently implicated "drivers" of infectious disease threats[6]; and The World Health Organization now recognises climate change as one of the major health challenges of the 21st century.[7]

KEY RECOMMENDATIONS

- Development, standardization, and implementation of climate change and health indicators requires multidisciplinary research collaborations and major investment
- A systematic assessment of climate sensitive infectious diseases is required to prioritize diseases for tracking
- Standardized methodologies across diseases are needed with outcomes linked to trends in other sectors
- Indicator outputs should be accessible and translated into languages and formats for diverse audiences, co-designed with policy makers and users
- Scientific reports should be paired with policy briefings, engaging narrative, and creative outputs to maximize media coverage and policy engagement

In such a rapidly changing world, how can researchers, health professionals, and policy makers keep track of the risks and intervene accordingly? How can policy options be evaluated, particularly when aiming to achieve globally agreed sustainable development, environmental (including the Paris Agreement), and health management targets?[8,9]

One emerging strategy is the use of climate change "indicators," which aim to keep track of historical and future predicted trends in key impact areas related to climate change. Such indicators have taken on a range of functions, including quantifying and characterizing exposure, vulnerability, and risk for both populations and health systems, identifying and tracking key impacts on population health, and evaluating changes in adaptive capacity and resilience.[10] Indicator initiatives explicitly aim to go beyond the fractured and often inconsistent evidence base presented in the primary scientific literature to bring together or generate relevant information in some generally consistent fashion. They also tend to focus more specifically on the analysis of trends through time, often with an emphasis on accessible yet powerful data sharing and visualizations to stimulate action across sectors and track progress towards some predefined targets. Here we illustrate how "climate-sensitive infectious diseases" (CSIDs) are being used as climate change indicators to help stimulate and inform public health responses to climate change.

Climate change and health indicators

An example of a benchmark for the quantification and comparison of varying health outcomes is the Global Burden of Disease (GBD) programme.[11] This quantifies death and loss of health and wellbeing from hundreds of diseases and their risk factors, and is used to guide health surveillance and improve global health management policies. However, although the GBD programme estimates the global burden of several CSIDs, it does not capture some important but difficult to define health impacts, including from health inequalities or climate change.[12]

Several climate change indicator initiatives exist that seek to partially fill this gap. Indicator initiatives specifically targeting climate change and health are relatively recent but have been advocated for widely, with key efforts including examples from learned societies,[12] health authorities (eg, the US Centers for Disease Control and Prevention (CDC)[13]), other government agencies (eg, the US Environmental Protection Agency,[14] the European Environment Agency, and the forthcoming proposal for an EU observatory for climate change and health and the EU Adaptation Strategy planned for 2021[15]), funders (eg, Wellcome Trust[16]), and academic consortiums (eg, the Inter-Sectoral Impact Model Intercomparison Project[17] and the Lancet Countdown on Health and Climate Change[18]). Such indicator initiatives range in scale from local to global.

Where numerous indicator initiatives have tackled some of the more direct impacts of climate change on health or those for which greater volume and quality of data exist (eg, heat-related mortality), few indicators exist for more complex, indirect impact areas such as infectious diseases. For example, the CDC Tracking Network currently reports on flood and heat vulnerability trends but not infectious diseases.[13]

Global trends in climate sensitive infectious diseases

Current CSID indicators focus primarily on the climatic suitability or population vulnerability components of disease transmission risk, as opposed to case or burden data.

To illustrate, we briefly highlight some of our work as part of the Lancet Countdown on Health and Climate Change,[19] for which we have developed indicators to: (1) assess spatial and temporal trends in the environmental suitability for CSID transmission (for dengue, malaria, and pathogenic *Vibrio* bacteria); and (2) evaluate the changing basis of population vulnerability to arboviruses (ie, factoring in national characteristics that define their propensity to be adversely affected by infectious disease threats, such as public health measures).

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Briefly, indicator analyses for dengue, malaria, and pathogenic *Vibrio* bacteria show increases in the environmental suitability for disease transmission over past decades. For example, 2017 was the second most suitable year on record for the transmission of dengue virus, with average increases of 7.2% and 9.8% in vectorial capacity observed in the past five years compared with a 1950s baseline for the key vectors *Aedes aegypti* and *A albopictus*, respectively (fig 1). Despite these increases, country level vulnerability to dengue outbreaks (ie, exposure to mosquitoes after controlling for the presence of disease-relevant public health measures) has decreased globally by 31% since 2010, although some regions remain more vulnerable than others and progress has reversed in these regions in recent years (fig 2). The number of suitable months per year for the transmission of malaria (*Plasmodium falciparum*) in the African highlands has increased by 29.9% in the past five years compared to a 1950s baseline. By contrast, other regions do not show an increasing trend for malaria, potentially due to some areas (eg, lowlands) becoming too warm or experiencing shifts away from the combinations of temperature, rainfall, and humidity that enhance transmission (fig 3). For waterborne diseases caused by pathogenic *Vibrio* bacteria, similarly strong increases in the percentage of coastal area suitable for transmission are observed at northern latitudes (40-70° N) (fig 4 top), in the Baltic Sea (fig 4 middle) and along the north east coast of the United States (fig 4 bottom). The number of days per year suitable for *Vibrio* in the Baltic reached 107 in 2018, double the early 1980s baseline (fig 4 middle).

Challenges

Each CSID indicator aims to capture environmental suitability of disease transmission by mathematically linking preferred conditions for transmission with climate input data. This allows the long term assessment of how environmental suitability for disease transmission has changed in recent decades, providing an initial step towards the attribution of disease risk to anthropogenic climate change.

Attribution of the underlying climate trends to human greenhouse gas emissions is highly robust[20]; however, it remains difficult to isolate the specific fraction of observed cases of each disease to climate change at large spatial scales given the range of other environmental and socioeconomic covariates at play. These include health inequality (ie, potential for the population to be harmed by a disease due to differential access to healthcare), land use, biodiversity, urbanization, travel and tourism, and global trade. Many of these factors are themselves influenced by climate change and exhibit strong spatial and temporal heterogeneities, illustrating the depth of the complexity of resolving realized climate change impacts on CSID burdens at continental or global scales.[21]

In addition, this set of indicators comprises several different methods (eg, threshold based, mechanistic, correlative models), datasets (eg, baseline gridded climate data), metrics (eg, percentage change versus raw change in suitability, indices of environmental suitability versus specific metrics such as vectorial capacity), and temporal windows (eg, baseline period, length of time series).

Different methods reflect the project's participatory, in kind, reformulation approach. However, a more systematic effort is needed to prioritize formally and objectively which diseases should be tracked, to develop standardized methodologies across diseases when possible, and to link outcomes to trends in other sectors, such as food security and access to healthcare, for a range of downstream uses.

Data sharing, use, and public health application

A wide range of public health stakeholders, ranging from the Global Climate and Health Alliance to the International Council of Nurses and the Royal College of Physicians, are increasingly engaged in climate change as a health issue. These professionals depend on both the generation of new medical evidence to drive this agenda forward, and the presentation of evidence in a way that they readily understand and can

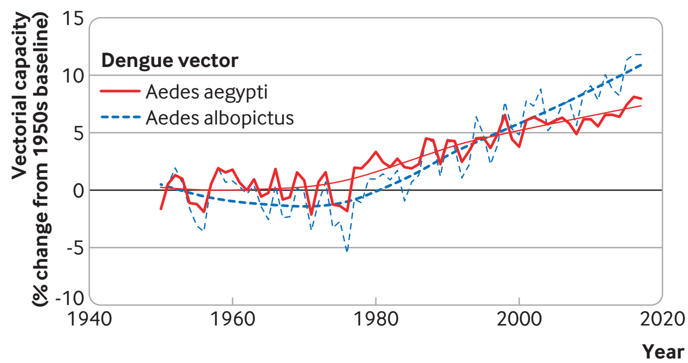

Fig 1 | Mathematical models of dengue vectorial capacity for *A aegypti* and *A albopictus* mosquitoes reveal temporal changes in the potential for dengue transmission due to a warming climate since 1950.

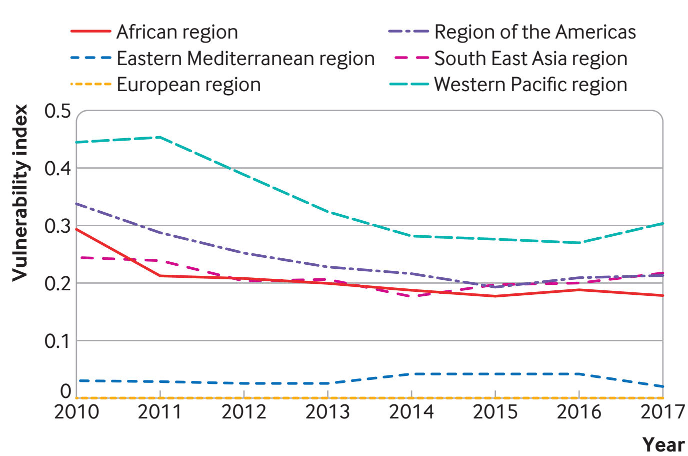

Fig 2 | Despite the increases in environmental suitability for dengue shown in fig 1, improved public health measures have on average lowered vulnerability to dengue outbreaks across most regions since 2010, although some recent reversals in this trend are observed in the more vulnerable regions.

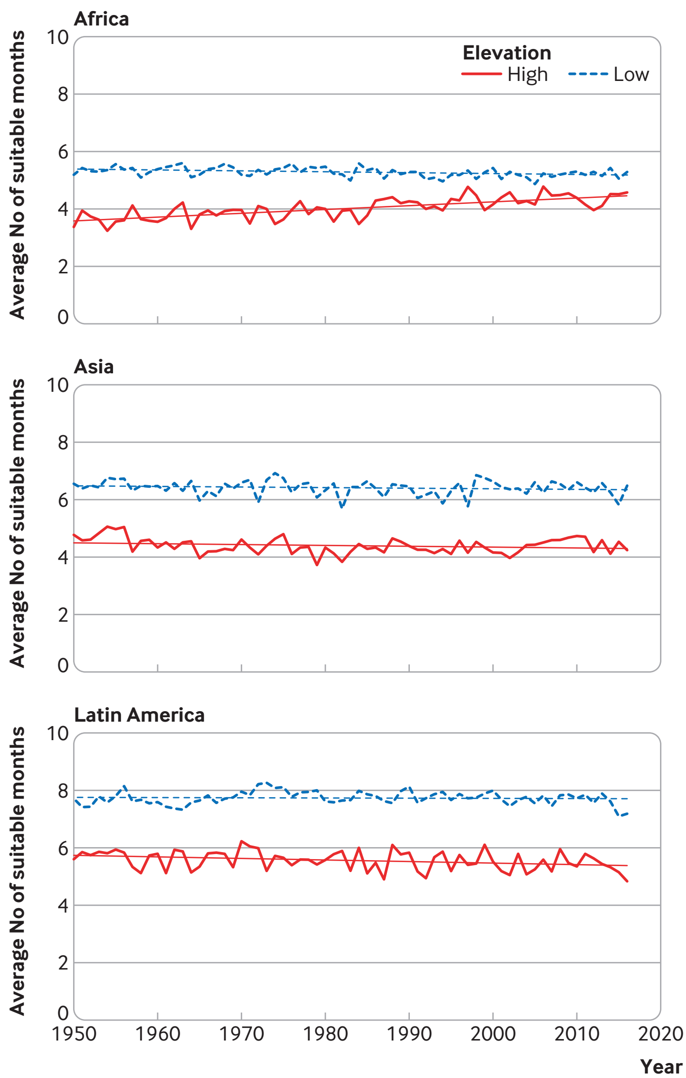

Fig 3 | The number of suitable months a year for malaria transmission during the period 1950-2017, as determined by combinations of temperature, rainfall, and humidity, are increasing predominantly in the African highlands (ie, elevation >=1500 m). No change or subtle declines in environmental suitability are observed in other regions.

amplify to help drive both mitigation (eg, actions to reduce greenhouse gas emissions of healthcare infrastructure and services) and adaptation strategies (eg, identifying CSID hotspots, designing surveillance networks, early warning systems) to prepare for the changing risks from CSIDs to reduce their impacts.

Improving access to robust climate change risk assessments for health exposures and outcomes allows users to explore and appreciate the spatial and temporal heterogeneities in climate-related health risks relevant to local and coordinated management. For instance, the Lancet Countdown CSID indicators can be explored through an online visualization platform[18] to highlight geographic areas that may be experiencing increases or decreases in disease risk, identify locations that require more research for a more accurate understanding of CSID risk, or highlight human populations where inequity gaps require urgent intervention to reduce their vulnerability to emerging climate change related public health threats. Accessible data sharing platforms provide a powerful avenue for users to visualize and interact with data, to appreciate the current situation in the context of the longer term trajectory, and to evaluate the growing momentum of certain trends through time and the often invisible build-up towards potential health crises. They also highlight the potential downstream impacts that greenhouse gas emissions today could have on health outcomes in the future.

Furthermore, given the scale and pace of the challenge that climate change presents, CSID indicator outputs must be paired with dedicated efforts to ensure they are translated into languages and formats that a wide range of audiences understand, ideally co-designed with policy makers and potential users. The development of an extensive network of policy and research partners is necessary to link key health bodies (eg, World Health Assembly, the World Health Summit, and the United Nations Framework Convention on Climate Change's decision making body) with health scientists and practitioners. Similarly, scientific literature must be paired with policy briefings, engaging narrative, and creative outputs if it is to engage across disciplines and help to draw out the local media and policy stories that may otherwise be hidden (for examples, see Lancet Countdown[22]).

Collaborations and investment

Climate change is increasingly being recognized as a public health emergency.[23] Health risks and impacts will continue to grow unless the global community raises its collective ambition to meet the Paris Agreement, which aims to keep the world below 2°C warming, and preferably below 1.5°C.[24] This goal, however, requires evidence-based, transformative, and immediate action to curb greenhouse gas emissions.

While monitoring changes in climate under the Paris Agreement is crucial, equally important is the monitoring of potential health risks related to climate change. Better data for tracking infectious disease in a warming world requires a robust evidence base, recogniing that the challenges posed by climate change to health are substantial in size, complexity, and scope.

Initiatives to track the impacts of climate change (including increased variability in extreme events) and the effects of adaptation efforts on CSIDs have recently emerged to meet this challenge. The development and implementation of indicators calls for international, multidisciplinary research collaborations dedicated to monitoring, analysing, anticipating, and communicating the links between climate change and health across the world.

Greater investment is required to help such initiatives realize their full potential to accurately identify the contribution of climatic drivers of infectious disease risk across space and time. In turn,

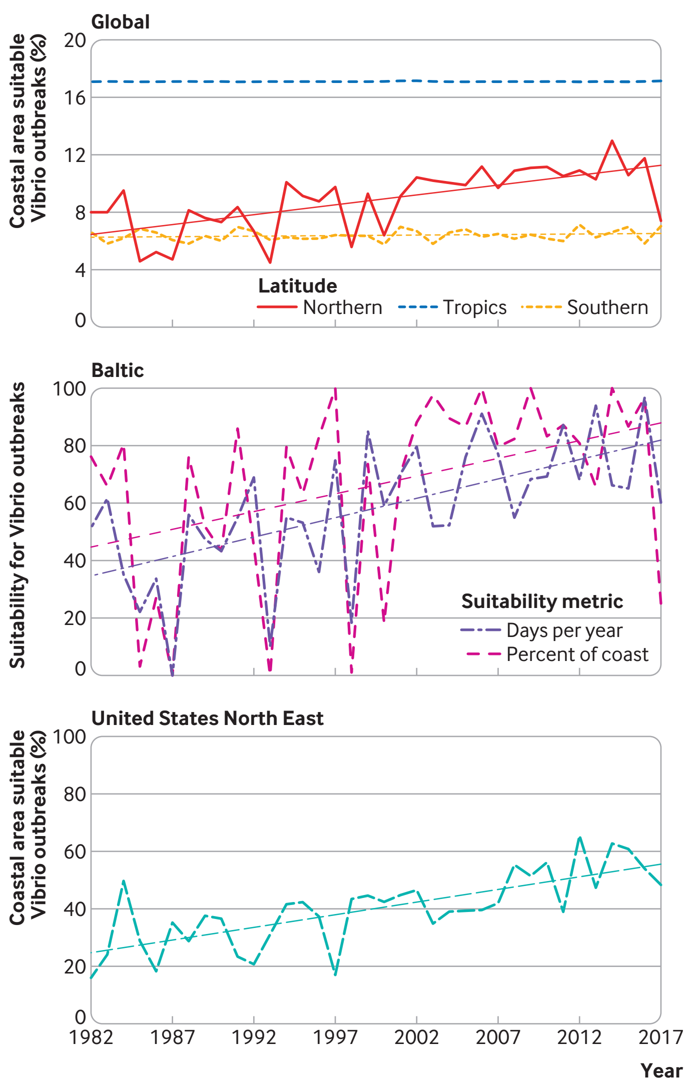

Fig 4 | Change in environmental suitability for pathogenic *Vibrio* outbreaks as determined by observed correlations with sea surface temperatures and ocean salinity. This model suggests that suitability is increasing predominantly in the northern hemisphere (top; northern latitudes=40-70°N; tropical latitudes=25°S-40°N; southern latitudes=25-40°S). More detailed analysis by regions shows, for example, that the Baltic Sea (middle) and the United States north east coast (bottom) are also increasingly suitable for *Vibrio* outbreaks due to climate change. For details on methodology and expanded interpretations, see the Lancet Countdown on Health and Climate Change[19]).

identification and dissemination of climate-disease trends will signpost researchers, policy makers, health professionals, and the general public towards more informed, pre-emptive mitigation and adaptation actions to guide public health practice to an accelerated response to what has been termed by WHO as the "greatest global health threat of the 21st century."[7]

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Scaling up cross border cooperation to tackle climate and disease threats

Examples of effective forums already exist in the Middle East, finds **Ingrid Torjesen**. Replication and expansion will be needed to tackle looming health threats

Climate change and infectious diseases do not respect borders, and tackling the threats they present requires dialogue, cooperation, and collaborative working. The challenges this poses cannot be underestimated in a region like the Middle East, beset by political differences, a long history of conflict, and huge displaced populations. The region is one of the most vulnerable in the world to the effects of climate change, and it is already experiencing temperature rises, reduced rainfall, and increasingly arid conditions.

These conditions have contributed to the recent surge of vectorborne diseases such as leishmaniasis, the re-emergence of West Nile fever, and the rise in foodborne diseases such as salmonellosis in the region. To tackle these, and emerging communicable diseases such covid-19 and Middle East respiratory syndrome (MERS), requires data sharing and cooperation among researchers and governments across political borders. Various diplomatic bridges exist, but these will have to be expanded and replicated. One long standing initiative is the Middle East Consortium for Infectious Disease Surveillance (MECIDS). It was established in 2003, with funding and support from the Nuclear Threat Initiative, a US non-governmental organization.

The aim of MECIDS is to improve laboratory capacity and infectious disease control among three neighbouring territories: Israel, Jordan, and the Palestinian National Authority. It was prompted by the World Health Organization's revision to the International Health Regulations, which set rules for improving communication between WHO and member states and mandated that every country have the laboratory capacity to rapidly identify outbreaks,[1] and to improve biosecurity after the 11 September 2001 attacks, to enable rapid response to intentional misuse of a pathogen.

Israel is considered part of WHO's European region rather than the Eastern Mediterranean region, and opportunities for dialogue between the three governments through WHO were limited. The consortium set out to develop dialogue among academia and the health ministries of the three partners on infectious disease surveillance. It created a channel for the exchange of information and a way to respond rapidly in the event of an emerging situation, such as the 2009 flu pandemic and outbreaks of severe acute respiratory syndrome (SARS) or MERS.

Salmonellosis as prototype infection

The consortium has developed a continuous surveillance system for foodborne diseases, which can easily be transmitted across borders through the exchange of food and displaced populations, for which salmonellosis was the prototype infection. Each of the three territories has a network of sentinel laboratories feeding into one of three central reference laboratories and data analysis units, and in turn these feed into a regional data analysis unit in Jordan.[2] The consortium is also increasing surveillance of resurging vectorborne diseases, such as leishmaniasis and West Nile fever.

Climate change is raising the incidence of all these infectious diseases. As temperatures rise, food spoils and bacteria multiply faster, and there have been increases in the populations of sand fly, mosquito, migratory bird, and rodent vectors.

MECIDS also provides training and networking opportunities for epidemiologists and laboratory technicians through summer schools and virtual events to build capacity and collaboration among the workforce. It claims its success in this challenging political environment is down to the involvement of both academia and the three territories' health ministries, so that it had the power to bring real change.

Models in Africa and Asia

The model has been extended and copied to other regions with political tensions and conflict, such as the Balkans and in Africa and Asia. This has been enabled through Connecting Organisations for Regional Disease Surveillance, an overarching organization also set up with the support of the Nuclear Threat Initiative and currently part of Ending Pandemics, a non-governmental organization aiming to find and stop pandemics before they spread.

In future MECIDS hopes to work with other neighbouring countries, perhaps including more permanent partners. Many other organizations are keen to enable more cooperation in the region to tackle common environmental and health threats.

The Gulf Cooperation Council, a forum of Arab states, is conversing on health security, infectious diseases, environmental health, and climate change—as well as how to shift Gulf economies from high to low carbon and towards more sustainable development.

The World Bank's stated aim is global poverty reduction and it funds projects at the nexus of climate change and infectious disease. Campaigners lambast it for continuing to subsidize fossil fuel extraction despite the bank screening all potential projects as part of its Climate Change Action Plan.[3]

More than 10 years ago the bank helped establish a platform to promote health policy dialogue and health system strengthening across the region—the MENA Health Policy Forum. Its initial focus was on health governance, service delivery, and quality of care, and it also has a keen interest in climate change and infectious diseases. The World Bank has tools that could be used to assess vulnerability at country level to the impact of climate change on health projections and health systems, which it has offered to the forum. These tools could highlight synergies between countries that regional level projects could target.

The World Bank says that its initiatives in Africa could be replicated in the Middle East and North Africa. These include the Africa Centres for Disease Control and Prevention, which focus on strengthening regional and continental infectious disease detection and response systems for public health emergency with cross border or regional implications. It is mandated to deploy responders in consultation with affected member states.

Another initiative is the Regional Disease Surveillance Systems Enhancement, which strengthens national and regional capacity for collaborative disease surveillance and epidemic preparedness in West Africa, including data sharing and an early warning system for outbreaks.

"Every country and every region must act in concert"

"The global covid-19 pandemic is a powerful reminder that we must look at evolving scientific data to make informed policy and program decisions, and we must act in open, collaborative, and constructive ways across borders. If not, the results can be catastrophic," physician and public health administrator Margaret Hamburg told *The BMJ*. She is former foreign secretary of the US National Academy of Medicine and the immediate past board chair and president of the American Association for the Advancement of Science, and she sits on the board of the non-governmental organization that established the Middle East Consortium for Infectious Disease Surveillance in 2004.

She continued, "Climate change—and it's widespread implications, including for health—represents an even more devastating 'pandemic in slow-motion.' Now is the time to take it seriously, and every country and every region must act in concert, knowing that we are all in this together."

Tamer Rabie, lead health specialist at the World Bank's health, nutrition, and population global practice, told *The BMJ*: "Climate change can act as a stress multiplier to the security situation in the [Middle East] region, adding additional pressures on already scarce resources. The region presents a unique context that requires efforts to establish how we can work across countries without necessarily getting involved in political and security issues."

MECIDS is "a ready made prime example" of the type of initiative that can work in the Middle East, he points out. "You could not have a worse political situation but Israel, Jordan, and the Palestinian Authority are working together."

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Better data are crucial for mitigating threats in the Middle East

Conflict and migration may compound harms from climate sensitive infectious disease in the Eastern Mediterranean and Middle East region. **Shlomit Paz**, **Azeem Majeed**, and **George K Christophides** suggest routes to mitigation

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The Eastern Mediterranean and Middle East region is characterized by rapid population growth, large differences in socioeconomic levels among countries, mass migration, increased water demands, and ecosystem degradation.[1] The recent spread of covid-19 highlights unpreparedness in the region, and some countries in particular, for infectious disease outbreaks.

While several rich countries (mainly the Gulf states) are the source of much of the carbon driving climate change, the whole region is experiencing a drier climate, longer and hotter summers, and more frequent and severe heat waves.[2] It is known that climate change may aggravate existing regional sociopolitical disputes. For example, severe drought and economic deterioration related to climate change were key contributors to displacement of people, food insecurity, and political instability in the Syrian war.[3] These diverse factors interact in complex ways, which may increase risks for infectious disease epidemics.[4]

Threats and potential threats

Several vectorborne diseases sensitive to climatic variations are common in different parts of the region, depending on local conditions, while others are a potential threat, including West Nile virus, Rift Valley fever, dengue, chikungunya, malaria, leishmaniasis, cholera, and leptospirosis.[5-7] Climate change also increases risk of foodborne and waterborne diseases prevalent in the region, such as gastroenteritis, including Salmonella spp.[8]

Reliable data are essential for targeting prevention measures—for example, test, trace, and isolate policies for containing the current covid-19 outbreak. Large parts of the region lack consistently available, reliable, and systematic data about infectious diseases as well as scientific knowledge about the impact of climate change on outbreaks and transmission.

Future scenarios predict that the region will be warmer and dryer, and climate change is projected to have a greater effect on the transmission of infectious diseases.[2 5] Risk assessment and health preparedness and adaptation strategies are essential. Better vector surveillance is needed in each country. Systematic collection of epidemiological data not only in urban environments but also in poorer and remote areas should be a priority.

Experience from Europe shows that regional cooperation is crucial to tackling infectious disease threats. For example, VectorNet is a European network for sharing data on the geographic distribution of arthropod vectors.[9] In parts of the Eastern Mediterranean and Middle East, conflicts limit cross border relationships. Nevertheless, collaboration should be a priority for national health agencies, even for countries lacking diplomatic relations. Such initiatives already exist, for example, the Middle East Consortium on Infectious Disease Surveillance (MECIDS) frameworks that operates across Israel, Jordan, and the Palestinian Authority, and the Cyprus government initiative for coordinating climate change actions in the region, spearheaded by the Cyprus Institute.

Refugee camps

People in refugee camps are at high risk of infectious disease outbreaks, such as cholera and covid-19, which can spread further. Provision of clean water and wastewater management, disease surveillance, and vaccination programs should be prioritized.

National health authorities should improve access to public health interventions and healthcare for vulnerable populations. Public awareness of behavior change should be strengthened with education through local media, community leaders, and health workers. For example, the risk of outbreaks of vectorborne disease could be reduced through community driven elimination of small breeding sites.

Without effective interventions and cross-border cooperation the changing climate will continue to impact on increased level of morbidity and mortality resulted from infectious diseases in the region, with the most vulnerable groups in society at greatest risk.

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Schistosomiasis and climate change

Giulio A De Leo and colleagues consider the effect of changing climates and human activity on schistosomiasis transmission and potential solutions to contain its spread

In 2014, a group of German and French tourists with no history of travel to tropical or subtropical countries were diagnosed with urogenital schistosomiasis, a debilitating parasitic disease that affects more than 200 million people in South America, Asia, and particularly sub-Saharan Africa. The European Centre for Disease Prevention and Control eventually tracked 120 cases of *Schistosoma* infection that were acquired in summer 2013 (and seven more, between 2015 and 2016) by people swimming in the Cavu River in Corsica. This French Mediterranean island is a popular summer destination for tourists from all over Europe. Until then, Corsica had been considered outside the geographic range of schistosomiasis transmission because of the near freezing temperatures of inland waters in the winter.

Genetic analyses showed that the parasites isolated in Corsica originated in the lower basin of the Senegal River, where schistosomiasis is hyperendemic. Its temporary establishment on Corsica was thought to have been caused by human movement and subsequent contamination of the river by parasite eggs that established locally in susceptible intermediate host snails and circulated for several seasons.[1] Interruption of disease transmission during Corsica's cold winters probably contributed to the natural gradual death of the parasite, and no cases of human schistosomiasis have been reported in the island since 2017. However, a small and short outbreak in this new territory raises concerns about the potential expansion of the range of schistosomiasis as the world becomes warmer.

Schistosomiasis is a tropical and subtropical disease (fig 1) caused by infection with parasitic blood flukes of the genus *Schistosoma* (fig 2), which use freshwater snails as necessary intermediate hosts. The schistosomiasis pathology results mainly from inflammatory processes caused by parasites' eggs in the human body, which may lead to several conditions such as abdominal pain, diarrhea, chronic anemia, cognitive impairment in children, growth stunting, infertility, a higher risk of contracting HIV in women, and death from liver failure or bladder cancer in cases of intense and chronic infection. These effects, combined with poverty and a lack of access to clean water, improved sanitation and hygiene make schistosomiasis one of the world's most important, but also most neglected, human diseases. The intermediate host snails of schistosome parasites are poikilotherm—that is, their body temperature changes depending on the environment. As a result, reproduction, survival, and dispersal are strongly influenced by ambient temperature, as is parasite development inside the snail. Therefore, rising water temperatures and altered precipitation associated with climate change could considerably alter the distribution and abundance of the intermediate host snail and its schistosome parasites, resulting in a shift in disease dynamics and transmission to people. Assessing the impact of global warming and its compounded effect with change in land use are important challenges that will face global health soon.

Predicting the effect of global climate change on schistosomiasis is a complex task,[2,3] because how the disease responds to climate varies with the specific ecology of many different snails and parasite species (table 1) as well as the geographic context that may respond differently to rising temperatures and changes in precipitation (fig 1). We discuss potential effects of climate change on schistosomiasis, its interactions with other determinants of disease transmission, and considerations for schistosomiasis control and elimination in a changing world.

KEY RECOMMENDATIONS

- Invest in research to better understand the likely spread of schistosomiasis with climate change
- Establish integrated surveillance-response systems in areas at risk
- Increase control strategies, medical treatment, and environmental interventions in endemic regions
- Ensure dams allow prawns to move along the river
- Control fertilizer and pesticide use in endemic areas

Africa

The past decade has seen increasing attention paid to the effects of climate change on schistosomiasis in Africa, where an estimated 90% of all human cases are concentrated. Whereas some studies predict that schistosomiasis infection risk may increase by up to 20% in eastern Africa,[3] others present a more complex pathogenic landscape, with decreases as well as increases in schistosomiasis transmission risk.[2,4] For example, a continental scale study predicted a 14% reduction in the total geographic area suitable for *Schistosoma mansoni* transmission in sub-Saharan Africa in 2061-2080 (fig 3a) as temperatures exceed the maximum thermal tolerance for the main intermediate host snail, *Biomphalaria pfeifferi*.[5] However, the same study also showed that other known intermediate host snail species tolerate increasing temperatures better, highlighting the importance of specific snail-parasite ecologies when developing prediction models.[5]

A similar modeling approach was used to map the predicted change in risk of *S. haematobium* for 2021-2050.[6] The model highlighted potential emerging, as well as contracting, areas in Africa, the Middle East, and southern parts of Europe (fig 3b). A different approach based on data from laboratory and field experiments was used to develop a simulation model to predict the effect of rising temperatures on *S haematobium* and its intermediate host snail *Bulinusglobosus*.[7] This model predicted that snail abundance and production of cercariae—the free living stage of the parasite shed by infected snails—may decrease by up to 14% and 8%, respectively, for each 1°C rise in ambient temperature. These results agree with the findings of other studies that suitable places for *S haematobium* in Africa near the equator will decrease under future climatic conditions.[2]

Yet concern is growing that urogenital schistosomiasis may further expand into areas with colder climates, such as South Africa and the Ethiopian highlands, where the presence of the suitable snail species, lack of access to clean water, and limited or no active surveillance may put an immunologically naive population at

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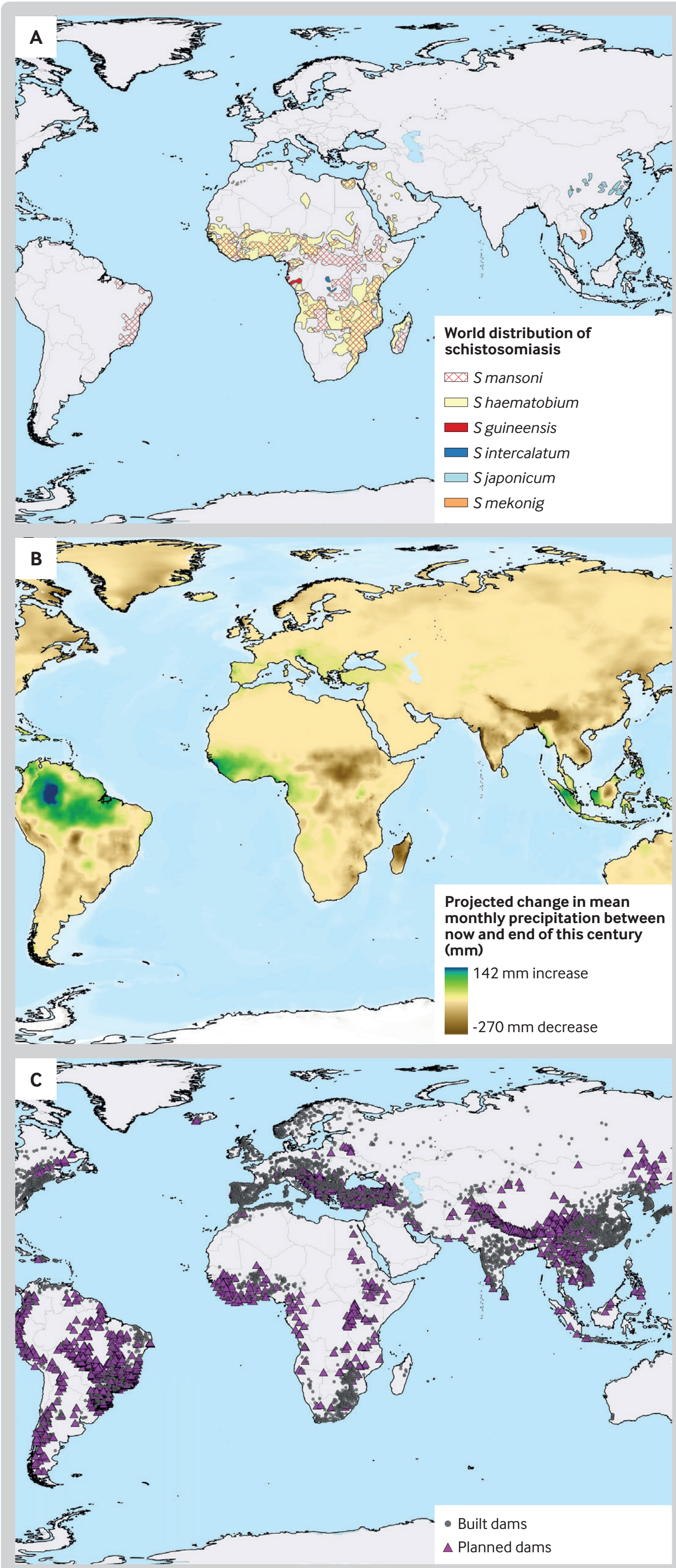

Fig 1 | a) World distribution of schistosomiasis (data from http://www.thiswormyworld.org); b) Projected precipitation changes to the end of the 21st century, under the high greenhouse gas emission scenario CMIP6 model BCC-CSM2-MR, ssp 585, from https://www.worldclim.org ("business as usual"); c) Built and planned dams, 2020-2028 (http://globaldamwatch.org/fhred/)

risk of infection. Given that many sub-Saharan African countries have limited capacity to adapt to the negative effects of climate change, increased investment in schistosomiasis surveillance and control is a public health priority.

Asia

S japonicum occurs in China, the Philippines, and the Indonesian island of Celebes. Unlike the schistosome parasites in the African continent, *S japonicum* is transmitted through a unique amphibian snail intermediate host, *Oncomelania hupensis*. Adult parasites can inhabit more than 40 vertebrate definitive hosts, including cattle, goats, water buffalo, and many rodent species; this many reservoir hosts makes control and elimination of schistosomiasis difficult.

Historical data suggest that average monthly temperatures below 0°C have prevented northward spread of *O hupensis*, but climate change is already altering the geographic distribution of schistosomiasis. A study in China found that the 0-1°C isothermal zone moved from latitude 33°15′ N to 33°41′ N between the 1960s and 1990s, corresponding to a 48 km northward shift in just 30 years.[8] This shift increased the potential schistosomiasis transmission area by over 40 000 km^2 with an additional 20.7 million people at risk of infection.

A new transmission risk index has been proposed based on growing degree days for parasites and the snail intermediate host,[9] which suggests that *S japanicum* transmission areas may increase by 662 373 km^2 by 2030 and by 783 883 km^2 by 2050 (fig 4). Recent analyses, based on projections from five global circulation models and representative concentration pathway 4.5 scenario in the fifth assessment report of the Intergovernmental Panel on Climate Change, confirmed future northern expansion of schistosomiasis in China by 2100.[6] At the same time, these analyses also suggested that the mountainous regions of Sichuan province, where schistosomiasis is currently prevalent, would become unsuitable for snail breeding, thus reducing transmission. However, the areas of the Yangtze River from Sichuan to Hunan and Hubei provinces, a stretch of river affected by the Three Gorges Dam, will still be favorable for snail survival.[6]

Climate change is also predicted to increase the frequency of extreme climate events, such as droughts, which might reduce the transmission season

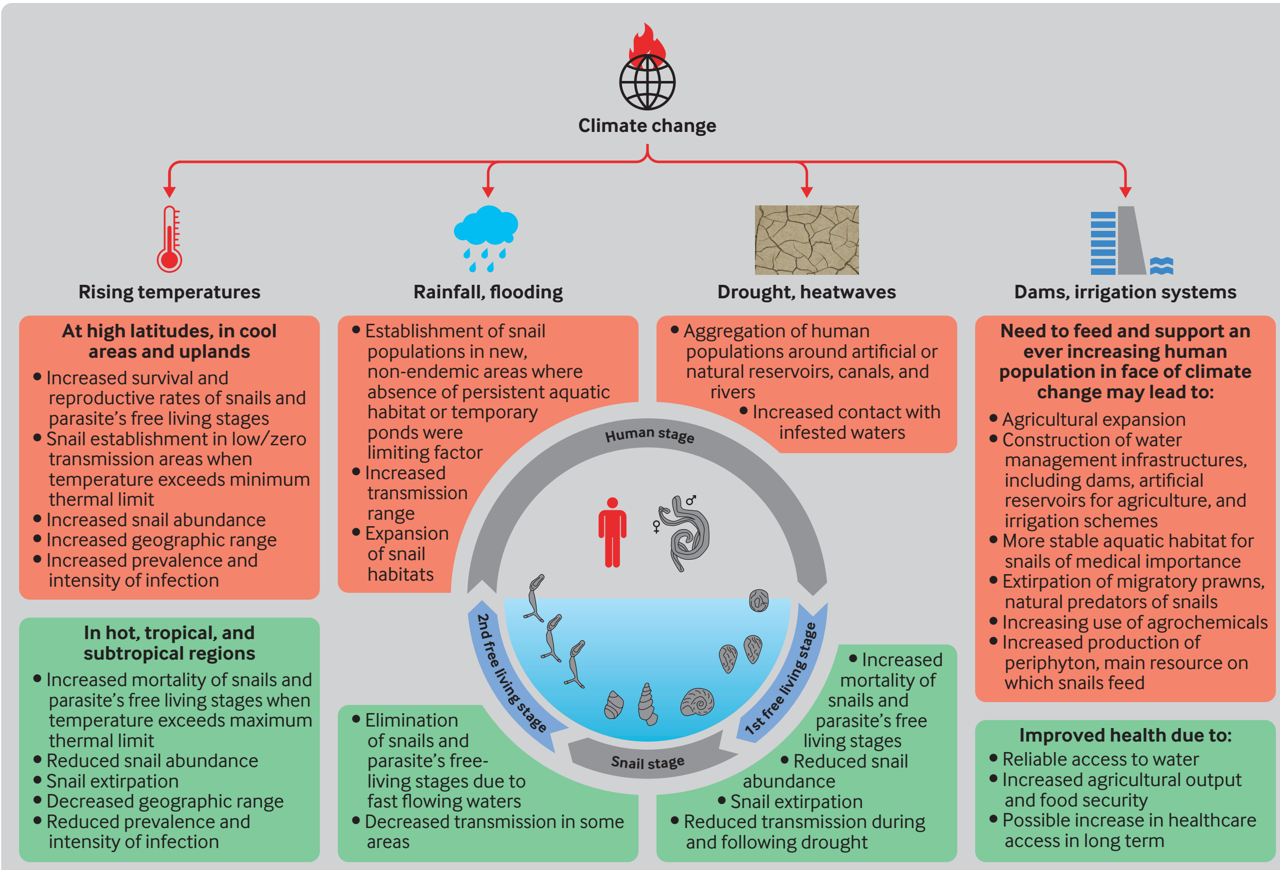

Fig 2 | Schistosomiasis life cycle (central panel) and pathways by which climate change, land use change, agricultural expansion, and development of water management infrastructure may affect disease transmission and human health. The red panels indicate an expected increase in transmission risk for schistosomiasis. The green panels indicate an expected decrease in transmission risk

for schistosomiasis, but also floods, which can locally help the spread of *O hupensis* snails.[10] To track changes in transmission risk for schistosomiasis in China, it will be important to establish early warning systems that report changes in the distribution of the intermediate snail host and possible new cases of human infection.[11]

The Americas

Few studies have examined the effect of climate change on schistosomiasis in the American region. Schistosomiasis is endemic to several territories, including Brazil, Dominican Republic, Guadeloupe, Saint Lucia, Suriname, and Venezuela. Most current schistosomiasis infections in the region occur in Brazil, one of the largest tropical countries, the leading dam building nation, and one of the largest agricultural producers in the region.

Climate change is predicted to be particularly severe in some parts of Brazil, including desertification and warming in the northeast of the country,[12] where schistosomiasis is endemic. Brazil's most populous areas, in the south east, are on the edge of the climate suitability range for the main intermediate host snails, so it is unclear whether more warming in this region could expand the habitat suitable for schistosomiasis transmission.[13]

Finally, schistosomiasis is traditionally considered a rural disease, but Brazil has many pockets of "urban schistosomiasis,"[14] where population growth has outpaced the ability of development to supply safe water and sanitation. This situation has created a complicated situation where poverty, development, land use, and climate change act together to influence transmission.

Ecological and socioeconomic determinants

The development and management of the infrastructure for water resources, such as dams and canals for hydropower generation, agricultural irrigation, and drinking water, will be important components of society's response to fight climate change and the associated potential water scarcity. Yet, these changes in land use can also increase the risk for schistosomiasis transmission. For instance, to lessen increas-

Table 1 | Geographic distribution of schistosomiasis and associated parasite and snail species

Disease	Parasite species	Snail species	Geographic distribution
Urogenital schistosomiasis	*Schistosoma haematobium*	*Bulinus* spp	Africa, Middle East, Corsica (France)
Intestinal schistosomiasis	*S mansoni*	*Biomphalaria* spp	Africa, Middle East, Caribbean, and Brazil, Suriname, and Venezuela
	S mekongi	*Neotricula aperta*	Several districts of Cambodia and Laos
	S guineensis; S intercalatum	*Bulinus* spp	Rainforest areas of Central Africa
	S japonicum	*Oncomelania hupensis*	China, Indonesia, Philippines

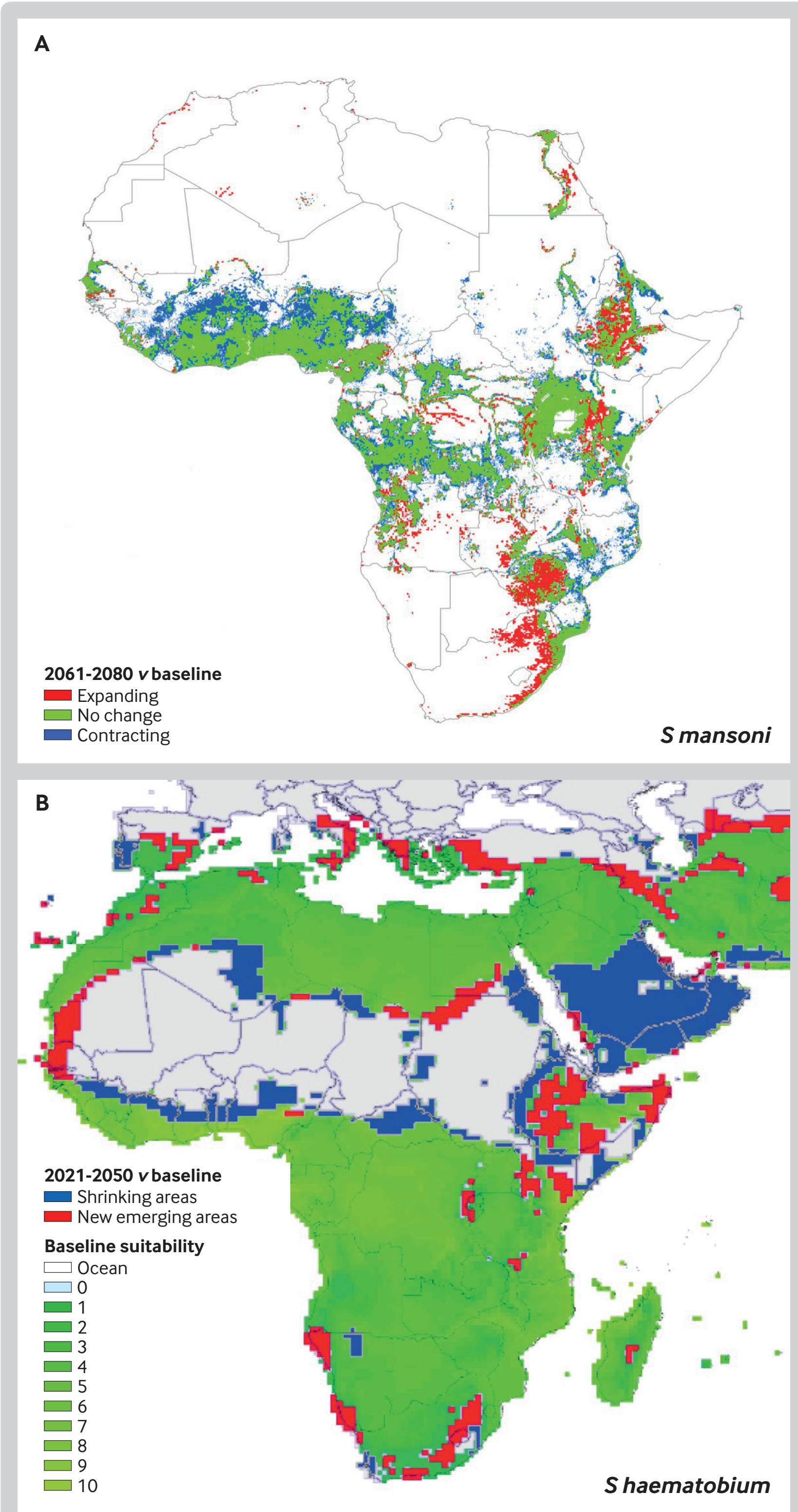

Fig 3 | Top panel: Predicted changes in the risk area for intestinal schistosomiasis transmission in 2061-2080 compared with present baseline in Africa. Blue color indicates predicted shrinking areas as the temperature becomes unsuitable for the intermediate host *Biomphalaria pfeifferi* (adapted from Stensgaard et al).[5] Bottom: Predicted changes in risk area for urogenital schistosomiasis in 2021-2050 compared with present baseline in Africa and Middle East. Suitability ranges from zero (not suitable conditions) to 10 (most suitable). Blue color indicates shrinking areas for schistosomiasis as the temperature becomes unsuitable for the parasite to persist (modified from Yang and Bergquist).[6]

ingly recurrent droughts in the northern part of China, the South North Water Transfer project has diverted water from the Yangtze River, the current schistosomiasis endemic region, to northern regions, thus increasing the risk of spread of *O hupensis* northward.[8]

Dams affect schistosomiasis transmission in many ways (fig 1). More stable water reservoirs inevitably lead to an increase in suitable snail habitat.[15] These reservoirs also support growing human settlements and foster expansion of irrigated agriculture and use of fertilizers and herbicides, which have also been shown to increase snail proliferation.[16] Dams not only change the habitat for the snails, but also have been shown to block migratory predators[17] that have historically kept snail populations in check. The history of the Diama dam in Senegal is a typical example. The dam was built in response to a climatic stress, a severe drought in the western Sahel region in the 1970s. In response, the countries of the region constructed a dam near the mouth of the Senegal River to stabilize flow, prevent saltwater intrusion, support agricultural development, and protect the availability of freshwater for communities. Within a few years of completion of the dam in 1986, and as a result of its construction, the landscape had changed substantially, the African river prawn—an effective predator of aquatic snails—had been wiped out, and schistosomiasis transmission had increased so that the lower basin of the Senegal river has become one of the most important regions of the world for schistosomiasis transmission.

Recommendations

In summary, schistosomiasis transmission is expected to decrease in central areas of its current climatic location (that is, tropical Africa), because temperatures will exceed the critical thermal maximum of snails as a result of climate change. Transmission is expected to increase at the margins of the cooler range, where temperatures are currently too low for transmission. Climate change is also expected to affect risk of transmission indirectly through interactions with poverty and rural subsistence livelihoods,[18] lack of sewage systems, lack of access to clean water and improved sanitation, lack of affordable healthcare, increasing human movement, dam development, and agricultural expansion.

Therefore, the effect of climate change on schistosomiasis can combine with the effects from land use changes, growing

Fig 4 | Areas of potential expansion of schistosomiasis (in red) in China, where schistosomiasis is expected to emerge as a result of climate change, and areas where it is currently endemic (in green), elaborated from Zhou et al[9]

human population, and subsistence livelihoods in unexpected ways. We need new research to reduce the uncertainty associated with potential shifts in the range of schistosomiasis with climate change. While addressing key research questions on climate change and schistosomiasis, decision makers, public health agencies, non-governmental organizations, and communities have several options to prepare for expected shifts in distribution of schistosomiasis caused by the compounded effect of climate and changes in land use.

Integrated surveillance and response systems need to be established in areas where models predict a high likelihood of schistosomiasis becoming endemic. Control strategies, including medical treatment and environmental interventions,[19] should be improved in endemic regions where transmission is expected to increase because of climate change, construction of new dams, or agricultural expansion.

Dams built in the historical range of distribution of migratory freshwater prawns, predating the snails involved in schistosomiasis transmission, should now be retrofitted with passages that allow prawns to move upstream and downstream. New dams should be designed with prawn ladders.[17] Excessive use of fertilizers should be avoided in endemic regions, and pesticides with minimum effect on natural snail predators should be used instead.[20] Although these interventions will not be enough to eliminate schistosomiasis, they may help limit the negative effects of climate change on schistosomiasis transmission.

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Malaria, mangroves, and migration: challenges for small island developing states in the Caribbean

Climate change and human behavior are making it harder to control infectious disease in the region, say **Ryan S Mohammed** and **Cock van Oosterhout**

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Besides climate change and unsustainable exploitation of the environment, socioeconomic inequality and political unrest may also contribute to infectious disease outbreaks in the Caribbean archipelago. Migration among rural coastal communities can reduce the effectiveness of disease monitoring and hinder the isolation of people in infected communities—both strategies underpinning integrated control of emerging infectious disease (EID).

Caribbean islands experience high rates of unregulated immigration from several South American counties.[1] The worsening economic and political situation in Venezuela in 2018 coincided with a sudden marked rise in malaria, with a reported 51% prevalence.[2] This, in combination with civil unrest, may result in more frequent outbreaks of malaria outbreaks in the Caribbean in the future.

Since the early 2000s the Caribbean has been considered completely malaria-free. Caribbean small island developing states have maintained this status through an integrated control approach, including continued and intensive monitoring, isolation of individuals within infected communities, and the control of mosquito breeding sites by draining stagnant water bodies, community fumigation and other environmental management schemes.[3 4]

Anopheles is the mosquito vector of Plasmodium; understanding this vector underpins effective malaria control strategies. This mosquito tolerates brackish water habitats, and recent global environmental changes and unsustainable exploitation of the environment have increased the size of this habitat. For example, about 10% of Trinidad's coastline is fringed by mangrove ecosystems,[5] which buffer inland saltwater intrusion. However, the loss of coastal mangrove caused by increased sea level and coastal erosion, coupled with coastal infrastructural development, has resulted in saltwater intrusion of watersheds and inland colonization by mangroves. This habitat provides fertile new breeding grounds for vectors such as brackish water-tolerant mosquitoes. In addition, the increased frequency of tropical storms across the Atlantic and flooding provides more stagnant water habitats for mosquito reproduction.[6] These changes undermine the treatment of stagnant water habitats that a successful approach to controlling emerging infectious disease relies on.

Increased investment

Control of EIDs such as arboviruses and malaria requires increased resources from governments, particularly focused on disease monitoring in rural coastal communities. However, more needs to be done. The United Nations has declared 2021 to 2031 as the decade of ocean science for sustainable development.[7] The aim is to reverse declining oceanic health caused by climate change, but control of EIDs is equally crucial, and this initiative has potentially much wider implications, as the One Health approach suggests.[8] Marine spatial planning, a strategy for capitalizing on the blue economy, directly addresses habitat use and loss.[9] Particularly in the Caribbean, this strategy should focus on halting the erosion of coastal mangroves.

Like the rest of the world, the small island developing states of the Caribbean face a multitude of challenges related to mass movement of human populations, elevated ambient air temperatures, changes in weather and rainfall patterns, coastal erosion, human induced habitat change, and the spread of infectious disease vectors. These changes put additional pressures on the control of EIDs, and the consequence is that Caribbean states may soon no longer be considered as completely malaria-free. Indeed, the status of EIDs is in constant need of re-evaluation, demanding increased investment with the vision that our health and wellbeing depend on the health and wellbeing of our environment. For example, the Mayaro arborvirus, which has its origins in South and Central America, is predicted to create a major epidemic in the future, following in the steps of the recent pandemics caused by Chikungunya and Zika viruses.[10] The vector *Haeamogus sp* mosquito was typically found in tropical inland forest but now as coastal temperatures rise consistently, the vector is also found within mangrove ecosystems.[10]

In line with the One Health approach,[11] we need to make significant investments to redress ecological and environmental imbalance resulting from human activities. We need to better anticipate how changes in habitat caused by human activities and climate change can result in range shifts of parasites and their vectors, enabling us to implement control measures before outbreaks take place. In keeping with the UN's sustainable development goals, we must critically assess and mitigate the novel risks for EID outbreaks associated with the environmental changes resulting from these activities. This is critical for the effective control of EIDs, and health and wellbeing in the Caribbean and elsewhere in the world.

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Emerging arboviruses in the urbanized Amazon rainforest

Degradation of rainforest, extreme weather events, and climate change affect the spread of mosquito borne diseases like dengue, chikungunya, and Zika, write **Rachel Lowe and colleagues**. Urgent action is needed

The rapidly changing fate of the Amazon, an ecosystem we all depend on, has been highlighted by rampant wildfires, extreme droughts, and deforestation in recent years. For indigenous communities, land is sacred and typically is used for sustainable subsistence. But these communities are increasingly threatened by illegal mining, livestock, and monoculture practices.

Brazilian satellite images show 64% more deforestation in 2020 than in 2019. This promotes conflict and environmental degradation, exacerbates health risks for indigenous populations, and leads to loss of ecosystem at local, regional, and global scales.

The Amazon region is at a critical moment of history. Action to protect the health and wellbeing of traditional communities, promote sustainable development, and protect forest habitat will not come from governments. How can the medical, public health, environmental, and policy communities engage effectively to tackle such a complex challenge?

We consider this question with a focus on arboviruses, including dengue, chikungunya, and Zika. The emergence and expansion of these arboviral diseases is an important global threat. They are transmitted to humans by females of two resilient mosquitoes, *Aedes aegypti* and *Aedes albopictus*. These vectors' geographical ranges have been expanding latitudinally and into the Amazon region, enabled by climate change and their adaptation to humans' domestic environment.

Environmental and climatic changes affect transmission of other vectorborne diseases, but arboviruses show these effects in the context of rapid urbanization. Malaria, another endemic disease in the Amazon, has been discussed extensively elsewhere, including recommendations for action.[1] It is primarily a rural and peri-urban disease and its mosquito vectors do not rely on the built environment and water stored by humans. Nevertheless, our recommendations related to arboviruses extend to vectorborne pathogens more generally. Although we focus on Brazil, the country containing the largest proportion of the Amazon ecosystem, disease transmission does not recognize national borders and cooperative regional efforts are required.[1]

KEY RECOMMENDATIONS

- Integrated surveillance methods for endemic and emerging infectious agents are needed across all countries in the Amazon region
- Action is needed to monitor deforestation in coordination with health surveillance and to build resilience to extreme weather events
- Climate forecasts should be used to predict and prepare for disease outbreaks
- Disease control and prevention strategies should include better representation of women and traditional communities

Arboviruses edging into the rainforest

Dengue is a climate sensitive disease that has substantially expanded its global range in the past 50 years. It now accounts for an estimated 10 000 deaths and 100 million symptomatic infections a year in over 125 countries.[2] Since 2005, chikungunya and Zika viruses have also begun to extend their reach beyond Africa and Asia.[3] Chikungunya emerged in the western hemisphere in 2013, leading to more than a million cases in the Americas within a year.[4]

Zika reached the Americas by 2014, and the discovery of links between Zika virus infection and a neurological complication in newborn babies, which later became known as congenital Zika syndrome, led the World Health Organization to declare a public health emergency of international concern in 2016.[5]

These arboviruses continue to affect the Americas, and in 2019 the region reported more than three million dengue cases, the largest recorded epidemic to date.[6] Dengue re-emerged in Brazil in the 1980s, with marked expansion in transmission in recent years. Spread into previously isolated Amazon regions (fig 1)[9] is associated with *Ae aegypti* re-establishing itself after a successful elimination campaign during the 1940s and 1950s.

Larger cities were the first to be affected, including Iquitos in Peru[10] and Belém and Manaus in Brazil.[11] In 2016, 90 Amazonian municipalities had reported presence of *Ae aegypti*, with 24 reporting high abundance. Importantly, *Ae aegypti* dwell in water holding containers, which are abundant in urban landscapes.[11 12] Dengue vectors have been expanding from urban centers to neighboring rural areas and into the urbanized forest (areas with increased presence of non-indigenous settlements but with gradients more complex than simple city versus rural classifications[13 14]). In the Peruvian Amazon, for example, proximity to Iquitos has been shown to increase the odds of *Aedes*'s establishment.[10]

The establishment of *Aedes* mosquitoes in the Brazilian Amazon has been accompanied by large outbreaks of arboviral diseases. Mean annual dengue cases doubled between 1998-2008 (27 900/year) and 2009-18 (52 363/year), with epidemics in 2001 (51 000 cases), when the type 3 virus first appeared in the country, and in 2010 and 2011 (98 000 and 119 000 cases), when the type 4 virus first appeared.[15]

The first municipalities to experience dengue outbreaks were urban centers, including Manaus and Boa Vista, with high population density but lower access to basic services such as piped water than in other parts of Brazil (figs 2 and 3). Large areas of the western Amazon have not yet seen dengue outbreaks, although the area of permanent dengue transmission is expanding west, and over the past 20 years

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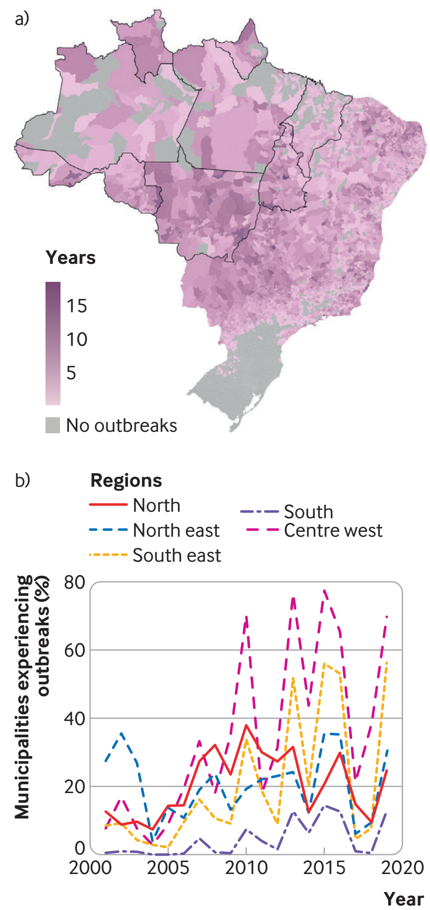

Fig 1 | Expansion of dengue transmission in Brazil during the 21st century. Top: Number of years each municipality experienced an outbreak between 2001 and 2019 (defined by the Brazilian Ministry of Health as ≥300 cases per 100 000 inhabitants).[7] The nine Brazilian states encompassing most of the Amazon forest biome with a population of about 27 million are outlined in bold[8] Bottom: Percentage of municipalities in each region experiencing an outbreak by year. The north region mostly comprises the Amazon rainforest.

increasing numbers of cities in the North region have had outbreaks (fig 1).

Chikungunya and Zika first appeared in Brazil in 2013 and 2014. Brazilian Ministry of Health data show a Zika epidemic occurred in 2016 (10 311 cases) and a chikungunya epidemic in 2017 (13 335 cases). Both viruses persist in the region, with new cases reported every year. Other arboviruses, including Mayaro, Oropouche, and yellow fever viruses have also been associated with epidemics in humans and pose a public health threat.[17]

New opportunities for mosquitoes to thrive

The Brazilian Amazon is one of the world's richest reservoirs of arboviruses,[18] with more than 180 identified. They are maintained within a sylvatic cycle in the forest, in which several insect species act as vectors and wild vertebrates are hosts. Forest disturbances (for example, deforestation, mining, and infrastructure projects such as highways and dams) create conditions that bring humans close to those areas, increasing the likelihood of new zoonosis[19 20] and resurgences of others. For example, illegal gold mining in the rainforest attracts non-immune workers into settler communities with inadequate healthcare, which has led to hotspots of malaria resurgence in Venezuela.[21 22]

Development projects in the Brazilian Amazon have spawned settlements without basic infrastructure such as access to piped water and waste collection. This can create ideal conditions for *Ae aegypti* to lay eggs.[1] Land use and land cover changes combined with unplanned, precarious urbanization and increased human mobility can allow invasive vector species and novel pathogens to travel greater distances. In Acre, Brazil, road construction and increasing connectivity between urban and rural areas correlate with emergence of dengue.[23]

Deforestation and associated human settlement are taking place against a backdrop of rapid shifts in the climate. The Brazilian Amazon region has experienced an increasing number of severe extreme weather events such as flooding, drought, and fires over the past two decades.[24] These hydrometeorological extremes are closely tied to intense El Niño and La Niña events[25] that affect precipitation and temperature in the Amazon basin.

El Niño leads to warmer, drier weather in the Amazon basin whereas La Niña brings wetter, cooler periods (fig 4).[26 27] There is some uncertainty, with studies indicating both a strengthening and a weakening of extreme El Niño in the future.[28 29] However, the Amazon rainforest experienced record breaking warming and extreme drought during the strong 2015-16 El Niño event.[30] Increased drought can lead to more frequent fires, generating further deforestation. Loss of trees alters the Amazon's hydrological cycle, influencing regional and global climate.[31]

Climate change projections show that by 2060-80 the Amazon is likely to warm 1-2°C above the global average increase in surface temperature because of periods of intense drought and reduced cloud cover, which increase net surface shortwave radiation.[8] This scenario points toward surpassing a tipping point to a degraded savanna-like ecosystem and increased droughts, which in turn will harm the global climate system.[32 33]

Temperature and precipitation are important drivers of seasonality and interannual variability in arbovirus transmission. As shown for dengue, the relation between anomalous climatic events and transmission is complex, non-linear, and often delayed by several months.[34] Ambient temperature affects mosquito reproduction, survival, and biting rates, with warmer temperatures increasing risk of transmission up to a maximum of 34°C.[35] Warm temperatures also affect the size and duration of arboviral disease outbreaks, with annual average temperatures 25-35°C producing the largest epidemics in areas with low seasonal temperature variation, such as the Amazon.[36]

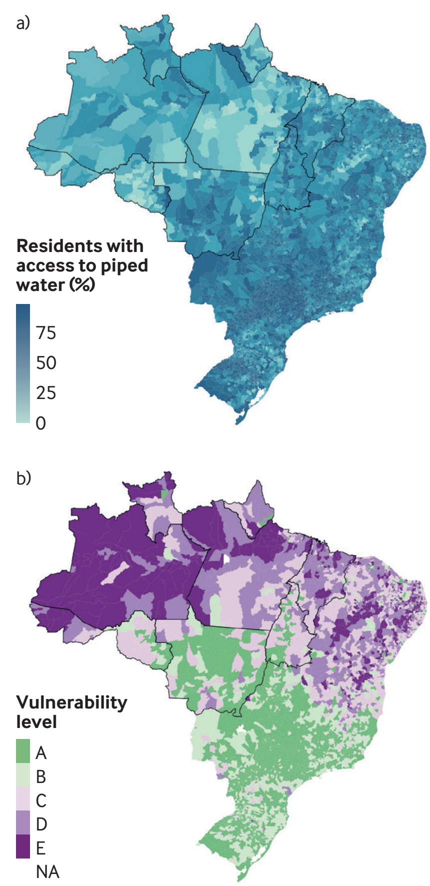

Fig 2 | Top: Proportion of Brazilian residents with access to piped water network (2010 population census, Brazilian Institute for Geography and Statistics)(IBGE). Bottom: Socioeconomic vulnerability index.[16] The index ranges from A (least vulnerable) to E (most vulnerable). The nine Brazilian states encompassing most of the Amazon forest biome are outlined in bold

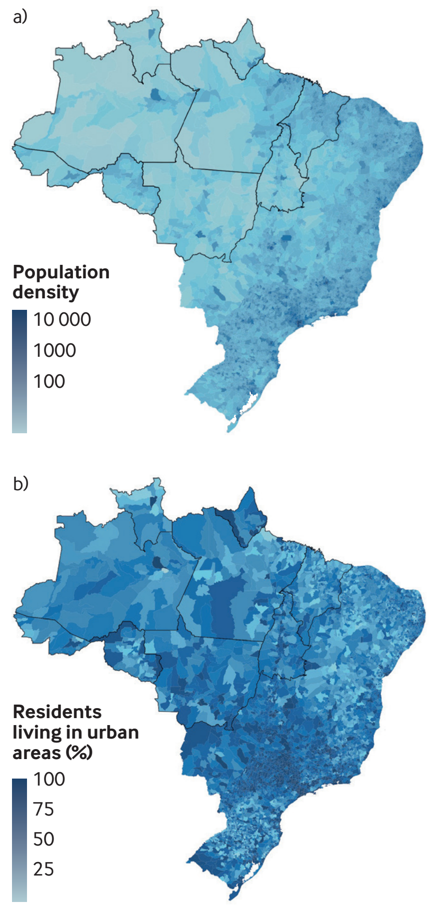

Fig 3 | Population density (per square km) of Brazil. Bottom: Proportion of residents living in urban areas (2010 population census, Brazilian Institute for Geography and Statistics).

Although rainfall is conducive to outbreaks of mosquito-borne disease through an increase in mosquito breeding sites, El Niño induced warm and dry conditions have also been associated with an increased risk of dengue fever in parts of the Americas.[34 37] Periods of drought may lead to water supply shortage, encouraging household improvised water storage, which can create additional vector habitats and increase contact between mosquitoes and humans. Despite its immense water resources, the Amazon basin has serious water disruption and sewage problems,[38] with an unacceptably low proportion of the population having access to the piped water network (fig 2). This region is also the most vulnerable in Brazil in terms of infrastructure and access to electricity and running water.

An increase in extreme weather events related to a changing climate is therefore likely to raise the risk of outbreaks of existing arbovirus diseases and the emergence of new ones. The climate effects will occur and act synergistically with the ongoing trend in urbanization of the rainforest. The variability, complexity, and uncertainty of the health responses argue for a precautionary approach based on surveillance, preparedness, and alert systems. These measures should accompany broader efforts to reduce changes to the environment itself, on deforestation, climate change, and a sustainable path for the region.

Holistic intersectorial surveillance systems

New surveillance methods for endemic and emerging infectious agents and management of people with fever are a priority.[31] In line with the Global Vector Control Response recommendations,[33] pathogen, vector, and epidemiological surveillance systems should be integrated with environmental and climate information systems. A One Health approach at the human-animal ecosystem interface is needed for effective investigation, prevention, and control of potential spillover and spread of emerging vectorborne zoonotic diseases.

The public health community should work with the environmental sector to monitor deforestation and biodiversity and to identify hotspots for sampling and active integrated surveillance. Pathogens, vectors, wildlife, and human hosts do not recognize geopolitical boundaries in the rainforest, which makes cross-border and regional alliances imperative. Thus, integrated surveillance system protocols should be compatible between all relevant countries.[1]

The covid-19 crisis has further exposed the vulnerability of the Amazon region to the effects of a large epidemic. Disease surveillance and control in this forest is a formidable task because of its size, limited communication infrastructure, cost of transportation, and lack of specific disease control protocols for diverse ethnic groups with different levels of vulnerability. Surveillance systems used in other areas (such as Infodengue[39]) could be adapted for the Amazon, with the inclusion of participatory surveillance efforts by indigenous groups (https://cimi.org.br/coronavirus/) and non-governmental organizations to improve outbreak detection in small communities (https://covid19.socioambiental.org/). These alerts can be easily integrated with a response protocol, improving the precision and speed of control actions.

Given the sensitivity of the Amazon rainforest to El Niño and La Niña events, outbreak prediction based on seasonal climate forecasts can give more time to prepare public health systems for heightened risk of disease outbreaks associated with extreme weather events.[34 40] Early interventions may include purchasing of diagnostic equipment and mosquito control supplies (such as insecticide and larvicide) and environmental hygiene, including maintenance of water storage containers.

Mosquito breeding habitats should be destroyed not only during the warm and rainy season but also during and after droughts.[34] Combining seasonal climate

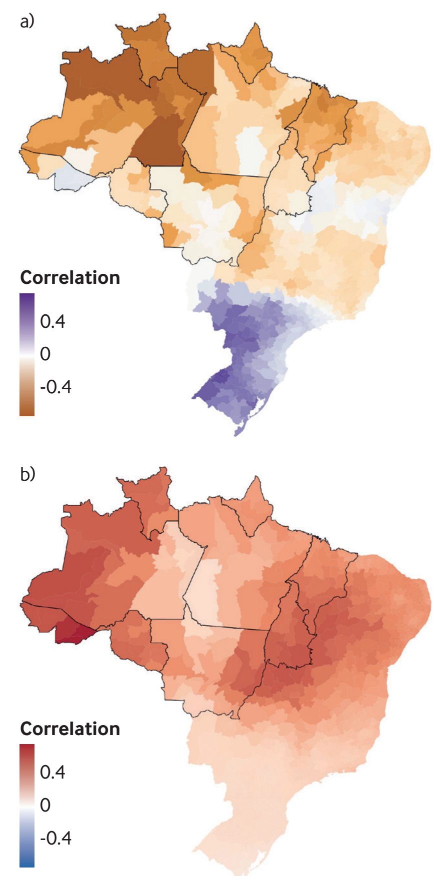

Fig 4 | Correlation between the Nino3.4 index (Nov-Jan) and the Palmer drought severity index (Feb-Apr) (top) and minimum temperature between 2001 and 2017 (bottom). The nine Brazilian states encompassing most of the Amazon forest biome are outlined in bold. The Niño 3.4 index is a measure of the sea surface temperature anomalies in the Niño 3.4 region of the Pacific Ocean. The Niño 3.4 index is negatively correlated with the Palmer drought severity index in the Amazon region, a measure of meteorological drought ranging from −10 (extremely dry) to +10 (extremely wet), and positively correlated with minimum temperature

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forecasts and Earth observations with local seroprevalence surveys could improve the detection of emerging diseases associated with anomalous climate events.[41] Use of existing networks of malaria diagnostic and treatment units has also been proposed to detect acute Chagas disease across the Amazon.[42]

For early warnings to translate to early action, health services must dedicate staff to educate and mobilize local communities, including schools, community organizations, and churches. Community engagement and educational programs on recognizing risk factors, symptoms, and vectors should become a key component of an integrated surveillance protocol. Ultimately, universal access to basic sanitation, clean water, and waste management should be provided, while respecting the needs and perceptions of local communities.[38]

Effective disease control and prevention strategies will also benefit from having more women and under-represented groups in higher ranking positions of power, decision making, or policy design.[43] Women are traditionally responsible for care and work in the household and water collection and storage, which places them in closer contact with mosquito breeding sites and provides insight into effective interventions.

Building capacity to confront novel pathogens

Medical and public health staff need to be trained to tackle the complexity of disease transmission and the context in which it occurs. Specifically, five areas should be part of the curriculum:

- Recognition of arboviruses that pose a threat to public health, even if the current burden is low
- Data literacy, including an understanding of the importance of data collection and data analysis as the backbone of evidence based decision making
- Field based collaborative learning,[44] or the unique opportunity to interact with local health staff, community members, policy makers, and government officials to discuss solutions for local problems
- Holistic view of health, or the understanding that disease transmission is often complex, and results from multiple layers of biological, genetic, medical, social, economic, ecological, and political factors
- The effects of climate change and climate variability on infectious disease.

While some countries have recommended the inclusion of social sciences in medical training, including Brazil, the breadth and depth of training remain uneven and needs better regulation.[45] Skills in these five areas would facilitate local engagement, better surveillance and data analytics for policy making, and a more humanistic approach to public health.

Enforcing environmental and indigenous community protection regulations may help mitigate forest disturbances, but it is unlikely that environmental change caused by development projects and deforestation will cease altogether in the near future. When considering the impacts of deforestation and climate change on the Amazon rainforest, and when planning for mitigation and regional and global solutions, it is imperative to consider effects, including unintended ones, on traditional ways of life.[46]

Interventions should be designed to respect local community needs, and perceptions and community engagement should be central to preparedness of protocols for the control of vectorborne diseases. Integrated surveillance protocols that track the circulation of pathogens and detect climate anomalies and early stages of disease outbreaks in all countries comprising the Amazon rainforest, are critical to prevent future spillover and explosive epidemics in one of the world's most vulnerable climate change hotspots.

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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**

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).

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.

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.

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

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).

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.

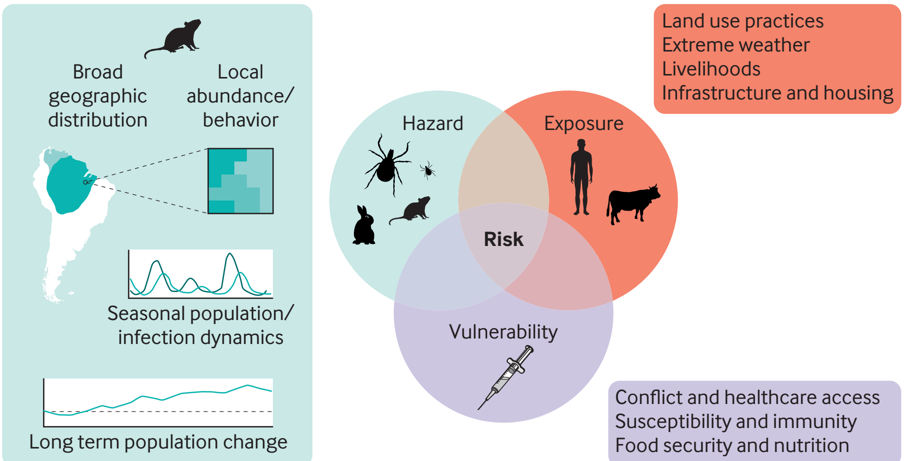

Fig 1 | Effects of global environmental change on zoonotic disease hazards and risks. Inset boxes highlight key socioecological processes through which climate and land use changes can affect hazard, exposure, and vulnerability. For example, zoonotic hazard (underlying potential for pathogen spillover)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

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]

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 *Amblyomma 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

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]

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]

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

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

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.

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