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REVIEW

Climate Change and Cascading Risks from Infectious Disease

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ABSTRACT

Climate change is adversely affecting the burden of infectious disease throughout the world, which is a health security threat. Climate-sensitive infectious disease includes vector-borne diseases such as malaria, whose transmission potential is expected to increase because of enhanced climatic suitability for the mosquito vector in Asia, sub-Saharan Africa, and South America. Climatic suitability for the mosquitoes that can carry dengue, Zika, and chikungunya is also likely to increase, facilitating further increases in the geographic range and longer transmission seasons, and raising concern for expansion of these diseases into temperate zones, particularly under higher greenhouse gas emission scenarios. Early spring temperatures in 2018 seem to have contributed to the early onset and extensive West Nile virus outbreak in Europe, a pathogen expected to expand further beyond its current distribution, due to a warming climate. As for tick-borne diseases, climate change is projected to continue to contribute to the spread of Lyme disease and tick-borne encephalitis, particularly in North America and Europe. Schistosomiasis is a water-borne disease and public health concern in Africa, Latin America, the Middle East, and Southeast Asia; climate change is anticipated to change its distribution, with both expansions and contractions expected. Other water-borne diseases that cause diarrheal diseases have declined significantly over the last decades owing to socioeconomic development and public health measures but changes in climate can reverse some of these positive developments. Weather and climate events, population movement, land use changes, urbanization, global trade, and other drivers can catalyze a succession of secondary events that can lead to a range of health impacts, including infectious disease outbreaks. These cascading risk pathways of causally connected events can result in large-scale outbreaks and affect society at large.

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We review climatic and other cascading drivers of infectious disease with projections under different climate change scenarios.

Supplementary file1 (MP4 328467 KB)

Keywords: Climate change; Infectious diseases; Cascading risks; Hazard; Vulnerability; Exposure; Malaria; Dengue; Chikungunya; Lyme disease

Key Summary Points

Why carry out this study?

Climate change is considered to be one of the greatest threats to human health in the twenty-first century, with significant increases in temperature extremes, heavy precipitation, and severe droughts.

These climate hazards can activate cascading risk pathways with a sequence of secondary, causally connected events that can disrupt critical infrastructure, vital for a functional society.

What was learned from the study?

This study examines cascading risk pathways from climate change for vector-, water-, food-, and air-borne infectious diseases in a global context.

Cascading effects from climate hazards include also stagnant water that serve as breeding ground for mosquitoes after a flood; contamination of drinking water after a storm surge; breakdown of vector control programs after a hurricane; cholera outbreak after a drought.

A narrow, siloed, and linear assessment of these risks will misinform decision- and policymakers of the magnitude and pattern of future risks, and of the opportunities to modify policies to reduce inherent vulnerabilities and enhance infectious disease control programs.

Elucidating cascading risk pathways from infectious diseases is a first step towards tacking infectious disease threats from climate change.

DIGITAL FEATURES

This article is published with digital features, including a Talking Head video to facilitate understanding of the article. To view digital features for this article go to https://doi.org/10.6084/m9.figshare.19621077.

INTRODUCTION

Global surface temperature increased at an unprecedented rate over the last 50 years and will continue to do so, until at least the mid-century under all greenhouse emissions scenarios [1]. Climate futures include increases in the frequency and intensity of hot extremes, heavy precipitation, and agricultural and ecological droughts. Pathogens, vectors, hosts, and disease transmission can be sensitive to these changing conditions [2]. Specifically, pathogens develop only within a narrow temperature envelope, with development ceasing at lower or higher temperatures. Temperature influences the reproduction and extrinsic incubation period of pathogens within a vector, with higher temperatures accelerating pathogen maturation. Mosquito biting rate is also a function of temperature, which can affect disease transmission. Moreover, ambient temperature affects the spatial–temporal distribution of disease vectors that carry and transmit pathogen to humans. Disease transmission can in turn be influenced by weather patterns, albeit indirectly, by altered contact rates between human and pathogen, human and vector, or human and host.

However, infectious disease transmission is also a function of underlying vulnerabilities in society (Table 1). Vulnerability is defined as the propensity or predisposition to be adversely affected by infectious disease or a susceptibility to harm and lack of capacity to cope and adapt (Fig. 1). There are multiple vulnerability factors for health impacts of climate change that can be grouped into biomedical (e.g., immunocompromised, malnourished), demographic (e.g., age, sex), geographic (e.g., land use, flood zones), socioeconomic (e.g., poverty, education), or sociopolitical (e.g., civil strife, political

Table 1 Combination matrix of climate hazards, vulnerabilities, cascading risks, and climate-sensitive infectious disease (ID) impacts

Climate Hazards	Vulnerability	Cascading risks	Climate-sensitive ID
Coastal flood	**Bio-medical**	**Cascading risk pathways from extreme precipitation and flooding**	*Borrelia* (Lyme)
Estuarine flood	Pregnant and breastfeeding women	Standing water serves as breeding ground for mosquitoes	Dengue virus
Flash flood	Immunocompromised populations	Flood water damages critical health care infrastructure	Tick-borne encephalitis
Fluvial (riverine flood)	Undernourished populations	Rain runoff from agricultural land and pastures results in turbid water runoff, which impedes water disinfection	*Vibrio spp.*
Storm surge/tides	Populations with high ID burden	Contamination of oyster farms from storm runoff that mobilizes and transports pathogens	*Leishmania*
Snowmelt flood	Populations with high chronic disease burden	Water treatment efficiency is overwhelmed or damaged by storm	*Campylobacter*
Surface water flooding	People with mental or physical disabilities	Storm water and floods overwhelm containment systems and discharge untreated waste water	Chikungunya virus
Glacial lake outburst flood	**Demographic**	Damage to critical water supply and sanitation infrastructure due to inundation	*Cryptosporidium*
	Age	Population displacement and inadequate sanitation infrastructure due to floods	*Giardia*
Low pressure or cyclone	Sex	**Cascading risk pathways from drought**	Hantavirus
Drought	Population movement	Crop failure, undernutrition, susceptibility to infectious diseases	Rift Valley Fever
Hail	**Geographic**	Concentration of pathogens in drinking water sources	*Salmonella*
Blizzard	Unplanned urban housing	Water collection at alternative (contaminated) sources due to water scarcity	*Shigella*
Cold wave	Flood risk zones	Intensified demand and sharing (e.g., with livestock) of limited water resources decreases water availability and quality	Vero toxin–producing *Escherichia coli*
Dzud	Drought risk zones	Cross-connections of water lines with sewer lines due to water shortages results in water contamination	West Nile virus
Freeze	Coastal storms and cyclone risk zones	Vector breeding in household water containers	*Cholera*
Frost (hoar frost)	Water-stressed zones	Poor water quality, hygiene and sanitation (WASH) due to water shortages	*Legionella*
Freezing rain	Food-insecure zones	Open defecation due to lack of WASH results in human exposure to pathogens	*Rickettsia*
Ground frost	**Socio-economic**	Low water availability augments travel distance to alternative (contaminated) sources	*Hepatatis A*
Heatwave	Poverty	**Cascading risk pathways from elevated temperature**	*Leptospira*
Thaw	Gender norms, roles, and relations	Longer transmission season for vector-borne diseases	*Tularemia*
Avalanche	Unsafe, informal occupation	Proliferation of marine bacteria at recreational beaches	Yellow fever virus
Mud flow	Reduced access to health care	Increased prevalence of pathogens in poultry flocks	*Yersinosis*
Rock slide	Reduced access to education	Extended pathogen survival and replication outside of host	*Anthrax*
Derecho	Unsafe water and sanitation	Runoff from areas affected by wildfires during heat waves compromises water quality	*Botulism*
Gale	Inadequate shelter	Reduced crop yields at higher ambient temperature	*Listeria*
Squall	**Socio-political**	Food spoilage due to behavior change (e.g., barbecue)	*Malaria*
Subtropical storm	Political instability	**Cascading risk pathways from sea-level rise**	*Coxiella* (Q Fever)
Tropical storm	Existence of complex emergencies or conflict	Inundation of drinking water supply and sanitation infrastructure	*Toxoplasma*
Tornado	Lack of freedom of speech and information	Saline intrusion into coastal aquifers and decline in soil and water quality	*Schistosoma*
Wind	Reduced civil rights and civil society movements	Damage of critical infrastructure (e.g., health care, first responders, electricity generation, transportation (e.g., fuel supply, streets, rail, airports, harbors), telecommunication, shelter, fuel extraction(e.g., natural gas, oil), water supply, agriculture, financial services)	Nairovirus (Crimean-Congo haemorrhagic fever)

This is not a complete list but is intended to be illustrative onlySources: UNDRR/ISC Sendai Hazard Definition and Classification Review Technical Report; The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment; Lindgren E, Andersson Y, Suk JE, Sudre B, Semenza JC. Monitoring EU Emerging Infectious Disease Risk due to Climate Change. Science 2012;336(6080):418–419. Semenza JC. Cascading risks of waterborne diseases from climate change. Nature Immunol. 2020 May;21(5):484–487

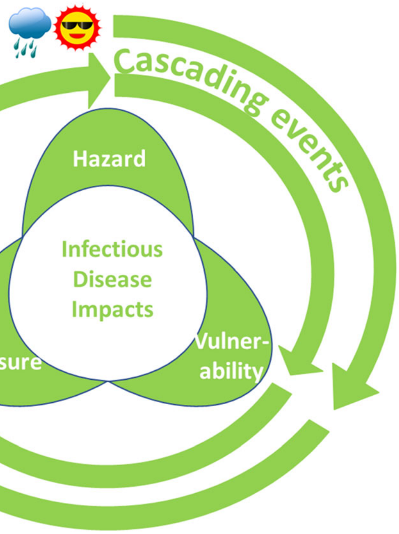


Fig. 1 Cascading risks from infectious disease, due to a nexus of hazard, vulnerability, and exposure. Climatic hazards (e.g., extreme rain event or heat; outer spiral), amplified by societal vulnerabilities can trigger new hazards, such as floodwater contaminated with pathogens or high mosquito densities. Cascading events (inner spiral) caused by these infectious disease hazards and amplified by newly attained vulnerabilities can result in population exposure and give rise to water-borne or mosquito-borne disease outbreaks, respectively

instability) (Table 1) [3]. From an infectious disease standpoint, vulnerability is also determined by the lack of safeguards such as door/window screens for vectors or flood barriers for storm surges [4].

Furthermore, infectious disease transmission depends on the exposure pattern in human populations, which is defined as the state of people, livelihoods, species, property, (eco-) systems, or other elements present in hazard zones that thereby could be adversely affected. Individuals or communities can be exposed to contaminated drinking water, vectors, or pathogens. The nexus of these three elements—hazard, vulnerability, and exposure—determines the current infectious disease impacts or future risks due to climate change (Fig. 1).

In addition to these impacts of weather and climate on pathogens, vectors, hosts, and disease transmission, a weather or climate event can activate cascading risk pathways with a sequence of secondary, causally connected events. Table 1 presents a combination matrix of how climate hazards can be combined with societal vulnerabilities that give rise to cascading risk pathways resulting in climate-sensitive infectious disease outbreaks. The dynamic interactions between climate hazard, exposure, and vulnerability set the stage for cascading risks (Fig. 1; outer spiral). For example, a hurricane can result in flooding or disrupt vector control programs as a result of infrastructure vulnerabilities. Contamination of floodwater with pathogens or high mosquito populations can cause population exposure to pathogens and then trigger cascading events (Fig. 1; inner spiral) such as water-borne or mosquito-borne outbreaks. These resulting impacts of a sequential chain reaction within natural and human systems can be significantly larger than the initial hazard and can cause additional physical, natural, social, or economic disruption (Fig. 1; inner spiral) [5]. If these secondary effects such as flooding disrupt critical infrastructure that is vital for a functional society, the consequences can be substantial. Such events can have a ripple effect across society and generate direct losses through immediate impacts or more secondary losses through consequential impacts. The combination matrix in Table 1 illustrates the predicament of climate change adaptation where virtually any climate hazard can be combined with specific vulnerabilities resulting in cascading risk pathways and infectious disease impacts. Examples of such cascading effects from climate hazards that have been described in the peer-reviewed literature include stagnant water after a flood that serves as a breeding ground for mosquitoes; contamination of drinking water after a storm; injuries from landslides or storm surges with risk of tetanus infections in populations with low vaccination coverage; or a cholera outbreak after a drought (Table 2).

Protecting and promoting health requires understanding and preparing for these causal interdependencies that permeate many aspects of society. A climate hazard can adversely affect one sector in society by surpassing a threshold that causes system failure (Fig. 1). As a result of

Table 2 Selected examples of climate hazards, societal vulnerabilities, and cascading events resulting in infectious disease outbreaks

Climate hazard	Vulnerability and cascading events	Infectious disease outcome	References
Hurricane	Lack of WASH in mega-shelter after hurricane Katrina	Widespread outbreak of norovirus gastroenteritis among evacuees	Yee EL, Palacio H, Atmar RL, et al. Widespread outbreak of norovirus gastroenteritis among evacuees of Hurricane Katrina residing in a large "megashelter" in Houston, Texas: lessons learned for prevention. Clin Infect Dis. 2007;44:1032–9
Typhoon	Serious flooding in Metro Manila	Outbreak of Leptospirosis	Amilasan A-shereT, Ujiie M, Suzuki M, et al. Outbreak of leptospirosis after flood, the Philippines, 2009. Emerg Infect Dis. 2012;18:91–4
Cyclones: Idai and Kenneth in Mozambique	Lack of access to safe water, poor sanitation, contact with stagnant floodwater, overcrowding in the camps for displaced people	Diarrheal diseases, malaria	Mugabe VA, Gudo ES, Inlamea OF, et al. Natural disasters, population displacement and health emergencies: multiple public health threats in Mozambique. BMJ Global Health. 2021;6:e006778. doi:10.1136/bmjgh-2021-006778
Heavy rainfall and elevated temperature	Contamination of surface water by compromised WASH systems	Cholera outbreaks in Yemen	Camacho A, Bouhenia M, Alyusfi R, et al. Cholera epidemic in Yemen, 2016–18: an analysis of surveillance data. Lancet Glob Health. 2018 Jun;6(6):e680–e690. https://doi.org/10.1016/S2214-109X(18)30230-4
Monsoon: heavy rain	Record-breaking deluge and floods	Acute diarrhea, skin and eye infections, leptospirosis, malaria epidemic, leishmaniasis, respiratory infections, hepatitis	Baqir M, Sobani ZA, Bhamani A, et al. Infectious diseases in the aftermath of monsoon flooding in Pakistan. Asian Pac J Trop Biomed. 2012;2:76–9

Table 2 continued

Climate hazard	Vulnerability and cascading events	Infectious disease outcome	References
Floods	Health care access	Inadequate access to health care after the disaster	Jacquet GA, Kirsch T, Durrani A, Sauer L, Doocy S. Health care access and utilization after the 2010 Pakistan floods. Prehosp Disaster Med. 2016 Oct;31(5):485–91
Floods, storms, droughts	Displacement	Infectious disease outbreaks including measles, cholera, cutaneous leishmaniasis, dengue	Desai AN, Ramatowski JW, Marano N, Madoff LC, Lassmann B. Infectious disease outbreaks among forcibly displaced persons: an analysis of ProMED reports 1996–2016. Confl Health. 2020 Dec;14(1):1–0
Heavy rain	Overwhelmed water treatment and distribution system	Water-borne disease outbreaks, e.g., cryptosporidium	Semenza JC, Nichols G. Cryptosporidiosis surveillance and water-borne outbreaks in Europe. Euro Surveill. 2007 May;12(5):E13–14
Extreme temperatures, droughts	Crop failures, undernutrition	Vulnerability to infectious diseases, especially diarrhea, pneumonia, and measles	Gwela A, Mupere E, Berkley JA, Lancioni C. Undernutrition, host immunity and vulnerability to infection among young children. Pediatr Infect Dis J. 2019 Aug 1;38(8):e175–7

Table 2 continued

Climate hazard	Vulnerability and cascading events	Infectious disease outcome	References
Droughts	Water scarcity, hygiene	Cholera outbreaks; infectious disease outbreaks	Charnley GE, Kelman I, Green N, Hinsley W, Gaythorpe KA, Murray KA. Exploring relationships between drought and epidemic cholera in Africa using generalised linear models. BMC Infect Dis. 2021 Dec;21(1):1–2 Jofre J, Blanch AR, Lucena F. Water-borne infectious disease outbreaks associated with water scarcity and rainfall events. In: Sabater S, Barceló D, editors. Water scarcity in the Mediterranean; 2009: pp. 147–59. Berlin, Heidelberg: Springer

the interconnected nature of modern society, this can have implications for other sectors [6]. The potential for cross-scale failures need to be defined in relation to the initial climate trigger. By doing so, the complexity of interactions within the public health network can be modeled mathematically. That way, cascading risk pathways can be simulated and analyzed. Understanding the weaknesses in the system can help advance adaptive capacity and intervention measures. Only then can cascading failures be anticipated and intercepted quickly with targeted measures that can prevent a public health impact. Here we critically review interlinked drivers of infectious disease transmission and elucidate the cascading risks associated with climate variability and change. We thoroughly examine cascading risk pathways from climate change for vector-, water-, food-, and air-borne infectious diseases in a global context, as opposed to a focused assessment of one infectious disease category [7] or one geographic area [4], which, to our knowledge, has not been attempted before. Such a comprehensive assessment is critical in order to elucidate cascading risk pathways from infectious diseases, in the context of the complex branching configuration of a globalized, dendritic society; indeed, it is a first step towards tackling infectious disease threats from climate change.

METHODS

Peer-reviewed research articles were retrieved from PubMed using the following search terms: infectious diseases, vector-, water-, food-, airborne diseases, climate change, climate variability, global warming, temperature, heat wave, precipitation, flooding. Disease-specific searches by pathogen name were also conducted. Keywords of the concepts and MeSH terms (when available) were used in the search strategies. A special focus was given to English language publications from the last 5 years. Of particular interest were publications that examined the specific aims of this study,

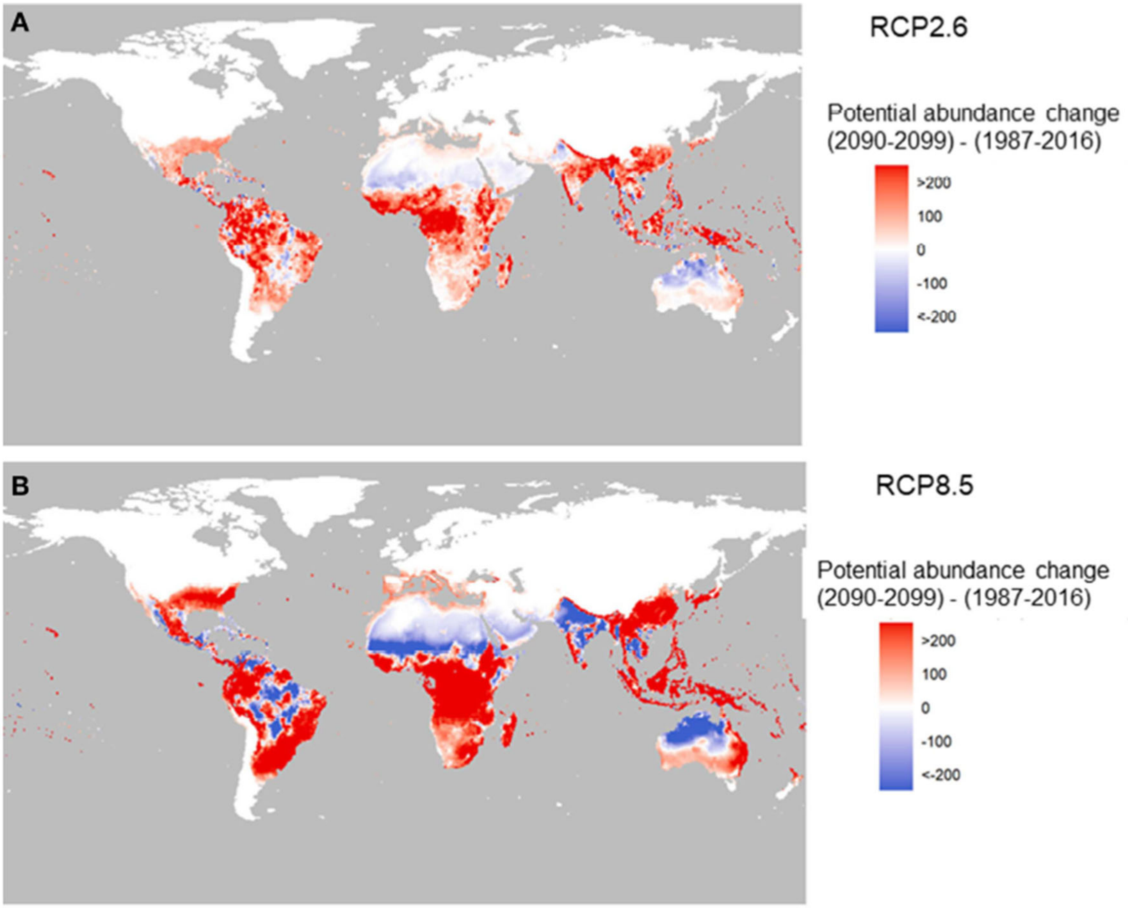


Fig. 2 Change in the potential abundance of *A. aegypti* (per larval site) over the twenty-first century (2090–2099 relative to 1987–2016). The two panels correspond to two carbon emission scenarios: RCP2.6 (**a**) and RCP8.5 (**b**). Source: Reference [27]

climate change and cascading risks from infectious disease, and assessed the association between climate change and disease transmission. Research reports from international organizations and gray literature were also included in our analysis. This article is based on previously conducted studies and does not contain any new studies with human participants or animals performed by any of the authors.

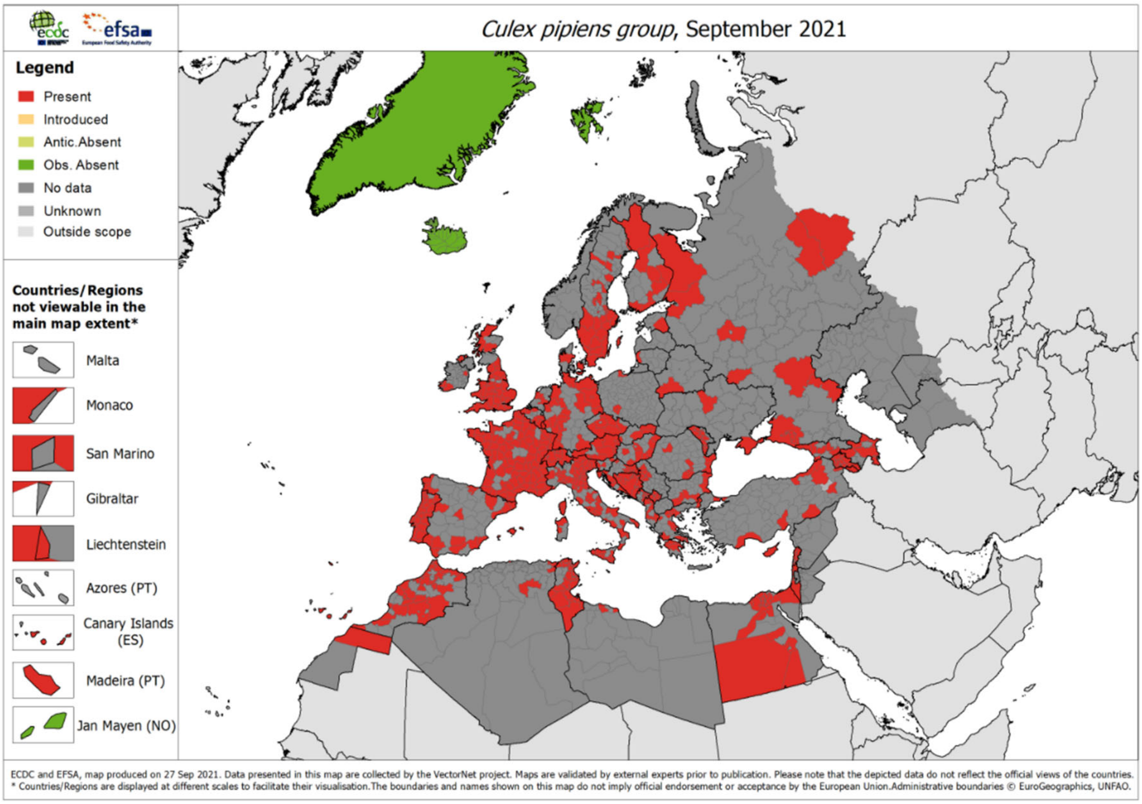
VECTOR-BORNE DISEASES

Climatic conditions indirectly affect vector-borne diseases such as mosquito- and tick-borne diseases. Alterations in environmental conditions can have secondary effects on vector populations, replication rates of pathogens, and vector–host interactions. Further, climatic events can result in cascading secondary effects that can alter the transmission pathway for vector-borne diseases discussed in this section.

Mosquito-Borne Diseases

Malaria

Malaria is caused by five species of plasmodium parasites that are transmitted by *Anopheles* mosquitoes. The disability-adjusted life years (DALYs) rate of malaria declined by almost 40% globally between 2007 and 2017. The largest burden of disease occurs in Africa where more than 90% of all malaria-related deaths occur [8, 9]. The RTS,S/AS01 malaria vaccine for the



ECDC and EFSA, map produced on 27 Sep 2021. Data presented in this map are collected by the VectorNet project. Maps are validated by external experts prior to publication. Please note that the depicted data do not reflect the official views of the countries.
* Countries/Regions are displayed at different scales to facilitate their visualisation.The boundaries and names shown on this map do not imply official endorsement or acceptance by the European Union.Administrative boundaries © EuroGeographics, UNFAO.

Fig. 3 The vector for West Nile virus: *C. pipiens* mosquito distribution in Europe as of September 2021. Source: ECDC, https://www.ecdc.europa.eu/en/publications-data/culex-pipiens-group-current-known-distribution-september-2021

prevention of *Plasmodium falciparum* malaria in children living in regions with moderate to high transmission in combination with chemoprevention should further decrease the disease burden [10, 11]. While there have been recurrent, local outbreaks of malaria in Europe [12], the risk for widespread transmission is relatively low.

Malaria has expanded its geographic range into higher altitudes during warmer years in the highland areas of Columbia and Ethiopia [13, 14]. Thus, without interventions, it is possible that declining trends in the number of malaria DALYs will be offset by additional climate change. Cascading risk pathways from a number of hurricanes disrupted anti-malaria vector control programs and resulted in a resurgence of *P. falciparum* malaria in Haiti, Guatemala, and Nicaragua in the 1980s and 1990s [15, 16]. In the Amazon region, the dry season is getting longer and the rainy season that used to start at the end of October now starts at the beginning of December; this exacerbates and accelerates the burning of the rainforest. Heat stress and fires in the Amazon rainforest along with deforestation, road density, and selective logging are associated with malaria risk in the Amazon [17–19]. Smoke exposure from the Amazon fires is associated with increased respiratory illnesses such as pneumonia, acute bronchitis, and asthma in indigenous populations [20].

The *Anopheles* vector is projected to expand its geographic range under different climate change scenarios, in part due to an increase in temperature and an expansion of the rainy season in the tropical areas of Africa [21, 22]. Similarly, an expansion is projected in South Africa and China but a contraction in India and Southeast Asia as a result of a reduction in climatic suitability [23, 24]. In China, *Plasmodium vivax* and *P. falciparum* malaria distributions are projected to increase under higher emission scenarios, such as representative concentration pathway (RCP) 4.5 and RCP8.5 [25]. Under a multi-scenario climate change framework, these are also the areas projected to experience a lengthening of the transmission season by 1.6 additional months in the tropical highlands in the African region, the Americas, and the Eastern Mediterranean region. The improvement in climatic suitability is expected to be greater in rural areas than in urban areas, and the epidemic belt would expand towards temperate regions [26]. Similarly, a general rise in months suitable for transmission is projected to increase in India; in other areas, the transmission season is projected to contract, when the climatic conditions will be too extreme for the vector species [27].

Arboviral Diseases

Dengue *Aedes aegypti*, the principal mosquito vector of many arboviral diseases, such as dengue, chikungunya, yellow fever, and Zika, has experienced a global expansion, threatening almost half of the world's population [28, 29]. This expansion is attributed in part to the global temperature increase [30] but also globalized population movement through air traffic and urbanization, and insufficient vector control measures [31, 32]. Dengue is responsible for an estimated 10,000 deaths and 100 million symptomatic infections per year in over 125 countries [33, 34]. Dengue incidence is positively associated with temperature, precipitation, and relative humidity in several settings worldwide, including the Americas [35], India [36], and Philippines [37]. Sea surface temperature, rain, and variation in wind associated with the El Niño Southern Oscillation over the Pacific Ocean has also been used as a predictor of dengue incidence [38]. Cascading risks due to a breakdown of vector control measures in countries of Central America after hurricane Mitch in 1998 resulted in almost 40,000 cases of dengue and dengue hemorrhagic fever [16].

The change in potential for global abundance in the future of the dengue vector *A. aegypti* is shown in Fig. 2, with big increased potential in Southeast Asia, China, Japan, East Australia, and Africa [39]. More favorable temperatures and increased rainfall by 2050 from climate change could increase the suitability for dengue in southern and western Africa, southeastern USA, central Mexico, northern Argentina, and inland areas of Australia. In addition, coastal cities in eastern China and Japan are projected to become more suitable by 2050 [29]. The potential transmission season will lengthen by 4 months because of an increase in climatic suitability, particularly in lowlands in the Western Pacific region and the Eastern Mediterranean region [26].

Chikungunya The chikungunya virus was first identified in Tanzania in 1952, where it caused a localized outbreak in Africa and parts of Asia, and then spread to countries around the Indian Ocean. Travel and trade have contributed to a continuous geographic spread to temperate areas [40]. The virus has also been repeatedly imported into Europe where conducive climatic conditions contributed to two large outbreaks in Italy in 2007 and 2017 [41, 42]. Projecting the chikungunya risk under RCP4.5 and RCP8.5 indicates an expansion of the transmission-suitable areas in China, sub-Saharan Africa, South America, the USA, and continental Europe, although also some contraction of the transmission risk along parts of the Adriatic coast of Europe as a result of unfavorable climatic conditions for example [43].

Zika The Zika virus has also expanded globally, causing large outbreaks in South America in 2016 following a period of record high temperatures and severe drought conditions in 2015 [44]. Storing drinking water in open containers at home as a result of the drought might have created ideal vector breeding and exposure conditions that contributed to the outbreak. Zika could expand north with longer seasons as temperatures move towards the predicted thermal optimum (29 °C) [45].

West Nile Fever Europe experienced uncharacteristically high spring temperatures in 2018 followed by an exceptionally early and intense West Nile virus (WNV) transmission season, with 2083 cases [46, 47]. These weather anomalies could have activated the mosquito breeding season early and reduced the extrinsic incubation period, which would explain the high prevalence of WNV in mosquito vectors (*Culex pipiens*) (Fig. 3) and avian hosts, compared to previous years. In fact, birds infected with WNV were discovered before the virus was detected in humans, in both the Netherlands and Germany [48, 49]. In Europe, progressive expansion of WNV is projected along the edges of the current transmission areas, which can result in a cascading risk to the safety of blood banks [50]. WNV-infected, but asymptomatic donors can inadvertently contaminate the blood supply which can arrest blood transfusion services. In order to prevent cascading risk pathways affecting the blood supply, a number of steps need to be taken, such as screening, deferral and pathogen reduction strategies [51].

TICK-BORNE DISEASES

Lyme Disease

Vector surveillance in Canada has documented a geographic range expansion of the black-legged tick *Ixodes scapularis*, the main vector of *Borrelia burgdorferi*, the agent of Lyme disease [52]. This expansion is associated with elevated temperatures, the emergence of tick populations, increases in their range and recent geographic spread, as well as with a rapid increase in human Lyme disease cases [53–56]. In Europe, transmission by *Ixodes ricinus* ticks is also determined by factors besides temperature, such as host populations and habitats [57]. A higher transmission risk is projected under all RCP scenarios for *I. scapularis* in some areas of Canada [58]. The season of Lyme disease is projected to expand in the USA under a 2 °C warming scenario with a 20% increase of cases over the coming decades and lead to an earlier onset and longer length of the annual Lyme disease season [58, 59]. In Europe, the risk of transmission could even be reduced under the low-emission greenhouse gas scenario [60].

Tick-Borne Encephalitis

Tick-borne encephalitis (TBE) is an important zoonotic infection, with an increasing disease burden and expanding geographic range across Europe, Russia, and parts of Asia. Among a number of contributing factors, milder winters and warmer springs due to climate change have been implicated in this range expansion [61–63]. TBE is a potentially serious disease, with 3411 TBE cases reported in EU/EEA countries in 2019 of which 20 died (case fatality, 0.7%). TBE cases generally display a seasonal peak in the months of July and August. Conducive climatic conditions can result in a cascading chain of events where goats, sheep, or cows are infected with the TBE virus that can result in alimentary infection of humans after consumption of unpasteurized milk and cheese from domestic ruminants [64–66].

Rocky Mountain Spotted Fever

Rocky Mountain spotted fever is the most common fatal tick-borne disease in the USA, with 21 fatalities between 2003 and 2016, caused by *Rickettsia rickettsia* [67]. Warmer wetter climates have led to an expansion of tick habitat range and distribution [68, 69]. For example, the range expansion of the lone star tick is correlated with an increased incidence of spotted fever group rickettsiosis in the USA [70].

Leishmaniasis

The protozoa *Leishmania infantum*, the main causative agent of zoonotic visceral leishmaniasis and cutaneous leishmaniasis, are transmitted by infected *Phlebotomine* sandflies. Leishmaniasis is found in southern Europe and northern Africa around the Mediterranean as well as parts of Asia [71]. The primary reservoirs of human infections are domestic and stray dogs that have experienced a progressive increase of *Leishmania* seroprevalence rates at higher latitudes and altitudes, more so than might be expected in Mediterranean countries [72]. There has been a climate change-related expansion of sandflies into more northern latitudes and higher altitudes in Italy [73], in the Pyrenees [74], and Germany [75]. The convergence of vector dispersion and the scattering of infected dogs (e.g., through adoption services) can compound this public health issue. The climate in Central Europe is projected to become increasingly more suitable for sandflies in the future, under climate change scenarios [76].

FOOD-BORNE DISEASES

Salmonella is climate sensitive and grows in a narrow temperature envelope with a strong seasonality. An increase in ambient temperature is associated with an upsurge in *Salmonella* incidence in a number of settings, indicating a direct impact on replication rates [77–79]. The situation for *Campylobacter* is different, because the pathogen cannot replicate outside of the host. Thus, warm weather conditions may not directly affect *Campylobacter* replication rates but rather reflect human behavioral issues such as riskier patterns of food production/consumption or other seasonal factors [80–82]. Nevertheless, with an increase in ambient temperature and extreme weather events, the food safety risk is anticipated to increase as a result of risks from existing and emerging food-borne pathogens along the food chain [83–85].

The transmission pathway of food-borne diseases through the food chain is complex and susceptible to several climatic drivers [86]. For example, in 2017, hurricane Irma contaminated many commercial fruit and vegetable fields in Florida with pathogens and parasites, which led the US Food and Drug Administration to warn against the consumption of fresh produce that had been in contact with floodwater [87]. Hurricanes can also disrupt food processing, preparation, transport and spoil foodstuff.

WATER-BORNE DISEASES

Water-borne diseases causing diarrheal diseases have been declining globally since the 1990s, owing to improvements in water, sanitation, and hygiene (WASH), reductions in poverty, and vaccination programs [88]. Despite this, the disease burden is considerable in low- and high-income countries [7] and is usually caused by microbial contamination of the drinking water supply [89–91]. Bacteria, protozoa, viruses, or parasites have been implicated in water-borne outbreaks due to an inability of the water treatment system to clear pathogens from the water supply [89, 91].

Water-borne outbreaks can occur because of climate variability and change followed by secondary events that are causally connected. Such cascading risk pathways can lead to a succession of system failures and damage critical infrastructure. For instance, extreme precipitation can mobilize pathogens from pastures and fields and overwhelm water treatment and distribution systems resulting in drinking water contamination [92]. In fact, empirical studies have documented cascading risks from heavy rain that give rise to water-borne outbreaks [93, 94]. Similarly, cascading risk pathways of floods can contaminate drinking water wells, treatment and distribution systems, and produce water-borne outbreaks [95, 96]. Conversely, water shortages and drought can also give rise to cascading risks and cause diarrheal diseases [97, 98], although this association has been documented inconsistently [99].

Cholera

Natural disasters can trigger a sequence of cascading events that can compromise WASH. For example, poor sanitation after a hurricane can result in cholera outbreaks [100]. Cholera, is an acute diarrheal disease, caused by the bacterium *Vibrio cholerae* that can result in severe morbidity and mortality; it has been associated with several climatic parameters, in situations with poor WASH and where cholera has already been seeded in the population [101–103]. For example, elevated ambient temperature is a key parameter for cholera incidence [104, 105], as well as lower and higher precipitation [106, 107]. The projected risk for non-cholera *Vibrio* cases, including gastroenteritis, wound infections, and septicemia, is projected to increase in the Baltic Sea region with higher sea surface temperatures [108].

Leptospirosis

Leptospira bacteria can contaminate water, soil, or food through the urine of infected animals, and cause leptospirosis, a bacterial disease that affects humans and animals. For example, recreational water use during hot weather increases the risk of exposure to water contaminated with *Leptospira* [109]. As part of a time series from 2006 to 2016, human leptospirosis notification was significantly associated with rainfall and land surface temperature in high-risk counties in China [110]. Floodwater or drinking water contaminated with *Leptospira* can cause outbreaks of leptospirosis [111, 112], vividly illustrating the nexus of climate hazard, societal vulnerability, and population exposure in creating cascading risk pathways for leptospirosis (Fig. 1).

Schistosomiasis

Infections with parasitic blood flukes of the species *Schistosoma mansoni, S. japonicum, S. intercalatum, S. mekongi,* and *S. guineensis* can cause intestinal schistosomiasis, associated with systemic inflammation. Cases have been reported in Africa, Latin America, the Middle East, and Southeast Asia [113–115]. Temperature is a determinant of the geographic distribution of flukes and a climate change assessment indicated increased transmission as well as potential shrinkages in certain areas [116]. For example, a decade-long drought between 2001 and 2009 resulted in the disappearance of significant clustering around historical transmission hot spots in coastal Kenya, due to the disappearance of the flukes from ponds along with urinary schistosomiasis transmission [117]. Conversely, extreme precipitation in June 2017 in Brazil resulted in a large schistosomiasis outbreak after a large flooding period [118].

Hotter areas in Africa are projected to experience reduced snail populations but higher populations are projected in areas with currently lower winter temperature [119, 120]. In China, currently endemic areas in Sichuan Province are projected to contract, but non-endemic areas in Sichuan and Hunan/Hubei provinces expand [116, 121].

Respiratory Infections

Respiratory infections tend to be highly seasonal, with higher incidence in the winter months, in part due to increased pathogen survival, indoor crowding, and elevated host susceptibility [122]. For example, temperature and humidity determine the incidence of influenza in temperate regions of the world. Low daily temperatures and both low and high relative humidity were associated with an increased risk of influenza incidence in Seoul, Republic of Korea [123]. Similarly, low temperature correlated with peaks of influenza virus activity in Northern Europe [124]. Conversely, warm winters tend to be followed by severe and early-onset influenza incidence the following season [125], partially due to waning population immunity to previous infections.

A respiratory disease outbreak caused by hantavirus in 1999 and 2000 in Santos, Panama was preceded by extreme precipitation [126]. Such unusual rainfall patterns may have led to increases in rodent populations and contact rates with humans [127, 128]. Infected rodents can harbor the hantavirus in their saliva, urine, or feces which can result in human exposure. Another aspect of cascading effects in a warming world is the increased risk for flooding, which can result in respiratory infections; the incidence of respiratory infections has been observed to increase after flooding in a number of settings [129–131].

CONCLUSION

Increasing climate variability is already leading to cascading risks from infectious disease. With projections of increases in multiple modes of climate variability with additional climate change, it is vital for health systems to prepare for more and more extreme cascading risks, taking into account multiple other drivers of outbreaks of infectious diseases. The preparation needs to consider that these changes will vary over time and space, so are inherently difficult to predict. That means health systems need to prepare for uncertainty as much as for climate change. This requires flexibility in planning modifications to vector control programs to ensure they are prepared for a range of possible futures.

Climate effects can have far-reaching implications for public health through inherent societal vulnerabilities that can magnify the impacts of cascading risk pathways (Fig. 1). A narrow, siloed, and linear assessment of these risks will misinform decision- and policymakers of the magnitude and pattern of future risks, and of the opportunities to modify policies to enhance infectious disease control programs, building from current programs. For example, current malaria control programs include treatment, bed nets, and vector control; also incorporating land use (e.g., wetland management, drainage of standing water) and socioeconomic determinants (e.g., housing, occupational exposure) can indirectly counteract the impacts of increasing climate variability on disease transmission.

A comprehensive understanding is critical of the interconnected nature of public health with social, demographic, and environmental drivers of infectious diseases. To this end, a better collaboration is warranted between public health practitioners, climate scientists, civil engineers, social scientists, network modelers, and decision-makers. Mathematical modelling of climate hazards, vulnerabilities, and exposures can improve projections of cascading events and facilitate transformative adaptation.

Failure to invest in research and health systems would jeopardize the resilience of individuals and communities to cascading impacts from infectious disease, leading to a sicker future.

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