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Perspective

A hot topic at the environment–health nexus: investigating the impact of climate change on infectious diseases

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A B S T R A C T

Climate change — the ultimate challenge of our time: COVID-19 pandemic aside, climate change is the ultimate challenge of our time. However, to date, there has been insufficient political thrust to make that much-needed climate action a reality.
Climate change and infectious diseases: Infectious diseases represent only one facet of the threats arising from climate change. Direct impacts from climate change include the more frequent occurrence and increased magnitude of extreme weather events, as well as changing temperatures and precipitation patterns. For climate-sensitive infectious diseases, these changes implicate a shift in geographical and temporal distribution, seasonality, and transmission intensity.
Sizing up the problem: Susceptibility to the deleterious effects of climate change is a net result of the interplay of not only environmental factors, but also human, societal, and economic factors, with social inequalities being a major determinant of vulnerability. The global South is already disproportionately affected by the climate crisis. The financial capacity to pursue adaptation options is also limited and unevenly distributed.
Conclusions: Climate change-induced mortality and morbidity from both infectious and non-infectious diseases, among other adverse scenarios, are expected to rise globally in the future. The coming decade will be crucial for using all remaining opportunities to develop and implement adequate mitigation and adaptation strategies.

Climate change, the IPCC report, and COP26

COVID-19 pandemic aside, climate change is the ultimate challenge of our time. However, to date, there has been insufficient political thrust to make that much-needed climate action a reality. In light of world leaders recently convening in Glasgow for the 2021 United Nations Climate Change Conference (COP26) (COP26, 2021), civil society, NGOs, and scientists around the world are alerting policymakers to all that is at stake, and urging them to take more action to tackle the climate crisis. In a 'call for emergency action' published in the run-up to the conference by more than 200 medical journals, health professionals stress that 'the greatest threat to global public health is the continued failure of world leaders to keep the global temperature rise below 1.5°C and to restore nature' (Atwoli et al., 2021). One of many predicted adverse effects of a global temperature rise above 1.5°C (as compared with 1990 levels) that Atwoli et al. identify in their emergency call is an overall increase in infectious diseases (Atwoli et al., 2021). Specifically, climate change is projected to impact both the endemicity and prevalence of infectious diseases (Lafferty, 2009). These changes are predicted to occur to varying extents in different localities around the globe, which is why a global perspective, together with local

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awareness and action according to the changes and challenges that lie ahead, is warranted.

In the *Special Report on Global Warming of 1.5°C*, the Intergovernmental Panel on Climate Change (IPCC) (IPPC Report, 2021) reports that climate change will affect human health by causing 'changes in the distribution and abundance of vector-borne diseases, such as dengue fever and malaria, which are projected to increase with warming of 1.5°C and further at 2°C in most regions' (Hoegh-Guldberg et al., 2019). Climate change impacts both vector and pathogen distributions, while being synergistically linked with other ecological challenges, including overcrowding, agricultural and industrial land use, excess consumption of natural resources, deforestation, and the pollution of water, air, and soil — all contributing to ecosystem degradation and biodiversity loss (Hess et al., 2020). In the Amazon basin — one of the extreme examples — deforestation has been shown to contribute to the spread of disease vectors (Ellwanger et al., 2020).

Climate change and infectious diseases

Climate change is predicted to alter the incidence, prevalence, and distribution of infectious diseases because it drives changes in temperature and precipitation (Semenza and Paz, 2021; Panic and Ford, 2013). Direct impacts from these changes include the more frequent occurrence and increased magnitude of extreme weather events, such as floods, droughts, and heatwaves. For climate-sensitive infectious diseases, these changes become implicated in a shift in geographical and temporal distribution, seasonality, and transmission intensity (Hoegh-Gueldberg et al., 2019; Semenza and Paz, 2021).

Climate (and climate change, since the beginning of time) is one of many discrete modulators of human, animal, and plant diseases (Nazarov et al., 2020; Heffernan, 2013), in the sense of providing context rather than being a major driver on its own behind disease evolution (Heffernan, 2013). This reminds us that interventions focusing predominantly on climate change as a root cause of changes in infectious disease processes might be falling short of acknowledging the full complexity of the interplay between both initiating and impacting forces (Heffernan, 2013). As Funari et al. emphasize, the simultaneous influences of other causes cannot be understated (Funari et al., 2012). Such causes include the destruction of natural habitats, drug resistance, increasing urbanization, rising population density, variable health service availability, poverty, and human migration and travel (Funari et al. 2012; Heffernan, 2018), which themselves are all closely intertwined with climate change.

Diverse effects of climate change — the examples of malaria and dengue

Across sub-Saharan Africa, warmer temperatures and changing rainfall patterns are likely to increase the suitable breeding habitats for several *Anopheles* species, leading to expansions of the suitable geographical range for malaria in some areas, with predictions of malaria endemicity reaching and intensifying in the African tropical highlands, as well as in the eastern Mediterranean region, and in the Americas (Akpan et al., 2019; Colón-Gonzalez et al., 2021). The same applies, not surprisingly, to other mosquito genera, including *Aedes* spp., with an expected increase in dengue prevalence in the western Pacific region, the eastern Mediterranean region, and beyond (Messina et al. 2019; Colón-Gonzalez et al. 2021). Malaria and dengue are just two examples of several diseases expected to expand their range as a result of climate change.

The multifactorial complexity of mosquito populations, with the associated disease dynamics waxing and waning, is highlighted by the sometimes forgotten fact that the emergence of dengue and its vectors in the Mediterranean region and more northern parts of Europe would be more of a re-emergence than an emergence (Schaffner and Mathis 2014). This highlights once more that climate is only one factor among others affecting disease prevalence.

Thus, not all geographical expansions of vectors and pathogens, or increases in the prevalence of infectious diseases, can simply be explained by climate change. For example, the recent spread of *A. stephensi* from Asia into Africa highlights the complexity of vector and disease expansion, which in this case is better explained by urbanization and migration phenomena (Sinka et al., 2020) rather than climate change and global warming. Moreover, climate change and global warming do not necessarily work unidirectionally in favour of the geographical spread of an infectious disease or an increase in its activity. Indeed, as in the case of *A. stephensi*, it has been shown that increasing temperatures in warmer regions can negatively affect mosquito reproduction and survival, and thus the transmission of *Plasmodium falciparum* (Murdock et al. 2016; Agyekum et al., 2021).

The secondary implications of climate change, such as flooding following torrential rains, or increasingly depleted and polluted global freshwater resources, exacerbate the existing vulnerabilities of health systems, as well as human and animal morbidity and mortality caused by vector-borne, food-borne, and water-borne infectious diseases (Funari et al., 2021; Sarkodie and Strezov, 2019; Ellwanger et al., 2020).

Factors governing climate change, and how to evaluate the problem

Susceptibility to the deleterious effects of climate change is not only a result of the interplay between environmental factors, but is also governed by human, societal, and economic factors, with social inequalities being a major determinant (Semenza and Paz, 2021). The global South is already disproportionately affected by the climate crisis. This is partly due to increased social vulnerability in low-income contexts, where disease risk is amplified by poverty and lack of healthcare services (Heffernan, 2018). The financial capacity to pursue adaptation options is also often limited, and unevenly distributed.

How can the full extent of the problem be correctly evaluated? Which models of thinking are most appropriate, and what practical solutions are at hand? Adaptation to and reaction towards one of those aspects (increasing the distribution and impact of infectious disease) is an important part of the picture, but can that be to any avail if the root causes are not tackled altogether?

Evaluating climate effects, for example on infectious diseases, remains challenging for a number of reasons. Metcalf et al. point out that some infectious disease processes occur hidden from plain view, and that most infections lead to at least partial immunity, possibly depleting the pool of susceptible individuals (Metcalf et al., 2017). This results in changes in transmission dynamics, which can obscure the contribution of climate change to the overall problem. Modelling approaches to simulating climate–disease correlations as they occur under natural conditions remain complex and thus error prone, because some variables might be difficult to factor in (Metcalf et al., 2017). While some models make the assumption that climate is the only factor influencing the distribution of infectious diseases such as *falciparum* malaria, Ostfeld emphasizes that both extrinsic variables, such as climatic effects, as well as intrinsic effects, such as the build-up of immunity in host populations, should be included in models (Ostfeld, 2009). Given that interventions need to be financially affordable, implementation is less feasible in low-resource settings than in developed countries (Ostfeld, 2009). Rohr and Cohen report on the wealth of progress that has been made over recent years in the understanding of how climate and climate change influence disease dynamics (Rohr and Cohen, 2020). However, whilst the logical nature of this concept makes it easy to comprehend and endorse, the science behind understanding how climate change impacts on infectious diseases remains complex.

Mitigation and adaptation

Deliberations on how to tackle both the spread and (re)emergence of infectious diseases under climate change would be incomplete without a discussion of the critical role that climate change mitigation can and needs to play in future damage control. To date, mitigation efforts have been insufficient. If 'business as usual' and the current levels of inaction continue, climate models place us on trajectories of much more than 1.5°C warming by the end of the century (Hoegh-Gueldberg et al., 2019). Intensified mitigation efforts within a very tight timeframe of a couple of years only are thus essential if we are to decelerate and ultimately terminate further global warming. Discourse on climate change mitigation needs to be stepped up, in order to trigger the drastic measures required. Given the IPCC's aforementioned finding that any further increases in temperature will have negative consequences for human, animal, and plant health (Hoegh-Gueldberg et al., 2019) — although we should not forget that the opposite, i.e. climate change in the other direction, would have similarly negative effects (Wan et al., 2019; Cui et al. 2019) — it is absolutely critical that urgent action is taken to limit the global mean temperature increase to below 1.5°C. This will require carbon emission reductions clearly beyond the current trajectory; the health sector alone accounts for 4% of the world's greenhouse gas emissions (Hess et al., 2020). Quite simply, the extent to which mitigation efforts are going to be implemented within the next decade will determine the future of the planet as we know it.

There are some concrete actions that can be undertaken to reduce, and adapt to, infectious disease and other health risks that will be exacerbated by climate change. First of all, adopting a one-health approach will help to understand and address the interactions between the environment, human health, and animal health (Ellwanger et al., 2020). Building on that, there should be increased funding for tackling climate change-related health risks (Hess et al., 2020) as well as pandemic preparedness. Enhanced surveillance is another strategy; this includes intensifying sentinel surveillance (Grobusch et al., 2021), and the development and expansion of overarching strategies linking surveillance activities on national and supranational levels, such as the recent WHO and European Union initiatives (WHO Pandemic and Epidemic Intelligence Hub, 2021; HERA, 2021).

Conclusions

Climate change-induced mortality and morbidity from both infectious and non-infectious diseases, among other adverse scenarios, are expected to rise globally in the future. Infectious diseases are only one facet of the threats arising from climate change. Whilst some infectious diseases will be reduced, climate change effects will mostly propagate infectious diseases. The coming decade will be crucial for using all opportunities left to develop and implement adequate mitigation and adaptation strategies.

Contributors

LCG and MPG jointly conceived and wrote the manuscript, and approved its final version as submitted.

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