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Article

Tackling AMR: A Call for a(N Even) More Integrated and Transdisciplinary Approach between Planetary Health and Earth Scientists

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Abstract: Antibiotic resistance is a pressing global and planetary health challenge. Links between climate change, antibiotic use and the emergence of antibiotic resistance have been well documented, but less attention has been given to the impact(s) of earth systems on specific bacterial livestock diseases at a more granular level. Understanding the precise impacts of climate change on livestock health – and in turn the use of antibiotics to address that ill-health – is important in providing an evidence base to tackle such impacts and to develop practical, implementable and locally acceptable solutions within and beyond current antibiotic stewardship programmes. In this paper, we set out the case for better integration of earth scientists and their specific disciplinary skill set (specifically, problem-solving with incomplete/fragmentary data; the ability to work across four dimensions and at the interface between the present and deep/geological time) into planetary health research. We then discuss a methodology that makes use of risk mapping, a common methodology in earth science but less frequently used in health science, to map disease risk against changing climatic conditions at a granular level. This will enable predictions of future disease risk and risk impacts based on predicted future climate conditions, and thus provide an evidence base for planetary health activists to influence policy and develop mitigations. Our case study – of climate conditions' impact on livestock health in Karnataka, India – clearly evidences the benefit of integrating earth scientists into planetary health research.

Keywords: Climate change; antimicrobial resistance; earth science; risk mapping; transdisciplinarity

1. Introduction

In this paper we highlight the need for more flexible and iterative research agendas to address the climate-change related root drivers of antimicrobial resistance (AMR). The recent addition of the United Nations Environment Programme (UNEP) to the Quadripartite Joint Secretariat on Antimicrobial Resistance between WOAH, FOA, WHO, and now UNEP is welcomed [1], but we argue that there needs to be further bridging between the work of this group and the United Nations Framework Convention on Climate Change (UNFCCC). Climate change and disease risks, including AMR, are two of the most pressing challenges of the Anthropocene and cannot be considered in isolation [2]. Planetary Health is already deeply invested in identifying the complex links between climate change and zoonotic disease [3], to raising awareness of the intersection of Anthropocene risks in general [4, 5, 6] and argues for addressing global and intergenerational

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risks from AMR through a lens of planetary health ethics [7]. Other fields have also made such links explicit [8, 9, 10]. However, fewer commentators focus on specific ways in which earth scientists, environmental scientists and infectious disease researchers can work together to evidence the exact conditions that drive emergence and transmission so that this knowledge can more readily inform both climate change and AMR policy and identify implementable solutions.

Thus far, for example, neither *Challenges* nor *The Lancet Planetary Health*, the planetary health field's two most prominent journals, have published a single original research paper evidencing links between antibiotic resistance and climate change explicitly. Only two short commentary papers [11, 12], the latter of which is by one of the authors of this paper, touch on the specifics of the issue. Whilst we appreciate and are well aware that the field of planetary health has already greatly expanded the range of disciplines whose scholars see their work as part of the future of human flourishing [5], we feel there is a need to reach out still further to additional disciplines that could be more fully engaged into research programmes and to further foster transdisciplinary collaboration, knowledge transfer and the utilisation of discipline-specific skills: in our case study, with earth scientists.

Earth scientists' work has deeply influenced the field of planetary health – not least the work of those involved in determining the earth systems trends of the Great Acceleration [13] and the planetary boundaries of a safe and just operating space for humanity [14] but it is less common to see earth scientists and health scientists working side-by-side on AMR within a single project team.

To begin to address this, in the second part of this paper we will present a case study based on our own research [15, 16] which we believe shows the value in allowing space for transdisciplinary research that more holistically and iteratively integrates earth scientists' discipline-specific skills into planetary health's conceptual framework. These skills include problem-solving with incomplete/fragmentary data [17–19], the ability to think across four dimensions [20] and at the interface between the present and deep/geological time [21]. This, we argue, enables the development of more compelling evidence on changing climate conditions' direct harms to the prevalence and spread of animal bacterial disease, the use of antibiotics to treat it, and thus the emergency of antibiotic resistance.

2. Transdisciplinary research: iterative, agile and adaptive

At this point, it is valuable to tell the story of how we ourselves came to see the value in working together. In the process of conducting research into the drivers of antibiotic use and poor antibiotic stewardship in the Indian livestock sector in a cross-disciplinary team containing microbiologists, veterinarians, anthropologists and economists [12, 22, 23], we listened to farmers and veterinarians in regions of India as far apart as Karnataka in the south and Assam in North-East India who spoke, openly and implicitly during ethnographic observations, of the pressures that climate change places on their livelihoods. The changing climate has already pushed these farmers from crop farming to livestock raising and now stresses the health of their animals [12]. These observations pushed us to consider a closer examination of the environmental drivers of ill-health in order to understand the root causes of antibiotic use intended to treat that ill-health; to consider not only *which* bacteria were present in the environment but *why* and *how* they are there. Whilst a focus on climate change was technically outside of the original remit of our funding and of the project intentions, COVID-19 travel restrictions pushed us into desk-based research using secondary data, and then enabled the replacement of ethnographic researchers, who left the project when they were unable to undertake further fieldwork, with earth scientists who were able to explore climate impacts more deeply.

The evidence produced by the work of the earth scientists [15, 16], highlights not only the value of their discipline to the immediate challenge at hand, but also the benefit of enabling research projects to break out of their original silos when there is clear value in doing so. The recent addition of UNEP to the (now) Quadripartite Secretariat on AMR will hopefully act as a rallying call to other human, animal and planetary health researchers to take an even wider, even more transdisciplinary approach to AMR (and to other health challenges of the Anthropocene) and to other earth and environmental scientists to consider how they too might work together.

There are already frameworks into which such more complex collaboration can fit. For example, the UNICEF-led Integrated Outbreak Analytics programme [15, 25] acts as not only a platform for researchers from diverse fields working with disease outbreak data but also a network through which collaborative researchers can connect, disseminate their work, share methodologies, and seek out future collaborators. We urge more planetary health researchers to connect and collaborate with them.

3. The value of more granular integration of earth science with planetary health

Understanding the impact of climate change on human and livestock health is critical to safeguarding global food supplies and economies and to plan global recovery from the COVID-19 pandemic [2] as well as to maintaining the efficacy of antibiotics. This raises a unique challenge for planetary and one health researchers and practitioners who will need to explore new (and perhaps even yet-to-be-developed) methodologies, knowledge, skills and networks in order to enhance environmental awareness. At least in the short term, such researchers are likely to be working with incomplete and fragmented data, as the regions of the world most affected by climate change are also those where surveillance is less robust [16]. Earth scientists, however, are more than familiar with the challenges of such data [17, 19]. Furthermore, AMR and other wicked problems of the Anthropocene are not only made visible by the earth system trends of the Great Acceleration graphs [13] but are likely to need additional international policies and treaties to solve them, which will need to be underpinned by robust evidence from outside of health science. For example, tempering the spread of antibiotic resistant bacteria and their genes across borders may require approaches similar to those used to address the transborder spread of pollution through air, water and soil, or through travel and trade networks. Providing the evidence to underpin international policy development is likely to require large and transdisciplinary programmes consisting of hydrologists, geologists, atmospheric and climate scientists, geochemists, civil engineers and others, well beyond the microbiologists who understand the emergence and transmission of resistant bacteria and their genetic material; this has been true in the past of, for example, of the development of the Stockholm Convention on Persistent Organic Pollutants [25]; and the development of the Montreal Protocol that protects the ozone layer [26]. Both of these treaties limit the use of chemicals detrimental to the environment, but in each case the impact on (human) health was a driver for the policy adoption and implementation. Future policies may be even more successful if they foreground the risks to health, evidenced by the well-understood risks imposed by earth system changes.

Current policies that govern such movements, such as the 'PICs and POPs' (Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemical and Pesticides in International Trade, and the aforementioned Stockholm Convention) should be considered key planetary health documents, but are less familiar to health systems researchers than to earth scientists. Their history, development, adoption and implementation rarely feature in medical or healthcare curricula, even though human health can be a strong lever for international agreement [27]. Earth science could be better used to understand risk and thus integrate this knowledge into the development of future

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health policy. Working together, earth scientists and health scientists can speak with a collective voice that will be harder for policymakers to ignore.

Recognising that the root drivers of antibiotic use lie outside the (traditional) power of health systems to address is a first step in achieving this end. For example, while microbiologists are able to quantify the levels of bacteria in the environment and their susceptibility (or not) to antibiotics [28] and genomics can map which genes they carry, how closely they are related to other strains and where else those strains are found [29], those same microbiologists will need to reach out to earth scientists to understand, map and predict the meteorological conditions that are most conducive to disease emergence and spread; and to soil and water chemists to understand which pollutants may help to drive antibiotic resistance [30]. The ground set by these collaborative relationships will be even more critical in the later stages of such work: after the mapping processes and meteorological relationships have been founded, the expertise of the microbiologists and veterinarians will be needed to divulge the true impact of the spatial-temporal mapping by carrying out disease surveillance and diagnosis that proves the model as the predicted climatic conditions unfold and disease incidence increases. Experts from both fields will then need to communicate the results of their observations to relevant stakeholders, including commercial farms, governmental bodies, local research institutes etc for true transdisciplinarity to be realised [31].

4. Mapping the spatial distribution of the conditions that drive ill-health

Earth scientists may in turn need to work with modelling specialists to build and automate the production of climate-related risk maps [16] to ensure such models can be utilised as widely as possible, whilst working with veterinarians and farmers to understand not only where these conditions will have impact but also whether those regions are the ones in which livestock production and farming livelihoods are currently located or where industries are planning to expand. In addition, this will require input from animal health observatories to share epidemiological data from regions at risk (including where and when the prevalence of cases and outbreaks changes). Neither epidemiologists nor animal health observatories are strangers to mapping skills and methodologies but earth science brings to the table different ways of interpreting risk and of working with fragmentary and incomplete data [18, 21] over longer timescales, into both the deep past and longer-term future [32]. Geographers are needed too, to map the topography and topology of regions in which those cases occur, and to consider how farmer’s livelihoods, access to veterinary services and patterns of sector transformation are intersecting with climate changes and local development agendas; for example, whilst environmentally controlled chicken sheds might on the surface appear to be a sufficient mitigation to the risks of heat-stress induced disbiosysis and thus reduced immune response that drives higher use of antibiotics in Indian poultry farms, the current failings of rural energy infrastructure prevent this being a practical solution [12]. Looking instead for regions which at present may be cooler than the ideal conditions for livestock rearing, but which may be warming and likely to reach such thresholds in future, so that expansion into such regions can be planned, or which currently favour poultry rearing but are becoming more suited to aquaculture, are alternative options. Such integrated methodologies and ways of working have value beyond livestock farming to human health, and also encourage working with public health officers to look at how else data can be combined, e.g. on the intersection of the spatial distribution of cases of human disease with distributions of social deprivation [33], location of healthcare infrastructure [34] and access to blue and green space [35]. There is growing interest in human health fields in ensuring the integration of air quality and health [36], soil pollution and health [37] etc, on increasingly granular spatial scales. The UK’s National Health Service [38] is a world-leader in setting a Green Agenda

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for health [39], aiming towards net-zero carbon operations by 2040, and this has, at least in part, been achieved by showing that improving public health cannot be considered without the integrated reform of transport systems, renewable energy and consideration of reduced plastic use [39]. This approach has been as dependent on earth science as it has on approaches that have come from inside health systems and medical science. *Figure 1* demonstrates the sizable shared space between health and climate science, seen through the skillset of an earth scientist, as well as the way in which this overlap is manifest across different stakeholders and geographical scales.

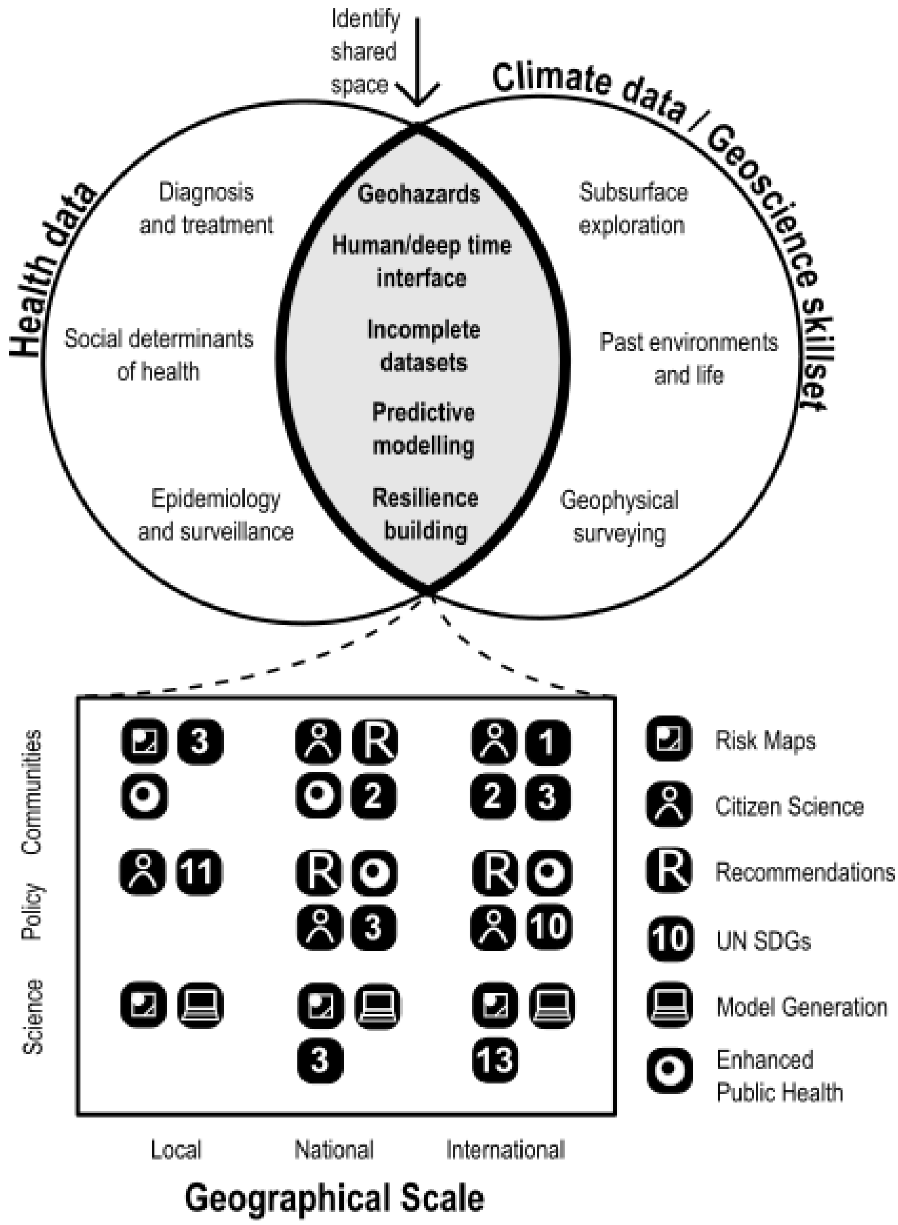

Figure 1. Conceptualisation of the shared space between health and climate/earth science, together with benefits to different stakeholders across different scales.

Practitioners of OneHealth (defined by the OneHealth Commission [40] as "an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems [that] recognizes the health of humans, domestic and wild animals, plants, and the wider environment including ecosystems are closely linked and interdependent") are quick to point out that animal health and human health cannot and should not be considered independently [41]. Furthermore, true transdisciplinarity must include practitioners and communities: farmers, like patients, can report symptoms of ill-health, bringing in value from citizen science, another methodology earth science has long embraced [42]. To understand what is making animals ill, however, a systematic and systemwide approach is needed to look at the holistic environment and the conditions within it that create disease 'situations' (where conditions such overcrowding and poor welfare stress animals' immune responses and causes otherwise commensal bacteria to become pathogenic: [43]), and to map the 'exposome', the ecosystem of external risk exposures [44].

How these risk exposures combine (with or without antibiotic exposure) to influence, support or challenge equally complex animal and human microbiomes is still poorly understood, despite the considerable work of the decade-long Human Microbiome Project [45]. Tellingly, this has included neither earth science nor a consideration of how climate drivers such as recent and rapid increases in the magnitude and severity of geohazards (e.g. heatwaves and monsoon rainfall) may impact microbiomes. Because of the complexity that is now developing, systems thinkers [46] and modellers will be needed, who will need to be able to combine multiple insights to model not only the risks that have already been identified, and help predict where they may increase (or decrease) in future, but also how the system-of-systems those risks inhabit are configured. Even then, ethnographers and economists will need to work with communities to determine what can be done to mitigate the predicted risks in a manner that is practical, acceptable and affordable; changing people's behaviour towards making more rational choices regarding the use of antibiotics, let alone for the overall health of themselves or the planet, is far from being a trivial exercise [47].

6. A new methodology for mapping the climate/disease risk interface

Having set the scene for why closer integration of earth scientists into planetary health research teams has scientific value, we showcase our recent work in southern India [16] to demonstrate how a methodology we have developed offers a first step towards the future integration of researchers from interrelated and overlapping fields, so that each can link their data with others through a causal chain of (in our case, animal) ill-health. This, we hope, will help to drive interest in the need to better understand the factors that govern environmental change (e.g. monsoon dynamics) in the present and future, and their implications on human and animal health.

Our research emerged from two Newton-Bhabha Fund projects that aimed to address drivers of Antimicrobial Resistance (AMR) in India, through quantifying and qualifying the presence of antibiotic resistant bacteria in food animals, the farms on which they are raised and the environments in which they are sold [28, 29, 48, 49] as well as understanding the behavioural drivers influencing the use of antibiotics by farmers [12, 23] and vets [22].

Farmers' insights and lived experiences [12, 22, 23], observed during a rapid ethnographic assessment of livestock systems and recorded in semi-structured interviews, focus groups and transect walks through peri-urban farming communities, led us to consider the role of climate change on animal ill-health as a trigger for antibiotic use. This in turn led us to develop a risk classification tool that assesses how disease risk varies in Karnataka in the present and in possible future scenarios. Despite a relatively limited epidemiological dataset (from the NADRES-v2 database [50]), clear relationships between bacterial disease and high-risk zones were defined using time-series data over a period of 33 years (1987–2020). By constructing risk maps, which are common across geoscientific (e.g. for volcanic hazard and flood risk) and epidemiological research, we used a physics-based statistical approach to define risk thresholds based on the inferred relationships between climate and disease data. The maps were constructed using open-source climate

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data (Climate Research Unit (CRU) TS 4.5 dataset). Thresholds for risk were defined by using the inferred relationships between the climate data and disease data after statistically investigating the spatio-temporal relations between the two, first with correlative statistical analysis (Spearman's rank) followed by principal component analysis (PCA). Through this methodology it is possible to interpret the individual climate variable contribution to risk in each grid box, providing insight into the varying climatic controls for higher and lower risk across the areas. Although there are far more socio-economic factors that also play a role in predicting disease outbreak risk (farm locations, population density, sanitation standards, food standards, veterinary access, vaccination campaigns etc.), these are typically more granular controls whilst climate-associated risk is useful for a ‘bigger picture’ perspective – identifying complete regions of higher and lower risk, which can then be investigated in more detail using the aforementioned socio-economic factors.

Our transdisciplinary approach led us to identify that hitherto unconsidered changes in the key climate variables of precipitation and vapour pressure (i.e. humidity) are the most important factor governing outbreaks of haemorrhagic septicaemia (HS), anthrax (AX), and black quarter (BQ) in livestock across the Indian state of Karnataka. Unaddressed, such outbreaks risk economic damage to the farming community, food security and, in turn, poorer livelihoods for those dependent on both the farming economy and the food it produces, but addressing them needs more granular data on precisely which climate conditions are likely to impact which specific diseases, in which species, in which regions and over what timescales, ensuring that those informed by the data will have sufficient time to act.

We intend to continue working with this methodology, improving the robustness of the risk maps by defining more quantitative thresholds upon which disease outbreaks may relate to specific climate variable change i.e. at what average rainfall, at what average temperatures, and at what average vapour pressure does risk increase; we will need to work across more disciplines, for example with computational modellers, livestock and human disease experts, ethnographers and local data collectors, to achieve these aims. We hope to provide a new platform through which planetary health researchers and earth scientists can come together in new transdisciplinary spaces. In order to achieve this, we seek more robust, long-term disease data across a variety of global case studies (currently Nepal, Egypt, Kenya, South America), preferably with diverse meteorological conditions to provide the best range of test scenarios – data that other planetary health researchers may hold or be encouraged to gather. Ideal outputs from this modelling work are captured in Figure 2, where each case study will have the raw data presented in time-series graphs, followed by the statistical correlative results, then finally the risk maps themselves. While our research in India was primarily interested in drivers of AMR, and thus bacterial diseases, this methodology can be replicated to investigate other diseases and other regions, or even climatic conditions that impact crop yields, as long as the climate and epidemiological/harvesting data cover similar time periods.

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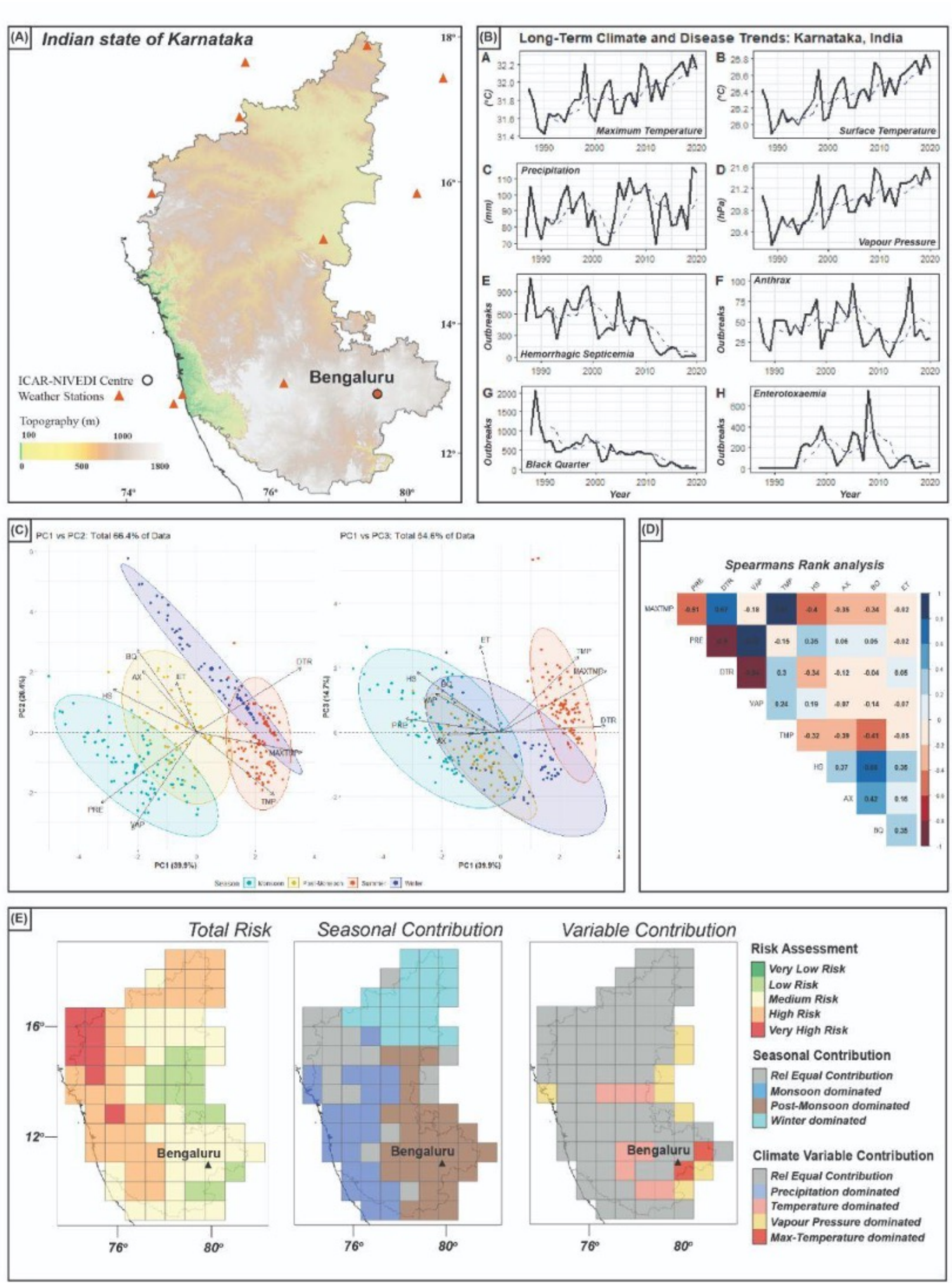

Figure 2. Generalised output for risk-mapping model, using state of Karnataka as an example: (A) Location map for Karnataka; (B) time-series graphs for both climate variable data and disease outbreak data; (C) PCA results for combined data; (D) Spearman's rank correlation statistics between climate and disease data; (E) final risk map output with seasonal contribution to risk, and individual variable contribution to risk also mapped in grid-box format. Data presented is modified from Eskdale et al. 2022.

7. Towards climate models for social justice

Beyond animal health, once earth scientists' skill sets are embedded into research investigating the underlying drivers of bacterial disease, antibiotic use and thus the emergence of resistance to antibiotics, they can be cascaded out to human health research more widely. Increasing unpredictability and magnitudes of annual hydrological budgets (inflows, outflows and storage of water), greater temperature and wet-bulb humidity extremes, as well as the effects of this on the environmental realm (such as exacerbating the magnitude of air and water pollution) increases the risks associated with human health conditions such as obesity, diabetes and hypertension, which in turn increases susceptibility to more severe symptoms of respiratory diseases, including COVID-19 [51], particularly during heatwaves [52]. On 7 October 2022, a joint report published by the Office for National Statistics and UK Health Security Agency indicated there had been 3,000 more deaths in England and Wales than would usually be expected during the year's unusually hot summer [53].

The impact of climate factors is known to intersect strongly with socioeconomic deprivation [54]: evidencing this impact may help to drive policy to tackle underlying socioeconomic drivers at source and thus help to deliver justice to the most vulnerable pockets of society, speaking to planetary health's strong ethical focus on championing equity and social justice [55]. Short of relocating agricultural operations to regions of the world less impacted by climate stress, and human populations to regions where their livelihoods will be made less precarious by climate change, developing a methodology for identifying, at very precise granular resolutions, where the areas of highest risk are found – today and in the short-mid-term future – so that limited resources for intervention can be prioritised to where they are needed most acutely provides a practical mid-term intervention strategy.

Thus, only by taking a system-of-systems approach to health, working simultaneously across all the societal systems and earth systems implicated in the Great Acceleration [13], will we be able to address the real underlying drivers that place pressure on those systems. For all planetary health's lauding of the conceptual framework of the Great Acceleration and planetary boundaries [13, 14], truly integrated, evidence-producing projects between earth scientists, health systems scientists and social scientists remain scarce. This is in spite of strong evidence that earth systems change profoundly challenges human, animal and plant health directly e.g. through ill-health caused by heat-stress [56, 57] and crop failure [58, 59], and indirectly e.g. through increased incidence of biological disease caused by pathogens that proliferate more in warmer conditions [60]; or food shortages [61] that cause malnutrition and reduce the immune response. In short, we argue that research on the drivers of antibiotic resistance can no longer afford *not* to embrace earth scientists, wider environmental considerations and earth systems science more fully.

Health researchers need to go further than just referring to the current climate science literature by meaningfully integrating earth systems scientists into their ongoing research across the entire lifecycle of a research project, from problem conception/definition, to co-development of data collection and analysis methods, to the dissemination of data/information to relevant stakeholders. This in turn leads on to other considerations: once engaged, earth scientists might look to develop enhanced process understanding of e.g. the monsoon; health scientists might want to determine under what specific climate conditions disease transmission or severity of cases increases, and if the relationship is linear, logarithmic or if it reaches a tipping point aligned to regime change [62]. Local communities will be able to use the evidence earth scientists provide to invest in or implement new ways to de-risk their livestock falling ill and thus safeguard their future livelihoods; government stakeholders will be able to use the same data to protect their population and economies. True earth/health collaboration would satisfy all of these stakeholder needs, and would involve an equitable and fair balance of resources and time, which goes far beyond just having a token health scientist on a largely earth science programme or vice versa.

8. Conclusions

Successful transdisciplinary research projects such as the one we have described in this paper have the potential to tackle larger, international and complex issues that affect global communities and speak directly to planetary health's willingness to face up to even the most complex and challenging 'wicked problems' of the Anthropocene [63, 64] The evidence our research provides, of granular links between specific diseases and specific climate conditions, highlights the need for greater synergies between earth scientists, climate change science, planetary and OneHealth research and policy formation. In the short-term, we argue this puts forward a(n even) strong(er) case for greater alignment between the Quadripartite Agreement (between WOAH, FOA, WHO, and UNEP) on antimicrobial resistance and the United Nations Framework Convention on Climate Change (UNFCCC) as these two pressing challenges of the Anthropocene cannot be considered in isolation.

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