The Interconnectedness of Knowledge in Times of Climate-Related Uncertainties and Unknowns

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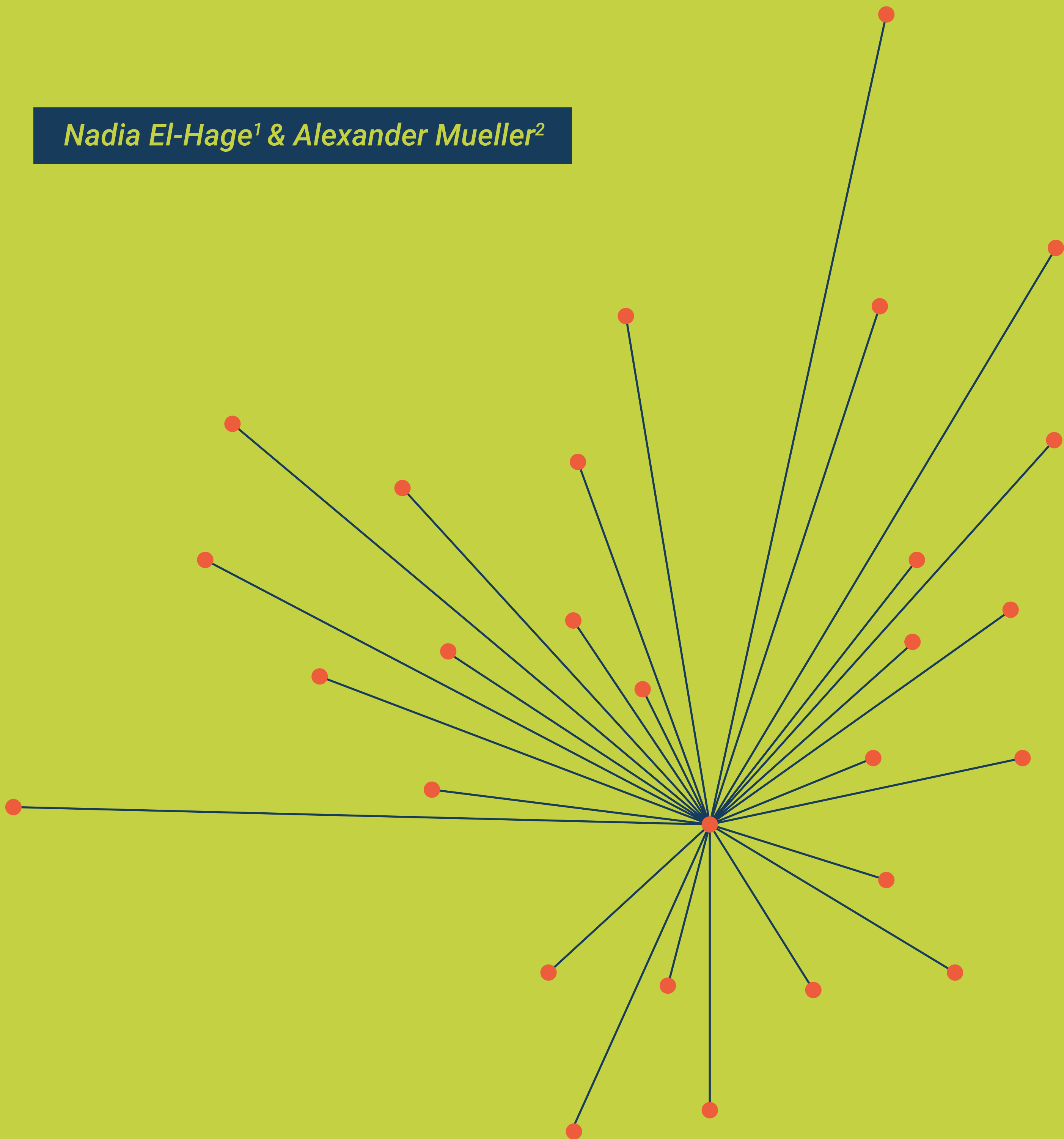

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Abstract

Climate-related risks and challenges compound threats posed by the impacts of human economic activities on natural systems, as climate change is bringing new and additional uncertainties and unknown risks. Climate change results in temporal or spatial mismatches in predator-prey, insect-plant and host-parasite relationships, and the rise in temperature is directly related to the emergence and re-emergence of vector-borne diseases and zoonosis that have become global human health threats. One 'known unknown' is that climate change is expected to impact the arthropod vectors and free stages of macro-parasites of animals, as well as eventual new transmission modalities and different host species.

The analysis of outbreak experiences such as Ebola, Nipah, cholera and Covid-19 strongly demonstrates that disaster preparedness responses must embrace incertitude. Science is able to inform us about climate change triggering new and different outbreaks of pests and diseases – but the concrete form and the timing of those events remains unknown. However, adaptation to and management of these 'unknown' risks and uncertainties is a necessity. Preparedness to risks requires a different approach, involving all types of knowledge to develop new and more appropriate coping strategies.

The One Health approach, based on networked and transdisciplinary research that considers the health of the "people-animals-plants" ecosystem as one continuum, requires knowledge of climate impacts on epidemiological and ecological interactions between pathogens, plants, animals, and the associated microbial communities. Citizen science is particularly important in researching novel pests and diseases where data on the presence, absence, abundance, expansion rate, and phenology of species is unknown, particularly in relation to post-border surveillance. By favouring quantity in data collection, natural variation of large-scale phenomena can be better captured and models that simulate natural phenomena can unveil emergent unknowns.

Considering that such inter-connected knowledge is nowadays feasible thanks to technological innovations to collect, analyse and share information across borders, a global competency Climate-Related Early Action Network (CREA-Net) is proposed to anticipate climate-related pest and disease hazards of planetary significance. East Africa, the region where conventional early warning systems have shown their limits, could be the first CREA-Net hub.

Keywords: *climate change . transboundary pests and diseases . uncertainties . unknowns . knowledge systems . citizen science . One Health .*

Introduction

Climate change is exacerbating biodiversity loss, pandemics, human and animal transboundary migrations, food and water insecurity, and loss of livelihoods, and this trend is expected to worsen in the future. In our era of protracted polycrises, decision-makers need 360 degrees insights that can only be generated by mobilizing diverse knowledge systems. In fact, the discussions held during a 2022 international conference[1] shared the view that the wealth of scientific knowledge available today remains untapped, due to disciplinary silos, slow response times, and lack of integration of scientists in crisis situations[2].

Risk assessment, risk management and risk communication must be designed in a way that new climate-related uncertainties could be integrated into a targeted approach that manages both well-known risks and new unknowns. Knowledge and management systems must be prepared to identify, as early as possible, every pest and/or disease outbreak, so that 'unknown threats' could be transformed into concrete action to mitigate and adapt.

Holistic responses require networked research design and co-produced strategies to allow timely and concerted action before a risk turns into a humanitarian emergency. Participatory uncertainty analysis that incorporates scientific and traditional knowledge can significantly enhance preparedness and resilience to unknown natural phenomena, such as crop and animal pest and disease epidemics and pandemics. To this end, rigid institutional boundaries must be overcome through both interdisciplinary and transdisciplinary science that involves all sectors and all stakeholders through global cooperation. Artificial Intelligence is based on a similar mechanism of globally drawing upon all types of knowledge by transcending institutional boundaries. Should humans upgrade this same principle with their collective creativity and intuition, a very powerful and effective science would develop for safely navigating uncertainties and risks.

Climate-related uncertainties and unknowns in agriculture

The climate crisis is a multiplier of already existing risks, while creating new ones. For instance, it alters the spread and the frequency of zoonotic diseases with pandemic potential. The ecology of landscapes is changing in par with climate change, and ecological risks are getting more complex because habitats and biodiversity are extraordinarily pressured. Humanity knows that sooner or later a zoonotic outbreak will happen … though nobody knows when, nor what these climate-related challenges are adding to the already known risks.

Crop and animal pests and diseases that climate science understands

According to the sixth IPCC Assessment Report (2022)[3], there is high confidence that climate risks are appearing faster and will get more severe sooner. Climate change-driven range shifts of wildlife, and loss of wildlife habitat quality, present increased opportunities for pathogens to spread from wildlife to human populations, which has already resulted in increased emergence of zoonotic disease epidemics and pandemics, including zoonoses increased incidence (e.g. anthrax) and polewards spreading. Species in all ecosystems have shifted their geographic ranges and altered the timing of seasonal events; half to two-thirds have shifted their ranges to higher latitudes, and approximately two-thirds have shifted towards earlier spring life events in response to warming. The move of diseases and their vectors has brought new diseases at higher elevations in mountain regions to which local wildlife and humans are not resistant. These processes have led to emerging hybridisation, competition, temporal or spatial mismatches in predator-prey, insect-plant and host-parasite relationships and invasion of alien plant pests or pathogens. Climatically disrupted ecosystems will make organisms more susceptible to disease via reduced immunity and biodiversity losses, which can increase disease transmission. Depending on location and human-wildlife interactions, climate-driven shifts in distributions of wild animals increase the risk of emergence of novel human infectious diseases, as has occurred with SARS, MERS and SARS-CoV-2.

Higher temperatures, combined with land use/land cover change, are making more areas suitable for the transmission of vector-borne disease outbreaks in humans, facilitating the spread of chikungunya virus in America, Europe and Asia, tick-borne encephalitis in Europe, Rift Valley fever in Africa, West Nile fever in southeastern Europe, western Asia, the Canadian prairies and parts of the USA, Lyme disease vectors in North America and Europe, malaria in eastern and southern Africa, and dengue globally. Regarding distribution of impacts, observed and modelled impacts indicate much more negative impacts on food security in low to mid-latitudes, with malaria, dengue, Lyme disease and West Nile fever projected to increase regionally and globally.

The Lancet Countdown on Health and Climate Change identifies the increasing consequences of infectious diseases as the foremost global health threat[4], and the rise in temperature is directly related to the emergence and re-emergence of vector-borne diseases[1] and zoonosis[5]. Because the main environmental

1 Vector-borne diseases, which are a subset of zoonotic diseases, are particularly susceptible to changes in the environment and exhibit complex epidemiology, allowing them to thrive in a dynamic world. Bartlow AW, Manore C, Xu C, Kaufeld KA, Del Valle S, Ziemann A, Fairchild G, Fair JM (2019) Forecasting zoonotic infectious disease response to climate change: mosquito vectors and a changing environment. Veterinary sciences 6(2):40.

exposure pathway interacting with climate risks that shapes human health is vector distribution and ecology (along with heat-related mortality), the solution space recommended by the IPCC is health information systems. These include integrated risk monitoring and early warning and response systems; vulnerability, capacity, and adaptation assessments; and the health component of national adaptation plans, health, and climate research.

Climate-related uncertainties and pests and diseases' unknowns

Current emergency preparedness approaches fail to address uncertainty, where outcomes or their probabilities are unknowns. The analysis of outbreak experiences such as Ebola, Nipah, cholera and Covid-19 strongly demonstrate that disaster preparedness responses must embrace incertitude. Looking beyond what is assumed to be risk, the diversity of contexts, pathogens and people shape how an outbreak unfolds in unpredictable ways, in which ongoing biological, social, and political dynamics interplay with each other over different time-scales. Future uncertainties are not necessarily apprehended as linear and ordered, but collapsed and layered. Thus, rather than expert-led risk management models, open-ended methodologies are needed to embrace uncertainty, while acknowledging that ignorance exists and surprises will occur[6]. For example, complex interactions of climate change, land use change, carbon dioxide fluxes and vegetation changes, combined with insect outbreaks and other disturbances, will regulate the future carbon balance of the biosphere - processes incompletely represented in current Earth system models. The exact timing and magnitude of climate–biosphere feedbacks and potential tipping points of carbon loss are characterised by large uncertainty, but studies of feedbacks indicate increased ecosystem carbon losses can cause large future temperature increases.

Change in temperature resulting in changes in species composition and interactions creates new ecological niches that are bound to augment the emergence of new diseases and pests. Unforeseen emergence of 'new' diseases and pests has been relatively common in the past decade (the global average temperature had already increased by 1°C from pre-industrial levels), as new vectors, selection and recombination of disease genotypes occur when animal species and breeds and plant species and varieties mix, or when insect pests and vectors are introduced without their natural enemies. A 'known unknown' is that climate change is expected to impact the arthropod vectors and free stages of macro-parasites of animals, as well as eventual new transmission modalities and different host species. Both developing and developed countries will be subject to increased incidence or newly emerging diseases that are difficult to predict but temperate countries will particularly be vulnerable to invasions by exotic arthropod-borne virus diseases and macro-parasites. Diseases caused by arthropod-borne viruses (arboviruses) include many vector-borne arthropods (mosquitoes, midges, ticks, fleas, sand flies, etc.) that are often zoonotic, predominantly RNA viruses, that can cause haemorrhagic fevers or encephalitis in humans. Emerging arbovirus disease complexes are by far the most important burden to public health worldwide. They mostly spill over from natural reservoirs, such as bats, birds, and rodents or other wild mammals - and climate change is only one factor altering disease ecologies. Climate change effects on livestock infectious disease may be extremely complex. Apart from the effects on pathogens, hosts, vectors and epidemiology, there may be other indirect effects on the abundance or distribution of the vectors' competitors, predators, and parasites. For example, in the pastoral areas of East Africa, drier conditions may mean fewer water points and thus, more intense interactions between livestock and wildlife.

Drivers of plant pest change include increase in temperature, variability in rainfall intensity and distribution, change in seasonality, drought, CO_2 concentration in the atmosphere and extreme events (e.g. storms). Change is also induced by intrinsic pest characteristics (e.g. diapause, number of generations, minimum, maximum and optimum growth temperature of fungi, interaction with the host) and intrinsic ecosystem characteristics (e.g. monoculture, biodiversity). Emerging pests are often plant pests of related species known as 'new encounter' pests, which meet new hosts that do not necessarily have an appropriate level of resistance, or are plant pests introduced without their biological control agents (in particular, insect pests, nematodes, and weeds)[7].

Preparing for uncertainties and unknowns

How can we start preparing to deal with the new unknowns? How to be prepared for a situation of uncertainty? Do we know what the next outbreak will be and when it will come? For sure, something will be coming with climate change, as habitats and biodiversity are pressured. To answer this question, a One Health knowledge system, based on networked and transdisciplinary research, is necessary[8]. Research interventions based on the One Health framework hold promise to effectively prevent climate change pest and disease risks[2].

Interdisciplinary science

Climate change and induced ecosystem changes expand pests and diseases across novel geographical and hosts ranges and thus, the dispersal of emerging and re-emerging pests and diseases. Creating climate-resilient agricultural and natural ecosystems through appropriate management practices requires knowledge of climate impacts on the molecular, epidemiological, and ecological interactions between pathogens, plants, animals, and the associated microbial communities. Within epidemiological models, climate change serves as one of the primary environmental factors that facilitates the spread of diseases; it creates a hospitable environment for disease agents such as bacteria, viruses, or secondary vectors, and plays a fundamental role in socioeconomic variations that are closely tied to public health[9]. Furthermore, risk is characterized by uncertainty, interconnectedness, and integration, influenced by factors such as global epidemiology, pathogen adaptation, changing demographics, evolving food production systems, and climate change[10].

There is a need for a better impact assessment of climate change on animal and plant pests and diseases. Methods exist for risk analysis but the application of methods within the context of climate change to assess risks of entry, establishment and spread of threats requires a large extensive and reliable data. In principle, it is possible to estimate the area that is climatically receptive to a species, with the usual caveats on genetic homogeneity, biotic interactions at both the source and destinations, and human-modified microhabitats, such as irrigated crops. To understand the contribution of climate change to pest and disease outbreaks, there is a need to monitor indicators of change in biosecurity in relation to rates of invasions by foreign species, rates of crop, livestock, forest, and fish losses. To enable such risk assessment, preven-

2 Arab nations are now far more prepared against MERS-CoV thanks to the One Health concept, involving enhanced monitoring, enhanced fast response capabilities, and enhanced international communication.

tion, monitoring and control, there is a need for data exchange mechanisms covering the distribution of diseases, pests, invasive alien species and correlated ecological conditions including climate.

The top priority for dealing with animal and plant pests and diseases is strengthening of national veterinary and plant health services and animal and plant health systems through better surveillance, rapid diagnostic tools and forecasting models. Basic sciences involved include climate change science, taxonomy, modelling, population ecology and epidemiology.

Transdisciplinary science

Climate-related problems are characterized by complex processes with nonlinear dynamics, indirect effects and feedbacks across spatial and temporal scales, emergent properties, uncertainties around the relationships between causes and effects, and challenging ambiguities. As global environmental change accelerates and intensifies, a diversity in both data and actors is needed to face unprecedented challenges. Transdisciplinary research bridges the gap between different pools of knowledge and social orientations, involving different actors in problem definition, knowledge generation and problem solution[11]. Socio-ecological system models can be co-designed for transdisciplinary applications[12].

In case of a zoonotic outbreak, early warning and action, and transdisciplinary science (i.e. expert and citizen science combined) will guide responses, as experiential and contextual knowledge of the actors dealing with complex questions is particularly relevant. The incorporation of indigenous knowledge, local knowledge, and associated scholars is essential. While expert scientific knowledge is crucial, indigenous knowledge contains unique information sources about past changes and potential solutions to present issues; such local knowledge can contribute to reducing the vulnerability of communities to climate change. Most importantly, and as the IPCC AR6 argues, since many solutions are rooted at the local level, strategies rooted in community engagement are needed before communities lose the ability to adapt.

Engaging local communities in the scientific process is often referred to as citizen science. Citizen science is particularly important in researching novel pests and diseases where data on the presence, absence, abundance, expansion rate, and phenology of species is unknown, particularly in relation to post-border surveillance[13]. Data generated by citizen science is currently widely employed to monitor biodiversity and detect biological invasions in all environmental realms[14,15], thanks to the availability of smartphone and web applications[16]. Given the way climate change is expected to alter species distributions[17], citizen science data is deemed important in future predictive models of biological invasions.

One Health approach

The One Health approach recognizes the interconnection between people, animals, plants, and their shared environment. Although this concept is not new, many factors have lately accelerated their interactions, such as climate change and increased movement of people and products across borders. In particular, Covid-19 showed the need for investing in One Health prevention and response systems to future threats. One Health is the pillar of the Global Health Strategy that the European Commission put forward in 2022 and is very much part of the international Pandemic Agreement that is currently under negotiation[18]. Thus far, the One Health approach, launched in 2001 following the mad-cow disease and rooted in veterinary science, rested on the people-animals-ecosystem health triad to target zoonotic diseases. One Health, however, extends into food safety related to plants (e.g. aflatoxin contamination), biosecurity risks, and invasive species in food systems (e.g. crop pests and diseases). With accelerating crop pest expansion due to climate change, One Health ought to globally extend to a more comprehensive framework by considering people-animals-*plants*-ecosystems' health.

Through a One Health lens, biological control offers global benefits to mitigate global chemical pollution, biocide resistance, biodiversity loss, and habitat destruction that remain critically under-appreciated despite over 60 years of integrated pest management. A systems-level, integrated approach to biological control research, policy, and practice considers the direct and indirect benefits for the four dimensions of One Health, from invasive crop pests and diseases, through antimicrobial resistance in livestock, to disease vectors that lack effective chemistry-based strategies (e.g. Wolbachia bacteria in arthropods)[19].

The example of the highly pathogenic avian influenza virus of the subtype H5 that caused spillover infections (black-headed gulls in Germany, gannets in the UK, grizzlies in the USA, sea lions in Chile and poultry in many countries) illustrates how diseases connectivity and dynamics are being researched from an inter- and trans-disciplinary perspectives. The KAPPA-FLU consortium of partners from three continents and different disciplines cooperates through the One Health approach, including the impact of climate change and zoonotic risks. Work packages are organised into interconnected research themes: disease ecology (HPAI dynamics in migratory waterbirds under global change and spill-over into poultry); virology (replicative fitness for wild and domestic birds and zoonotic risks and genotype-phenotype relations); and agro-ecosystem risk (understanding and managing risks to poultry through geospatial predictive modelling of outbreaks and other tools) – all linked by an overarching work package for coordination and management, including a multi-actor Panel[20].

Unveiling unknowns

Reducing uncertainties through transdisciplinary science is essential to strengthen scientific outcomes and detect novel or re-merging pests and diseases and their dynamics across space and time. Addressing uncertainty starts by identifying potential sources of pests and diseases. The occurrence of an unknown natural variation (i.e. a general knowledge gap around the biology and dynamics of a given species) will trigger the motivation to investigate the phenomenon by collecting relevant data and analysing epidemiological and ecological interactions between pathogens, plants, animals, and the associated microbial communities. Collaborative partnerships involve different levels of experience and skills of community members and experts to unveil varying types and degrees of uncertainty. Uncertainty is due to incomplete information in the data collection stage and subsequent analysis of data; by favouring quantity in data collection, natural variation of large-scale phenomena can be better captured[21]. Information learnt during data analysis may lead to new research questions that require refinements of the research model.

The inter- and transdisciplinary enquiry framework used for biological invasions, and that applies to climate change and conservation science, unfolds along four steps: clearly *circumscribe* the phenomenon (i.e. biogeographic invasion process); measure and provide evidence for the phenomenon by acquiring temporal data at various spatial scales (i.e. *confirmation*), ideally through citizen science; understand the mechanisms that *cause* the phenomenon, including both species invasiveness and the receiving socio-ecological environment factors (i.e. ecosystem invasibility); and understand the mechanisms through which the phenomenon results in *consequences* (i.e. negative impacts)[22]. Understanding undelaying mechanisms turns 'known unknowns' into 'known knowns'.

Furthermore, mechanistic modelling allows moving beyond 'known unknowns' (i.e. patterns previously observed but not fully understood) to discover 'unknown unknowns' (emergent predictions unconfirmed in the literature), through *pattern-oriented models* of intermediate complexity that reproduce multiple patterns. When a simulation model produces patterns or phenomena that have not yet been observed or studied in the real world, these can be verified through experimentation or new data exploration, and lead to what can be called 'emergent unknown questions'[23]. To this end, well-validated simulation models ought to reproduce the most significant drivers in the natural system's structure and dynamics, according to the model research question and testable predictions (e.g. pest management). Such pattern-oriented modelling holds significant potential to empower researchers to make groundbreaking discoveries.

Towards a new global knowledge governance model

Considering the vast areas of on-going research in crop and animal pests and diseases and the new digital tools humanity possess for sharing and cooperating, it becomes feasible to envision the iterative development of a global competency centre to anticipate climate-related pest and disease hazards of planetary significance.

A Climate-Related Early Action – Network (CREA-Net) seeks to anticipate all kinds of climate-related crop and animal pests and diseases, by providing a novel approach to knowledge generation. Interdisciplinary and transdisciplinary knowledge management and communication predicting hotspots of important pests and diseases is the first stepping stone of effective disaster risk reduction strategies, in the face of increasing unpredictability brought by climate change. One Health scientific research and evidence will assemble, analyse, store data, and provide evidence and tools for monitoring disease progression and risks of new pest/disease ecology and biology, encompassing climate, ecology, agronomy, entomology, veterinary science and innovative space and digital technologies. Scientists, local communities, and private enterprises, in partnership with national, regional, continental, and international institutions, will empower preventive action through the 'right' measures to deal with unknown problems and mitigate new emerging or fast-spreading risks.

Formed through alliances of existing institutions, CREA-Net is envisioned as an "institution without walls" with distributed governance. The organization will be a network of collaborative arrangements between research centres formally within CREA-Net, as well as partnerships with research institutes and networks outside of the system. Acting as one entity, CREA-Net's vision is that multi-source, robust and trusty climate-related transboundary crop and animal pests and diseases knowledge is readily available to multi-hazard early warning-early action systems by 2030.

The expected outcome of CREA-Net is advancing One Health applied research in crop and animal pests and diseases. Research will integrate various sectors and actors, such as laboratory scientists, field researchers, farmers, local communities, research institutes and universities involved in agriculture, climate change and ecology. Scientists will investigate phenomena with practitioners detaining local ecological knowledge (e.g. farmers, indigenous communities) to foster joint learning, ownership, and early action. Training institutions will partner with CREA-Net Centres to develop curricula and extension work that uses and disseminates research results, thus moving research results from the "laboratory" into the field.

CREA-Net's mission will be to produce high quality and transdisciplinary research that creates a new model for the development community to deal with emerging and uncertain challenges.

Getting started in East Africa

The IPCC AR6 maps of relative vulnerability to climate hazards clearly show that Africa, especially south of the Sahara, rates as very highly vulnerable, with severe challenges on all nine aspects of vulnerability: extreme poverty, access to health care, dependency ratio, access to basic infrastructure, gender inequality, food security, adult literacy rate, health status and governance. East Africa is further hampered by conflicts, political instability, natural hazards, severe hydro-meteorological phenomena, inappropriate information facilities, and ineffective-delayed action when a hazard strikes. Conventional early warning systems have shown their limits, as demonstrated by the 2020-22 Desert Locust outbreak in the region, demonstrating that anticipatory knowledge to prevent emergencies is clearly insufficient.

By establishing a first CREA-Net hub in East Africa, the world community would seed a knowledge base where most needed, while preventing today's vexing transboundary pest and diseases risks. Compared to the high amount of scattered international emergency investments in East Africa, CREA-Net constitutes a sustainable foundation for long-term gains in agriculture and health, as region-based institutes will support high-quality research for climate-related transboundary crop/animal pests and diseases. Vibrant research networks will be supported by cutting-edge technologies stimulating novel international collaborations, and synergies with be built with regional and continental multi-hazard early warning-early action efforts.

Conclusion

Preventing climate-related transboundary pest and disease threats requires extensive and reliable data in climate change science, taxonomy, modelling, population ecology, and epidemiology. With the help of technological breakthroughs to model and analyse natural variations of large-scale phenomena, cooperation across disciplines of both scientists and citizens along the One Health approach is the currently best available solution for effective risk assessment, prevention, monitoring and control of diseases, pests, invasive alien species and correlated ecological conditions, including climate. The proposed Climate-Related Early Action – Network (CREA-Net) will help transform unknown theoretical threats into known and manageable challenges by timely identifying pests and diseases and thus will empower early warning and early actions, mitigate threats, and adapt to climate change. A first CREA-Net hub could be established in East Africa where climate-related emergencies are most pressing and substantial scattered efforts could converge along the common CREA-Net objective.

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