

Results

Cite this article: Fernandez de Cordoba Farini C (2023). Are current warning and responses systems suitable to respond to emerging infectious diseases? *Research Directions: One Health*, 1, e17, 1–12. <https://doi.org/10.1017/one.2023.10>

Received: 7 March 2023
Revised: 3 August 2023
Accepted: 8 August 2023

Keywords:

warning and response systems; disease drivers; disease ecology; multi-sectoral collaboration; infectious diseases


Corresponding author:

Claudia Fernandez de Cordoba Farini;
Email: claudia.farini.18@ucl.ac.uk †

†The original version of this article was published with an incorrect author email address, and a misspelling on page 1. A notice detailing these has been published and the errors rectified in the online and print PDF and HTML copies.

© The Author(s), 2023. Published by Cambridge University Press. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

Are current warning and responses systems suitable to respond to emerging infectious diseases?

Claudia Fernandez de Cordoba Farini 

UCL Warning Research Centre - Science and Technology Studies and Institute for Disaster Risk Reduction, University College London, London, UK; Transforming UK Food Systems Centre for Doctoral Training, University of Greenwich, London, UK and Department for Environment, Food and Rural Affairs (DEFRA), His Majesty's Government of the United Kingdom of Great Britain and Northern Ireland, London, UK

Abstract

Socio-economic, environmental and ecological factors, as well as several natural hazards, have repeatedly been shown to drive emerging infectious-disease risk. However, these drivers are largely excluded from surveillance, warning and response systems. This paper identifies, analyses and categorises 64 warning and response systems for infectious diseases. It finds that 80% of them are “reactive” – they wait for disease outbreaks before issuing an alert and implementing mitigating strategies. Only 6% of the warning and response systems were “prevention-centred.” These both monitored and were linked to strategies that addressed drivers of disease emergence and re-emergence. This paper argues that warning systems’ failure to conceptualise emerging infectious diseases as part of an integrated human, animal and environmental system stems from inadequate multi-sectoral collaboration and governance, compounded by barriers to data sharing and integration. This paper reviews existing approaches and frameworks that could help to build and expand prevention-centred warning and response systems. It also makes recommendations to foster multi-sectoral collaboration in governance and warning systems for infectious diseases. This includes proposing solutions to address compartmentalisation in international agreements, developing One Health national focal points and expanding bottom-up initiatives.

Introduction

Warning and response systems

The COVID-19 pandemic has led to an unprecedented global focus among international and civil society organisations and member states on warning and response systems for infectious diseases as a key tool to mitigate the risk of future pandemics (Butchard and Balogun, 2023; Faviero et al., 2022; Gostin et al., 2021; Krofah et al., 2022; Rogers et al., 2020; Sirleaf and Clark, 2021; The White House US Government, 2021; UK Government, 2021).

The United Nations Disaster Risk Reduction Office (UNDRR) defines an early warning system (EWS) as “an integrated system for hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities, systems and processes that enables individuals, communities, governments, businesses and others to take timely action to reduce disaster risks in advance of hazardous events” (UNDRR, n.d.). This key concept applicable to both natural and biological hazards underlines the importance of coordinated prevention, preparedness and mitigation efforts.

However, it is important to note that while the shared effort to enhance warning and response systems for infectious diseases is unique, the disease itself is not. Understanding and addressing the broader trends, drivers and systems that enable their emergence and spread are essential for long-term effectiveness in handling COVID-19 and other emerging infectious diseases (EIDs).

Context, systems and trends linked to EIDs

Several studies suggest that for the past half-century, with trends beginning in the 1940s, the risk of EIDs, particularly zoonotic diseases, has been rising over time as a result of ecosystem changes (as measured by the frequency and richness of zoonotic disease outbreaks and the number of the first occurrence of zoonotic EIDs “events”) (Baudron and Liégeois, 2020; Cunningham et al., 2003; B. A. Jones et al., 2013; K. E. Jones et al., 2008; Keesing et al., 2010; Ostfeld, 2009; Rohr et al., 2019; Smith et al., 2014; Taylor et al., 2001; Weiss and McMichael, 2004). The rise of EIDs has been established after controlling for biased reporting of outbreaks over time. However, after controlling for internet usage, outbreak cases per capita appear to be declining over time. In

combination, these findings suggest that while we are becoming more effective at reducing the number of infected people through early detection, control and treatment, the impact of human activities on wildlife is simultaneously increasing the risk of spill-overs and new infectious-disease outbreaks (K. E. Jones et al., 2008; Smith et al., 2014). Furthermore, in the long term, efforts to quickly mitigate infectious diseases may not be sufficient to compensate for the impact of ecological changes in promoting their emergence.

It is estimated that most EID outbreaks in the human population, as many as 70% are zoonoses – diseases caused by a spill-over of pathogens from animal hosts to humans (K. E. Jones et al., 2008; Taylor et al., 2001). The influence of socio-economic, environmental and ecological changes, including forest loss and fragmentation, agricultural encroachment, development and irrigation, human and livestock demographics, antibiotic use, wildlife hunting and trade and climate change, on infectious-disease emergence and spread is difficult to disentangle due to the complex webs of interactions and feedback loops. While not all anthropogenic changes impact infectious-disease emergence and transmission, a significant amount has been showcased to influence it. A systematic review of 305 scientific articles investigating how specific types of anthropogenic land use change influence infectious-disease dynamics found that more than half of the studies (56.9%) documented an increase in pathogen transmission, whereas 10.4% of the studies observed a decrease in pathogen transmission (Gottdenker et al., 2014). Agricultural intensification and intensive livestock production, resulting in land-use change, deforestation, habitat fragmentation and antimicrobial resistance, is estimated to be the primary driver of infectious-disease risk (Allen et al., 2017; Baudron and Liégeois, 2020; Cunningham et al., 2003; Keesing et al., 2010; Olson et al., 2015; Rohr et al., 2019).

However, there are barriers to which such trends can be accurately quantified, including limits of available zoonotic disease datasets, difficulties in disaggregating the probability of occurrence from the probability of detection and reporting and spatial-temporal heterogeneity in health surveillance. While measures to control for confounding factors have also been used (e.g., press freedom and internet usage, academic publication output, population size and density and GDP per capita), the validity of these has not been proven.

Nevertheless, even without including quantitative analyses, the correlations between anthropogenic changes and emerging infectious diseases have also been demonstrated through a wide range of case studies and individual analyses over the last two decades. For instance, the emergence of the Nipah virus in Malaysia was linked to the establishment of a sizable intensive pig farm combined with fruit trees within the foraging range of two roots of Nipah virus-infected fruit bats (B. A. Jones et al., 2017); schistosomiasis transmission has been repeatedly linked to agricultural expansion, including dam construction and agro-chemical pollution (Hoover et al., 2020; Sokolow et al., 2017); irrigation of desert land has been shown to lead to a dominance of *Phlebotomus papatasi*, a highly competent vector for visceral leishmaniasis (Garchitorena et al., 2017). Climate change has also been correlated to a range of natural hazards, including floods, tropical cyclones, droughts and heatwaves, which in turn impact outbreaks of climate-sensitive infectious diseases (water-borne and vector-borne diseases) (Alcayna et al., 2022).

Hence, COVID-19 and infectious diseases more broadly should not be tackled as isolated health events, as they often result from economic and political systems that rely on unsustainable

exploitation of resources and create the ecological and environmental conditions necessary to drive their emergence.

Purpose of this study

Considering the previous research on the context, systems and drivers linked to the emergence of infectious diseases, this study evaluates whether past and current warning and response systems account for these conditions and are thus suitable to prevent and respond to EIDs. It aims to provide an overview of the global trends and gaps in warning and response systems for infectious diseases, pinpoint areas of focus and identify opportunities to improve these systems worldwide.

The study enquires whether there is a failure in current warning systems to frame and address EIDs in ways that integrate human, animal and ecosystem health. It goes on to discuss the value, potential and limitations of monitoring and addressing the driving conditions that increase the risks of new and re-emergent infectious diseases. Finally, it discusses future directions to facilitate cross-sectoral governance and enhance the capabilities of warning and response systems to monitor and address EIDs drivers.

Methodology

This study is based on a mixed-method approach combining elements of a critical and mapping review (Grant and Booth, 2009). As with a critical review, this study extends beyond merely describing identified articles; it incorporates analysis and conceptual innovation, developing unique categories for classifying warning systems. The methodology also borrows from the mapping review approach, aiming to contextualise the breadth of the literature, identify evidence gaps within warning systems and highlight key insights relevant to policy and practice (Grant and Booth, 2009). The combination of these two methods allowed for a comprehensive exploration of the grey literature, including reports, conference documents, websites and articles, in addition to scientific articles. This is an indispensable element in this study given the nature of warning systems, many of which are informal and thus underrepresented in scientific journals.

The research was based on a combination of the following keywords: “early warning systems,” “warning systems,” “infectious diseases,” “health warning systems,” “pandemic,” “surveillance,” “alerts,” “notification,” “risk assessment,” “epidemic responses,” “preparedness,” “prevention,” “environmental health,” “ecological factors,” “drivers” and “driving forces.” The review further targeted specific scales of analysis, identifying “local/community-based,” “regional,” “national” and “international” warning systems. The papers were extracted from Google Scholar, PubMed, Scopus, Google and Safari databases. The research often followed a “snowballing” approach, extracting further resources from the already found ones, per Sayers’s definition (2007).

This research resulted in the identification, analysis and categorisation of 64 warning and response systems for infectious diseases. Warning systems were divided into four categories representative of their overarching objective and function: Reactive, Prevention-centred, Anticipatory and Preparedness-centred. Each system was carefully examined and sorted into a category based on several criteria, including data sources, surveillance methods, risk assessments, alert thresholds, communication platforms, forecasting methods and action mechanisms.

While not all systems included in the database are named or labelled as “early warning systems” or “warning system,” they align with the UNDRR’s latest definition of an EWS, as applied in the field of disaster risk reduction (2017). Specifically, each has a feedback loop where some surveillance mechanism leads to an alert, risk assessment and/or action protocol. This core functionality forms the key inclusion criteria to classify or not a system as a warning and response system and include it in the database. Surveillance alone, which is purely defined as monitoring and observation, does not in itself constitute a warning and response system. The database includes warning and response systems for animal and human infectious diseases, several of these systems integrating both. All warning systems identified from both grey and scientific literature, included in the database were confirmed to be operational or to have been operational in the past, rather than being theoretical models.

Categories

Reactive/passive warnings: disease surveillance

Reactive warning systems do not monitor the drivers or factors leading to new or re-emergent infectious diseases, but only the diseases themselves, often only once they have reached the human populations, but also, at times, the animal populations (Morin et al., 2018). They can be correlated with strategies that predict the further spread of viruses and passive/reactive strategies dedicated to stopping and reducing further transmission.

Prevention-centred warnings: surveillance of driving forces and proposed actions to prevent re-occurring spill-overs

Prevention-centred warning systems monitor the driving factors leading to spill-over events and increased infectious-disease emergence, such as environmental, social and climatic factors. They are connected to preventative strategies which aim to reduce the risk of spill-overs. They can also be used to predict future spill-overs and outbreaks to improve efforts for early detection and response once a disease has reached the human or animal populations.

Anticipatory warnings: surveillance of driving forces to anticipate new outbreaks and reduce disease spread

Similar to prevention-centred warnings, anticipatory warning systems are characterised by monitoring the drivers leading to spill-overs of infectious diseases. However, these warning systems are generally not linked to preventative strategies aiming to address the drivers leading to spill-overs of new or re-emergent infectious diseases. The information collected is mainly used to anticipate, that is, predict and detect future outbreaks more rapidly to initiate reactive strategies dedicated to stopping their spread.

Preparedness-centred warnings: monitoring and assessment of public health sector capabilities

Preparedness-centred warnings assess the health sector’s capabilities, or more broadly, the countries’ capabilities to monitor and respond to future outbreaks, identifying critical gaps and opportunities for improvement. They are linked to preparedness strategies aiming to improve responses to future outbreaks, such as training, improving information networks and platforms of communication, and capacity-building strategies, i.e., strengthening laboratory systems, reporting, medical countermeasures, personnel deployment, etc.

Even though other studies have also categorised warning systems as a method for analysis (Day and Fearnley, 2015; Nichols et al., 2014), this same categorisation structure has yet to be used. While the database is not a complete assessment of all the warning systems involved or linked to infectious disease, it provides an overall perspective of the focus of warning systems, particularly at international and national levels. See “Limitations” section in this study for further information, and Figure 4a and b in Section “*The value, potential of and limitations in creating prevention-centred warning and response systems*” for visual representation.

Results

Analysis of EIDs warning and response systems

Overall, most warning systems (80%) within the database followed a reactive approach, also known as a passive approach (Morin et al., 2018). They monitor the threat only once it has reached a detectable threshold within the population and can only be linked with reactive strategies aiming to reduce disease transmission. Examples of reactive warning systems include Health Map (Bhatia et al., 2021) or Epi tweeter (Espinosa et al., 2021), which use informal internet data sources to detect potential health threats, such as monitoring tweets by time, place and topic, as well as larger organisations and more formal systems, such as WHO’s Global Outbreak Alert and Response Network (Christensen et al., 2021; Mackenzie et al., 2014; Sondorp et al., 2011) which monitors acute public health events, deploying staff and resources to the affected countries. While reactive warning systems that monitor the disease once it has reached the human population to reduce its spread, e.g., the United States COVID-19 Forecast Hub (Cramer et al., 2022), Global Influenza Surveillance and Response System (WHO, 2020) and during humanitarian emergencies, e.g., Red Cross, EWARS and EWARN; (Cambodian Red Cross, 2016; Mala et al., 2021), are needed, they only address one aspect of infectious-disease risk (Figure 1).

In comparison, anticipatory warning systems (9%) and prevention-centred warning systems (6%) that monitor the socio-economic, environmental and ecological conditions leading to increasing spill-overs are limited. In addition, only a few warning and response systems took a multi-hazard, multi-sectoral approach that jointly evaluated various hazards, their interdependencies and cascading impacts. Nevertheless, a few examples of prevention-centred warning systems from which we can learn exist, and these will be explored later in the paper.

In addition, few warning and response systems were linked to preparedness and capacity-building strategies (5%). Nevertheless, it is essential to be cautious when interpreting these findings. Any set-up warning system is in itself considered a preparedness measure, and efforts towards evaluating and improving public health sector capabilities are not often measured or constructed in the form of an interactive monitoring and warning system and therefore do not feature in this study. Furthermore, based on the literature review, the COVID-19 pandemic appears to have resulted in a significant push towards preparedness. This focus is apparent throughout various strategies and policy documents following the COVID-19 pandemic. Examples include WHO’s Independent Panel for pandemic preparedness and response (2020) (Sirleaf and Clark, 2021), Biden’s administration report on “American Pandemic Preparedness Transforming Our Capabilities” (The White House US Government, 2021), the UK government’s Partnership on Pandemic Preparedness (UK

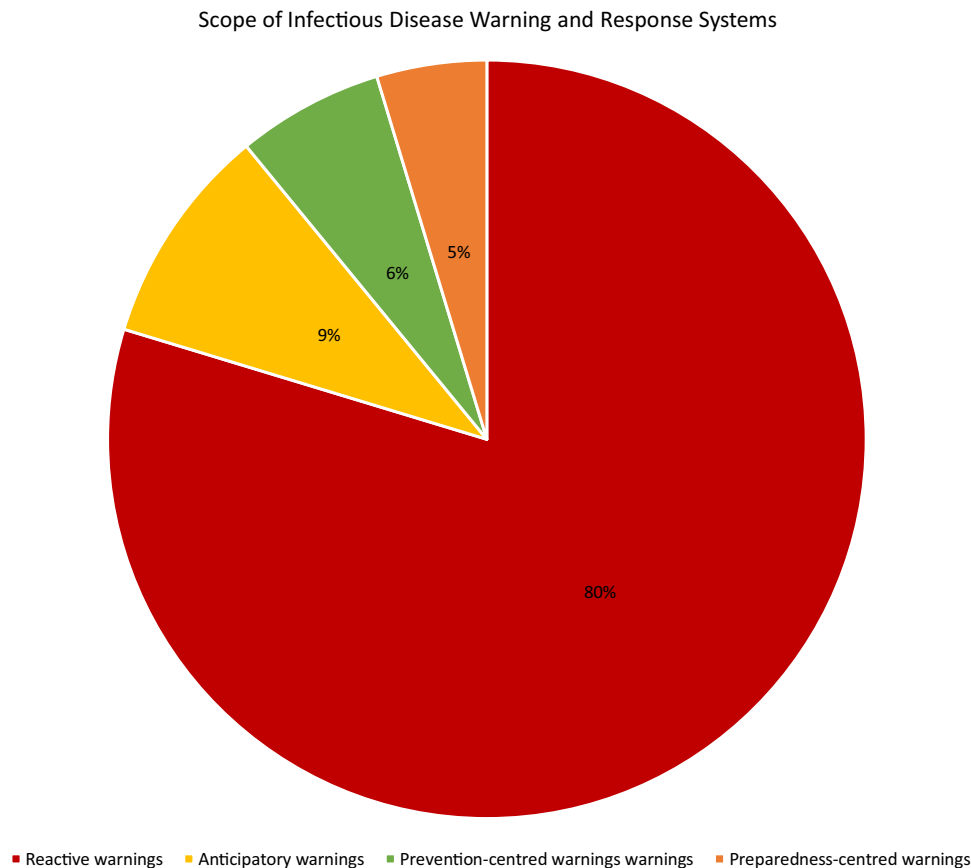


Figure 1. Scope of infectious-disease warning and response systems. ■ Reactive/passive warnings: 80%, 52/65 warning and response systems. ■ Anticipatory warnings: 9%, 6/65 warning and response systems. ■ Prevention-centred warnings: 6%, 4/65 warning and response systems. ■ Preparedness-centred warnings: 5%, 3/65 warning and response systems (Fernandez de Cordoba Farini, 2023).

Government, 2021), the G20 panel on “Financing the Global Commons for Pandemic Preparedness and Response” (G20 High Level Independent Panel, 2021). All these strategies are centred around strengthening the capabilities of the human health sector (e.g., vaccine manufacturing, test and tracing, diagnostics etc.) to respond to and contain a public health crisis; no significant objectives or commitments to address the upstream drivers¹ of infectious diseases are mentioned.

The emphasis and shift towards prevention are yet to be realised and integrated with public health measures, despite substantial research and evidence showcasing its critical importance (Figure 2).

The links between equitable cross-disciplinary collaboration and EID prevention

A critical issue which explains the lack of prevention and anticipatory strategies is the need for multi-sectoral collaboration, particularly between public and environmental health sectors. Currently, most warning systems available for infectious diseases are designed by human health specialists, not veterinarians and particularly not ecologists. The focus on public health shapes how the problem is conceptualised and narrows the type of responses that can be taken. This is simply and clearly illustrated by Kenyon’s “schematic representation of the contrast between ecological and biomedical individualist conceptual frameworks for understanding the origins of SARS-CoV-2 and other zoonoses” (Kenyon, 2020,

p. 3). Warnings systems led by public health practitioners fail to account for the links between environmental and health issues, limiting the extent to which preventative and anticipatory strategies are deployed (Figure 3).

One of the most prominent interdisciplinary frameworks looking to respond to zoonotic diseases is One Health. In principle, One Health pushes forward inclusivity, collaboration and multi-disciplinarity between frameworks. In practice, the responses issued as One Health have been limited by an anthropocentric hierarchy, e.g., WHO’s One Health agenda has traditionally been defined as “an approach to designing and implementing programmes [...] in which multiple sectors communicate and work together to achieve better public health outcomes” (World Health Organisation, n.d.). The problem with anthropocentrism is that it can lead to a simplification of the interdependencies between humans, animals and the environment.

The risks of solely focusing on human interests in infectious-disease responses were seen during the H1N1 pandemic in Egypt. Political and religious narratives stigmatised pigs and supported a cull of 300,000 pigs under the pretext of safeguarding public health (Davis and Sharp, 2020; Leach and Tadros, 2014). However, pigs were used by a religious minority, the Zabbaleen, to sort through much of Cairo’s waste (Fahmi and Sutton, 2010). The culling led to a substantial urban waste problem, with people resorting to secretly disposing of garbage in irrigation channels and illegal dumping sites, leading to a range of public and environmental health issues. The focus on contamination and framing of animals as diseases

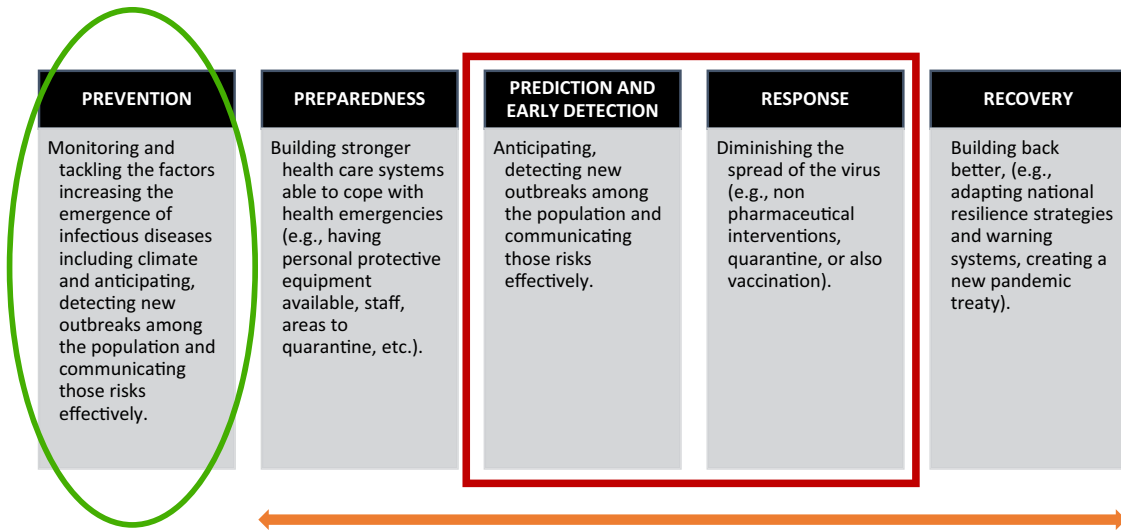


Figure 2. Components involved in responding to emerging infectious diseases, a simplified analysis of the current status quo. Primary focus of infectious-diseases strategies, warning and response systems. ↔ Secondary focus as a result of the COVID-19 pandemic. Missing links to strategies focused on prevention (Fernandez de Cordoba, 2023).

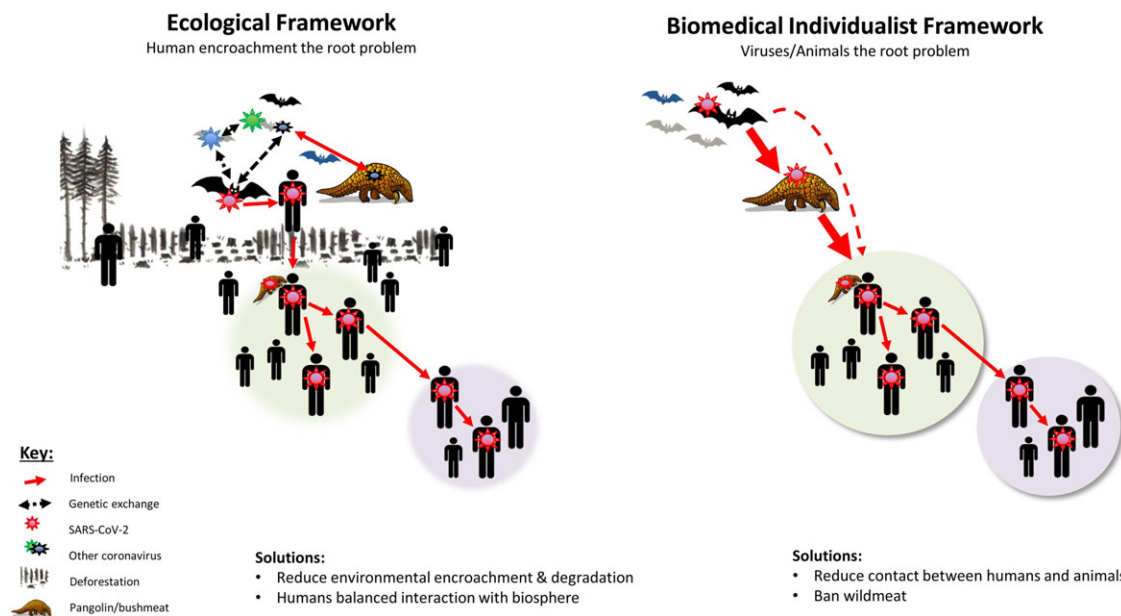


Figure 3. Schematic representation of the contrast between ecological (left) and biomedical individualist (right) conceptual frameworks for understanding the origins of SARS-CoV-2 and other zoonoses. Figure from Kenyon (2020).

failed to account for the agency and the positive impact animals had on human lives. Similarly, Kamenshchikova et al. (2021) criticised OH as conducive to hierarchical collaborations in international responses to AMR. They argued that anthropocentric framings fail “to create a discursive space for exploring and acting upon the different values at stake in antimicrobial resistance prevention” (Kamenshchikova et al., 2021, p. 8). Furthermore, an analysis of 184 Global One Health networks (OHNs) (Mwatondo et al., 2023) found that only 60% of them included the three sectors (human health, animal health and the environment or ecosystems), with the environmental sector being the most excluded. They note that over the last 15 years, the focus has been on “health security priorities” with “little regard” for the “upstream drivers of

disease emergence” “or other crucial hazards and health emergencies” (Mwatondo et al., 2023, p. 609).

The hierarchy assigned to One Health priorities has proven detrimental to all three sectors, including human health. Equitable collaboration is needed to create healthy interactions and feedback loops between species and maintain a sustainable environment. The inclusion of the United Nations Environment Programme (UNEP) in the Quadripartite – a coalition with the World Health Organisation (WHO), the World Animal Health Organisation (WOAH) and the Food and Agriculture Organisation (FAO) – marks a significant stride towards this objective. In 2021, the One Health High-Level Expert Panel, a body of experts from these organisations, put forth an updated One Health definition

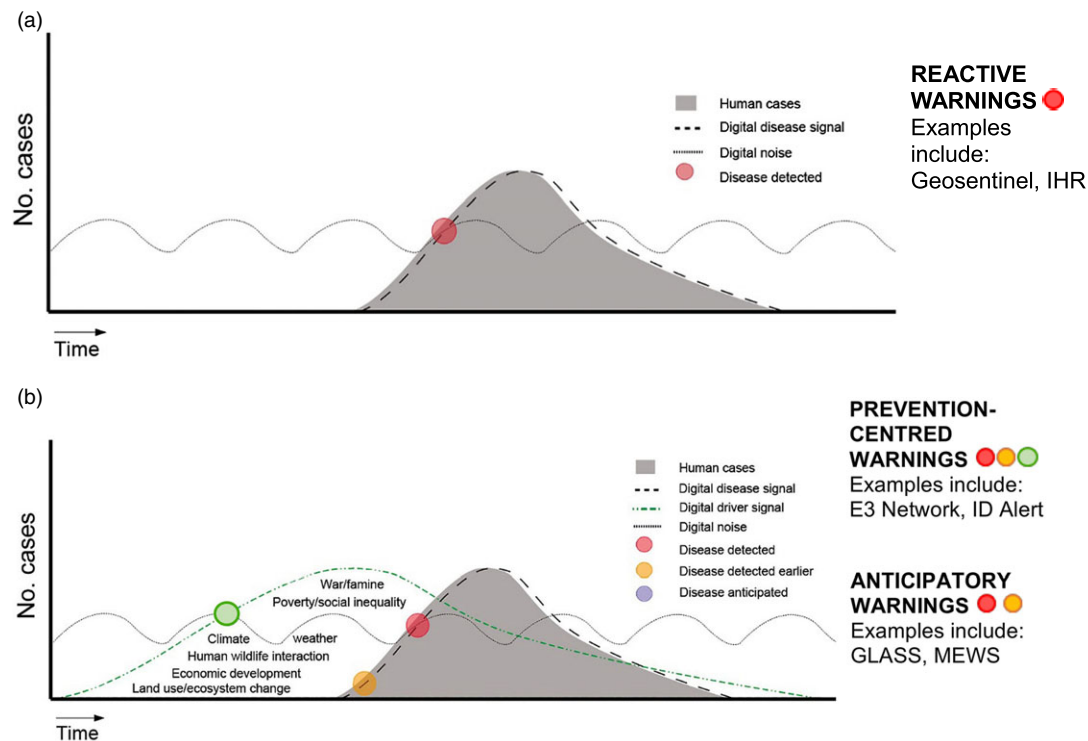


Figure 4. (a) Linking Theory and Practice – Adaptation from Olson et al., figure 1, graph A, from paper “Drivers for emerging infectious diseases as a framework for Digital Detection.” (b) Linking Theory and Practice – Adaptation from Olson et al., figure 1, graph C from paper “Drivers for emerging infectious diseases as a framework for Digital Detection.”

(Nzietchueng et al., 2023). This new interpretation highlights principles of equity, stewardship and balance and acknowledges crucial elements such as clean water, energy, air, nutritious food and climate change action. This expanded scope represents a substantial shift in One Health, from its traditional focus on infectious-disease transmission and human and veterinary medicine to adopt a more equitable, humble perspective of the natural world wherein the welfare of non-human animals and the environment is accorded the same significance as human welfare. However, environmental determinants of health are yet to be thoroughly understood by all sectors. The Quadripartite’s One Health Joint Plan of Action identified environmental integration as one of six vital action tracks for the coming years (Jesudason, 2022; “One Health Joint Plan of Action, 2022–2026,” 2022). The subsequent section will explore various examples and case studies demonstrating how to achieve this integration, especially in the context of warning and response systems.

The value, potential of and limitations in creating prevention-centred warning and response systems

For warning systems to work more equitably across sectors and subsequently result in preventative strategies, they need to consider and address the drivers leading to the emergence of infectious diseases. This paper reviews existing frameworks, approaches and warning systems focused on the drivers of EIDs and prevention. It analyses their benefits, potential and limitations.

In 2015, Olson et al., envisaged what a driver-centric surveillance system could look like compared to traditional disease surveillance and detection systems (Olson et al., 2015). This paper reviews their theoretical framework, linking it to practical

examples and existing warning systems to assess the status and progress towards reaching that framework. Olson et al., portrayed a traditional disease detection surveillance system (see Figure 4a) as a simple association between the number of cases and a digital disease signal which acts as a warning. These types of surveillance systems lead to what has been termed in this paper as a reactive warning or approach. They can be used to control and mitigate the transmission of diseases only once they have reached the human population. Examples of this type of approach could be Geosentinel (Hamer et al., 2021), a warning system which tracks disease among travellers and releases reports to control and avoid the transmission of health threats cross-borders, or IHRs, which issues warnings for public health events of potential international concerns such as an Ebola epidemic.

In contrast to a traditional disease detection system, according to Olson et al., a driver-centric surveillance system would monitor the drivers leading to the emergence of diseases such as climate, weather, economic development and poverty (Olson et al., 2015). Hence, driver-centric surveillance could result in anticipatory warnings that shorten the time of disease detection resulting in early action and mitigation strategies. An example of an anticipatory warning system is the Columbia university framework for a Malaria Early Warning system which was used to forecast malaria epidemics based on seasonal climate forecasts, weather monitoring and case surveillance (Grover-Kopec et al., 2005; Thomson et al., 2003). Another example is PREDICT I, which collected information on disease drivers to strengthen country-level capacities for routine infectious-disease detection and outbreak response (Joly et al., 2016). Driver-centric surveillance systems could also result in Prevention-centred warnings that identify and reduce risk factors leading to infectious-disease

emergence. An example of an already existing driver-centric and prevention-centred warning system is the European Environment and Epidemiology Network (Semenza, 2015; Semenza and Paz, 2021), whose approach is discussed later in the paper. Another initiative which is being created as prevention-centred is IDAlert. IDAlert aims to develop new climate and health indicators of disease drivers to strengthen monitoring mechanisms, provide innovative early warning systems that integrate the environment and inform policy development in human, animal, and environmental sectors (IDAlert, 2022).

While there are scarce streamlined approaches which collect and jointly analyse data across sectors to evaluate EIDs' risk, relevant data sets exist separately across these sectors. However, these have not necessarily been conceptualised to be used and analysed jointly. For instance, the FAO–WOAH–WHO Global Early Warning System (GLEWS+) – a tool designed to handle health threats and emerging risks at the human–animal–ecosystems interface – has customarily not effectively monitored and integrated information on environmental drivers of disease emergence and transmission in its early warning and intelligence efforts (Quadripartite, 2022). The lack of integration of environmental health insights limits the scope and effectiveness of subsequent responses for EIDs developed based on that intelligence. The integration of the UNEP provides an opportunity to address this gap and leverage the range of information and databases the UNEP reports on e.g., trends in biodiversity, ecosystem health and environmental health (UN Biodiversity Lab), international wildlife trade per CITES (the Convention on International Trade in Endangered Species of Wild Fauna and Flora), the Global Forest Watch and CLIMsystems a climate insights data portal.

Similarly, a range of data sources and information from different sectors including human (e.g. the WHO and the European Centre for Disease prevention and Control (ECDC) data repositories, the Global Health Security Index, the Institute for Health Metrics and Evaluation (IHME) Global Burden of Disease, the Global Health Observatory, Our World in Data, government resources, etc.), animal (FAO, WOA, Action for Animal Health data repositories etc.) and environmental sectors (IPCC report, World Bank data repository, Databases from Sustainable Development Goals Lancet Countdown, OECD Stat, Environmental Performance Index, Global Ocean Health Index scores, UNEP, etc.) exist, particularly in developing countries. It is essential to further investigate the interconnections among these databases and information systems and explore how they can be leveraged to foster cross-sector initiatives and multi-sectoral warning and response systems.

Cross-sector collaboration is critical to optimise the use of the diverse data collected, offering a more integrated approach to addressing complex problems. For instance, the smartphone application Ethiopian differential diagnosis information environment is a diagnosis system, developed by The University of Strathclyde, Addis Ababa University and Brooke, to help veterinarians and veterinary paraprofessionals determine the most likely diagnosis affecting an animal and, therefore, helping them decide the most appropriate treatment (Beyene et al., 2018). The system is beneficial when access to laboratory diagnosis is not available. While it provides a form of passive animal health surveillance data, the system is currently not being leveraged as a warning and response system. However, the data collected could, in the future, have much broader applications. It could be used to analyse what recurrent diseases and systemic issues the country is

most likely facing and issue alerts. If sufficient environmental data was collected, it could be used to determine which environmental factors are driving these diseases and take preventative, earlier action. Similarly, the system could be used to assess “cold spots,” areas where there is a lack of monitoring of disease outbreaks, and subsequently, potential health risks are not being evaluated. This demonstrates opportunities for expanding the application of existing information systems to function as warning systems, including prevention-centred warnings. Thus, developing an effective driver-centric or prevention-centred warning system will not always require collecting data from scratch but rather mapping existing data sources that could be taken advantage of and gaps where there is a need to collect further information.

Furthermore, collaborative platforms exist from which we can learn, such as the European Environmental Epidemiology Network (E3 Network). For example, E3 data was used to stop and prevent the continuous emergence of malaria in Greece (Semenza, 2015). From 2009–2012, Greece experienced re-emergent malaria cases, despite control and endemic elimination programmes (Sudre et al., 2013). To help guide malaria control efforts, the E3 network attempted to identify areas suitable for malaria emergence and transmission. Geo-referenced climatic and environmental information from Greece and other data sources were retrieved and processed for spatial modelling, such as seasonal variations of vegetation, land cover categories, temperature, etc. These data sources were used to characterise the climatic and environmental profiles of locations with active transmission cycles to predict other sites at risk of malaria re-emergence in Greece. For example, among several other factors, areas suitable for transmission had warmer temperatures and intensive irrigated agriculture. Based on that information, the E3 Network produced a disease risk map, which they shared with Greek public health practitioners responsible for preparedness and response activities. This combined approach enabled the disruption of malaria transmission in 2013 through targeted entomological and epidemiological surveillance, vector control activities and rising awareness among the public and health workers of the areas that are environmentally suitable for transmission. The E3 Network's capacity to interrupt malaria transmission showcases how collaboration across disciplines can help reduce spillover events and prevent the continuous rise of EIDs. A crucial step, if viable, is to harness data from anticipatory warning systems to confront the root causes, effectively transforming these systems into ones centred on prevention. While the E3 network's approach is mainly based in European countries, other joint strategies, such as the Shanghai Multi-hazard Warning System (Tang et al., 2012) or PulseNet (Ribot et al., 2019) exist internationally that can be used as reference models to advocate and guide collaboration efforts in the prevention of EIDs.

Nevertheless, issues hindering the integration of datasets will need to be addressed. “*The effects of global environmental change do not adhere to typical effect-response relationships which traditional epidemiological methods have been refined (and perfected) to measure*” (Semenza, 2015, p. 6336), but they are often based on complex pathways which can be direct but also often indirect, diffused (impacts are not constant), or delayed (Mcmichael, 2013; Olson et al., 2015). Whether is it to develop scenario-based models that account for those complexities or to create real-time multi-sectoral warning and response systems, several issues in integrating datasets demand attention. Firstly, navigating issues related to data access and ownership is critical. Crafting data-sharing agreements, though demanding, can

facilitate collaboration among stakeholders from different departments or organisations, enabling data sharing and access. Nevertheless, even after that first step issues with data compatibility², temporal resolution³ and spatial scale⁴ will need to be addressed for the data to be effectively integrated (Olson et al., 2015; Semenza, 2015). Moreover, in some cases, such as with GLEWS+, direct data sharing is not feasible. In order to circumvent this issue, the quadripartite has developed agreements to share key insights derived from the data, rather than the raw data itself (Quadripartite, 2022). This approach proves particularly relevant in ensuring proper contextualisation and interpretation of the information, as experts from different disciplines adhere to varying standards for data collection, quality and time frames. Whether sharing data or the derived insights, effective communication of the assumptions surrounding the information, including limitations, expectations and appropriate usage, is critical. This transparent approach ensures the success of cross-sectoral warning and response systems and prevents potential unintended consequences that may arise from barriers in language and understanding across different disciplines.

Facilitating cross-sectoral governance

Establishing prevention-centred warning systems requires changes in governance that foster equitable engagement within and across sectors, hazards and organisations. Internationally, organisations like the World Bank, the UN, the WHO, the FAO and WOAHA possess well-defined mandates that delineate their responsibilities and the scope of their work. Similarly, government departments also tend to address human, animal and environmental health as separate concerns. However, these divisions can result in fragmented decision-making and responses, limiting the scope and effectiveness of warning and response systems. Several recommendations are presented underneath to address these silos and strengthen interagency and multi-sectoral collaborations at the international and national levels.

First, addressing silos across international agreements stands as a pivotal approach to achieving this objective. For instance, despite the clear links between health and natural hazards, the UN's 2022–2027 Early Warning for All Initiative⁵ – aiming for universal protection from hazardous meteorological events – has yet to reference or integrate health and infectious diseases within its objectives and strategy (World Meteorological Organization, 2022; Alcayna et al., 2022). This represents a gap that if addressed correctly could result in more effective cross-sectoral warnings at the international, national, regional and local levels, that account for the drivers and cascading impacts of climate and meteorological hazards. Similarly, the new pandemic accord currently under negotiation by WHO member states needs to strive to be aligned and integrated with other international agreements and strategies addressing EID risks, including the Convention to Combat Desertification, the Convention for Biological Diversity (CBD), the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) and the United Nations' Early Warnings for All Initiative. Although not originally designed to reduce EIDs, these agreements significantly influence EID risk, and their interconnections should be acknowledged and utilised.

Furthermore, despite the unique mandates of international organisations, it is essential to incorporate shared multi-sectoral objectives into the international agreements they spearhead, to prevent international compartmentalisation from fostering

national divisions. The 2022 Kunming-Montreal Global Biodiversity Framework (GBF) serves as an example of good practice, exemplifying the promotion of cross-sectoral collaboration and the establishment of unified objectives. Historically, health-focused civil society organisations have shown limited participation in the CBD and its negotiations (Willett, Comeau, et al., 2023). However, this trend has been changing and in 2022 five such organisations became accredited and attended the agenda-setting and decision-making meetings at the 15th UN Biodiversity Conference (COP 15). As a result, several of the targets of the GBF integrate health and biodiversity considerations such as “reduction of disease [...] through nature-based solutions” (target 11), or “Ensure that the use, harvesting and trade of wild species is sustainable, safe and legal [...] reducing the risk of pathogen spill-over” (target 5). The commitment of 186 states to revise their national biodiversity strategies and action plans (NBSAPs) by 2024, guided by these targets, presents an opportunity to strengthen integrated decision-making, policy coordination and cross-sectoral collaboration, particularly concerning the linkages between biodiversity and health (Willett, Siegel, et al., 2023). Valuable insights can be drawn from the recent integrated decision-making efforts of the CBD to support the development of integrated strategies and targets in other agreements, such as the pandemic accord and the Early Warning for All Initiative.

Moreover, in addition to strengthening multi-sectoral cooperation in international agreements; mechanisms to facilitate collaboration at the national level need to be further developed to prevent fragmented responses. For instance, the international health regulations (IHR) set obligations for countries to detect and report a potential public health event of international concern. However, the responsibility often falls solely within the public health department resulting in siloed approaches, as showcased by the survey of IHRs National Focal Points (NFPs) experiences in carrying out their functions (2021) which found that one key challenge was “insufficient inter-sectoral collaboration within their countries, including limited access to, or a lack of cooperation from, key relevant ministries” (Packer et al., 2021, p. 1). To address this gap, an obligation that could be implemented is to designate One Health NFPs, that coordinate across all relevant ministries to address complex transdisciplinary issues such as pandemic prevention. These should communicate with existing NFPs as part of the IHRs. Support for this new objective is prevalent across various civil societies and organisations in the context of the new pandemic accord (Action for Animal Health Organisation, 2022; Wildlife Conservation Society, 2022). Additionally, to promote equitable multi-sectoral collaboration and assessment, it is essential to strengthen incentives, such as making it a prerequisite to secure funding for projects related to complex, intersectional problems. This strategy could position NFPs as a central element in the development of driver-centric, multi-hazard and multi-sectoral warning systems that are adapted to the individual threats faced by each country (Vlieg et al., 2017).

Finally, community-based and bottom-up initiatives must be further developed in the context of pandemic prevention. Currently, most warning systems work in a top-down manner, led by international and national organisations, and only involve communities as system users (Mwatondo et al., 2023). In contrast to international organisations, which tend to be divided into sectors and are prone to working in silos, local communities experience problems and their context first-hand and are not discipline-bound. Empowering them in the

decision-making process and design of warning systems is crucial to ensure warning systems are context-based and adapted to the distinct vulnerabilities and drivers leading to the emergence of infectious diseases in different populations and world regions.

Limitations

While this study incorporated numerous local and community-based infectious-disease warning systems into the database, the proportion of such systems identified at the local level was significantly smaller compared to the national or international level. This discrepancy could be attributed to the informal character of these systems, which might not be as prominently featured in literature, potentially resulting in a less representative sample. A systematic review of community-based Early Warning Systems (EWS) found that the majority of the documented systems focused on natural hazards such as floods, droughts and landslides (Macherera and Chimbari, 2016). Conversely, community-based early warning systems targeting human diseases were found to be relatively scarce, even though similar systems operate at national, regional and global levels (p. 1). This observation could suggest that community-based EWS for infectious diseases are indeed less prevalent than those for other hazards, which could explain the observed gap in research.

Moreover, language barriers could also have impeded the recognition of certain warning systems from different countries. Only papers in English, Spanish and French were examined, which could impact how representative the sample is. It is important to stress that this research doesn't present a systematic review of all infectious-disease warning systems but aims to highlight overall trends, gaps and opportunities. It should serve as a starting point for further evaluations rather than an endpoint. Furthermore, due to the broad scope of this study, the specific differences among disease drivers and the necessary adaptations for warnings according to these variations were not examined. This aspect warrants additional research for a more specific understanding. In addition, the categorisation of warning and response systems and the information presented is derived from publicly available sources. Consequently, there may be inaccuracies in the categorisation of certain warning systems if there have been changes to them that have not been publicly disclosed.

Finally, although this paper underscores the role of emerging infectious-disease drivers and the need for prevention-centred warnings, it is necessary to recognise that in many settings there is still not yet the capacity or resources to routinely collect information on human disease cases, let alone gathering data on animal diseases, especially in wildlife. Consequently, there still remains a necessity to further refine and develop "reactive" warning and response systems.

Conclusion

Despite the impact of socio-economic, ecological and environmental factors in driving EIDs risk, these factors are largely excluded from warning, surveillance and response systems. Of 64 warning systems examined in this study, 80% are "reactive." They can only signal a warning and response once the disease reaches a detectable threshold in the population. Currently, warning systems are predominantly used as a method of adaptation, reducing the impact of existing risks rather than addressing them directly.

Nevertheless, there is potential for change and efforts to develop driver-centric surveillance systems that monitor and address EIDs drivers appear to be increasing. Indeed, 6% of warning and response systems within the database were "prevention-centred," they both monitored and were linked to strategies to address disease drivers and prevent new or re-emerging infectious-disease spill-overs.

A key element that explains the disconnect between research and warning systems for EIDs is the lack of multi-sectoral collaboration in strategies to respond to these diseases. Current governance systems, both within and between international organisations, as well as in national governments, tend to divide responsibilities across departments and sectors. EIDs are perceived as a problem that falls within the responsibility of the public health sector. As a result, most warning systems are managed by human health specialists, not veterinarians and especially not ecologists. This shapes how the problem is conceptualised and how warning systems are designed, and subsequently, the responses issued.

Moreover, while more interdisciplinary efforts such as *One Health* are being developed, they largely continue to rely on an anthropocentric perspective which reproduces the same limitations of systems acting within disciplinary silos. Engagement between organisations and sectors needs to strive to be equitable rather than hierarchical to ensure that the interdependencies between human, animal and environmental sectors are not simplified, leading to unintended consequences (e.g., Avian Flu, Egypt).

The study highlights several overarching recommendations to facilitate cross-sectoral governance for EIDs, and transition from a reactive to a preventative approach. These include addressing silos across different international agreements such as the UN Early Warnings for All Initiative and the Pandemic Accord and developing shared multi-sectoral objectives within international agreements as exemplified by the 2022 Global Biodiversity Framework. This study also urges the development of *One Health* national focal points to enable multi-sectoral collaboration at the national level. Finally, it advocates for the development of bottom-up initiatives and community-based warning systems. Further research is needed to explore how to develop multi-sectoral, multi-hazard warning systems that account for the risks, cascading impacts and feedback loops between sectors and hazards.

We must take advantage of the momentum for change created by COVID-19 to switch from a responsive to a preventative approach that does not merely wait and prepares itself for the next pandemic but addresses the systemic, multi-sectoral issues that are making us more likely to experience another one in the first place.

Notes

- 1 Upstream Prevention: measures to reduce the risk of pathogen emergence.
- 2 Issues with data compatibility: issues regarding how the data is stored and processed.
- 3 Temporal resolution: sufficient data collected over a time period.
- 4 Spatial scale: data sets with significant geographical coverage would need to be addressed.
- 5 The United Nations Initiative Early Warnings for All consist in significantly increasing the availability of and access to multi-hazard early warning systems and disaster risk information and assessments to people by 2030.

Supplementary material. The supplementary material for this article can be found at <https://doi.org/10.1017/one.2023.10>

Connection references

Fernandez de Cordoba Farini C (2023) How can we improve and facilitate multi-sectoral collaboration in warning and response systems for infectious diseases and natural hazards to account for their drivers, interdependencies and cascading impacts? *Research Directions: One Health*. **1**, 1–2. <https://doi.org/10.1017/one.2023.4>.

References

- Action for Animal Health Organisation** (2022) *ADVISORY NOTE Addressing the Essential Role of Animal Health in Pandemic Prevention*. Available at <https://actionforanimalhealth.org/wp-content/uploads/2022/03/Advisory-note-Pandemic-Treaty-negotiations-final-UPDATED.pdf> (accessed 13 September 2023).
- Alcayna T, Fletcher I, Gibb R, Tremblay L, Funk S, Bhargavi Rao and Lowe R** (2022) Climate-sensitive disease outbreaks in the aftermath of extreme climatic events: A scoping review. *One Earth, Science Direct* **5**, 4. <https://www.sciencedirect.com/science/article/pii/S2590332222001440>.
- Allen T, Murray KA, Zambrana-Torrel C, Morse SS, Rondinini C, Di Marco M, Breit N, Olival KJ and Daszak P** (2017) Global hotspots and correlates of emerging zoonotic diseases. *Nature Communications* **8**, 1. <https://doi.org/10.1038/s41467-017-00923-8>.
- Baudron F and Liégeois F** (2020) Fixing our global agricultural system to prevent the next COVID-19. *Outlook on Agriculture* **49**, 2, 111–118. <https://doi.org/10.1177/0030727020931122>.
- Beyene TJ, Asfaw F, Getachew Y, Tufa TB, Collins I, Beyi AF and Revie CW** (2018) A smartphone-based application improves the accuracy, completeness, and timeliness of cattle disease reporting and surveillance in Ethiopia. *Frontiers in Veterinary Science* **5**. <https://doi.org/10.3389/fvets.2018.00002>.
- Bhatia S, Lassmann B, Cohn E, Desai AN, Carrion M, Kraemer MUG, Herring M, Brownstein J, Madoff L, Cori A and Nouvellet P** (2021) Using digital surveillance tools for near real-time mapping of the risk of infectious disease spread. *Npj Digital Medicine* **4**, 1. <https://doi.org/10.1038/s41746-021-00442-3>.
- Butchard P and Balogun B** (2023) What is the proposed WHO Pandemic Preparedness Treaty? Available at <https://commonslibrary.parliament.uk/research-briefings/cbp-9550/> (accessed 13 September 2023).
- Cambodian Red Cross** (2016) *Community Based Disaster Preparedness (CBDP) Training Manual for Red Cross Volunteers*. Available at <https://www.rcrc-resilience-southeastasia.org/document/community-based-disaster-preparedness-cbdp-training-manual-for-red-cross-volunteers/> (accessed 13 September 2023).
- Christensen R, Fisher D, Salmon S, Drury P and Effler P** (2021) Training for outbreak response through the Global Outbreak Alert and Response Network. *BMC Medicine* **19**, 1. <https://doi.org/10.1186/s12916-021-01996-5>.
- Cramer EY, Huang Y, Wang Y, Ray EL, Cornell M, Bracher J, Brennen A, Rivadeneira AJC, Gerding A, House K, Jayawardena D, Kanji AH, Khandelwal A, Le K, Mody V, Mody V, Niemi J, Stark A, Shah A, Wattanchit N, Zorn MW and Reich NG** (2022) The United States COVID-19 Forecast Hub dataset. *Scientific Data* **9**, 1. <https://doi.org/10.1038/s41597-022-01517-w>.
- Cunningham AA, Daszak P and Rodriguez JP** (2003) Pathogen pollution: Defining a parasitological threat to biodiversity conservation. *Journal of Parasitology* **89**, S78–S83.
- Davis A and Sharp J** (2020) Rethinking One Health: Emergent human, animal and environmental assemblages. *Social Science and Medicine* **258**, 113093. <https://doi.org/10.1016/j.socscimed.2020.113093>.
- Day S and Fearnley C** (2015) A classification of mitigation strategies for natural hazards: Implications for the understanding of interactions between mitigation strategies. *Natural Hazards* **79**, 2, 1219–1238. <https://doi.org/10.1007/s11069-015-1899-z>.
- Espinosa L, Wijermans A, Orchard F, Höhle M, Czernichow T, Coletti P, Hermans L, Faes C, Kissling E and Mollet T** (2021) EpiTweeter: Early warning of public health threats using Twitter data. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.3811673>.
- Fahmi W and Sutton K** (2010) Cairo's contested garbage: Sustainable solid waste management and the Zabaleen's right to the city. *Sustainability* **2**, 6, 1765–1783. <https://doi.org/10.3390/su2061765>.
- Faviero G, Stocking B, Hoffman S, Liu A, Bausch D and Galea S** (2022) An effective pandemic treaty requires accountability. *The Lancet* **7**, 9, e730–e731.
- G20 High Level Independent Panel** (2021) *G20 High Level Independent Panel Releases Report on Financing the Global Commons for Pandemic Preparedness and Response*. Available at <https://pandemic-financing.org/report/foreword/> (accessed 13 September 2023).
- Garchitorena A, Sokolow SH, Roche B, Ngonghala CN, Jocque M, Lund A, Barry M, Mordecai EA, Daily GC, Jones JH, Andrews JR, Bendavid E, Luby SP, Labeaud AD, Seetah K, Guégan JF, Bonds MH and De Leo GA** (2017) Disease ecology, health and the environment: A framework to account for ecological and socio-economic drivers in the control of neglected tropical diseases. *Philosophical Transactions of the Royal Society B: Biological Sciences* **372**, 1722. <https://doi.org/10.1098/rstb.2016.0128>.
- Gostin LO, Halabi SF and Klock KA** (2021) An international agreement on pandemic prevention and preparedness. *JAMA - Journal of the American Medical Association* **326**, 13, 1257. <https://doi.org/10.1001/jama.2021.16104>.
- Gottdenker NL, Streicker DG, Faust CL and Carroll CR** (2014) Anthropogenic land use change and infectious diseases: A review of the evidence. *EcoHealth* **11**, 4, 619–632. <https://doi.org/10.1007/s10393-014-0941-z>.
- Grant MJ and Booth A** (2009) A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal* **26**, 2, 91–108. <https://doi.org/10.1111/j.1471-1842.2009.00848.x>.
- Grover-Kopec E, Kawano M, Klaver RW, Blumenthal B, Ceccato P and Connor SJ** (2005) An online operational rainfall-monitoring resource for epidemic malaria early warning systems in Africa. *Malaria Journal* **4**. <https://doi.org/10.1186/1475-2875-4-6>.
- Hamer DH, Rizwan A, Freedman DO, Kozarsky P and Libman M** (2021) GeoSentinel: Past, present and future. *Journal of Travel Medicine* **27**, 8. <https://doi.org/10.1093/JTMM/TAAA219>.
- Hoover CM, Rumschlag SL, Strgar L, Arakala A, Gambhir M, de Leo GA, Sokolow SH, Rohr JR and Remais JV** (2020) Effects of agrochemical pollution on schistosomiasis transmission: a systematic review and modelling analysis. *The Lancet Planetary Health* **4**, 7, e280–e291. [https://doi.org/10.1016/S2542-5196\(20\)30105-4](https://doi.org/10.1016/S2542-5196(20)30105-4).
- IDAlert** (2022) IDAlert website. Funded by the European Union's Horizon Europe Programme under Grant Agreement. Available at <http://idalertproject.eu/> (accessed 13 September 2023).
- Jesudason T** (2022) A new One Health Joint Action Plan. *The Lancet. Infectious Diseases* **22**, 12, 1673. [https://doi.org/10.1016/S1473-3099\(22\)00751-4](https://doi.org/10.1016/S1473-3099(22)00751-4).
- Joly D, Johnson CK, Goldstein T, Anthony SJ, Karesh W, Daszak P, Wolfe N, Murray S and Mazet J** (2016) The first phase of PREDICT: Surveillance for emerging infectious zoonotic diseases of wildlife origin (2009–2014). *International Journal of Infectious Diseases* **53**, 31–32. <https://doi.org/10.1016/j.ijid.2016.11.086>.
- Jones BA, Betson M and Pfeiffer DU** (2017) Eco-social processes influencing infectious disease emergence and spread. *Parasitology* **144**, 1, 26–36. <https://doi.org/10.1017/S0031182016001414>.
- Jones BA, Grace D, Kock R, Alonso S, Rushton J, Said MY, McKeever D, Mutua F, Young J, McDermott J and Pfeiffer DU** (2013) Zoonosis emergence linked to agricultural intensification and environmental change. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 21, 8399–8404. <https://doi.org/10.1073/pnas.1208059110>.
- Jones KE, Patel NG, Levy MA, Storeygard A, Balk D, Gittleman JL and Daszak P** (2008) Global trends in emerging infectious diseases. *Nature* **451**, 7181, 990–993. <https://doi.org/10.1038/nature06536>.
- Kamenshchikova A, Wolffs PFG, Hoebe CJPA and Horstman K** (2021) Anthropocentric framings of One Health: An analysis of international antimicrobial resistance policy documents. *Critical Public Health* **31**, 3, 306–315. <https://doi.org/10.1080/09581596.2019.1684442>.
- Keesing F, Belden LK, Daszak P, Dobson A, Harvell CD, Holt RD, Hudson P, Jolles A, Jones KE, Mitchell CE, Myers SS, Bogich T and Ostfeld RS** (2010) Impacts of biodiversity on the emergence and transmission of infectious diseases. *Nature* **468**, 7324, 647–652. <https://doi.org/10.1038/nature09575>.

- Kenyon C** (2020) Emergence of zoonoses such as COVID-19 reveals the need for health sciences to embrace an explicit eco-social conceptual framework of health and disease. *Epidemics* 33, 100410. <https://doi.org/10.1016/j.epidem.2020.100410>.
- Krofah E, Choe SH, Sud A and Degarmo A** (2022) A Global Early Warning System for Pandemics: A Blueprint for Coordination. Available at <https://milkeninstitute.org/report/global-warning-system-pandemic-blueprint-coordination> (accessed 13 September 2023).
- Leach M and Tadros M** (2014) Epidemics and the politics of knowledge: Contested narratives in Egypt's H1N1 response. *Medical Anthropology: Cross Cultural Studies in Health and Illness* 33, 3, 240–254. <https://doi.org/10.1080/01459740.2013.842565>.
- Macherera M and Chimbari M J** (2016) A review of studies on community based early warning systems. *Jamba: Journal of Disaster Risk Studies*, 8, 1. <https://doi.org/10.4102/jamba.v8i1.206>.
- Mackenzie JS, Drury P, Arthur RR, Ryan MJ, Grein T, Slattery R, Suri S, Domingo CT and Bejtullahu A** (2014) The global outbreak alert and response network. *Global Public Health* 9, 9, 1023–1039. <https://doi.org/10.1080/17441692.2014.951870>.
- Mala P, Abubakar A, Takeuchi A, Buliva E, Husain F, Malik MR, Tayyab M and Elnoserry S** (2021) Structure, function and performance of Early Warning Alert and Response Network (EWARN) in emergencies in the Eastern Mediterranean Region. *International Journal of Infectious Diseases* 105, 194–198. <https://doi.org/10.1016/j.ijid.2021.02.002>.
- Mcmichael AJ** (2013) Impediments to comprehensive research on climate change and health. *International Journal of Environmental Research and Public Health* 10, 11, 6096–6105. <https://doi.org/10.3390/ijerph10116096>.
- Morin CW, Semenza JC, Trtanj JM, Glass GE, Boyer C and Ebi KL** (2018) Unexplored opportunities: Use of climate- and weather-driven early warning systems to reduce the burden of infectious diseases. *Current Environmental Health Reports* 5, 4, 430–438. <https://doi.org/10.1007/s40572-018-0221-0>.
- Mwatondo A, Rahman-Shepherd A, Hollmann L, Chiossi S, Maina J, Kurup KK, Hassan OA, Coates B, Khan M, Spencer J, Mutono N, Thumbi SM, Muturi M, Mutunga M, Arruda LB, Akhbari M, Ettehad D, Ntoumi F, Scott TP, Nel LH, Ellis-Iversen J, Sönksen UW, Onyango D, Ismail Z, Simachew K, Wolking D, Kazwala R, Sijali Z, Bett B, Heymann D, Kock R, Zumla A and Dar O** (2023) A global analysis of One Health Networks and the proliferation of One Health collaborations [Article]. *The Lancet (British Edition)* 401, 10376, 605–616. [https://doi.org/10.1016/S0140-6736\(22\)01596-3](https://doi.org/10.1016/S0140-6736(22)01596-3).
- Nichols GL, Andersson Y, Lindgren E, Devaux I and Semenza JC** (2014) European monitoring systems and data for assessing environmental and climate impacts on human infectious diseases. *International Journal of Environmental Research and Public Health* 11, 4, 3894–3936. <https://doi.org/10.3390/ijerph110403894>.
- Nzietchueng S, Kitua A, Nyatanyi T and Rwego IB** (2023) Facilitating implementation of the one health approach: A definition of a one health intervention. *One Health* 16, 100491. <https://doi.org/10.1016/j.onehlt.2023.100491>.
- Olson SH, Benedum CM, Mearu SR, Preston ND, Mazet JAK, Joly DO and Brownstein JS** (2015) Drivers of emerging infectious disease events as a framework for digital detection. *Emerging Infectious Diseases* 21, 8, 1285–1292. <https://doi.org/10.3201/eid2108.141156>.
- One Health Joint Plan of Action, 2022–2026** (2022) *One Health Joint Plan of Action, 2022–2026*. <https://doi.org/10.4060/cc2289en>.
- Ostfeld RS** (2009) Biodiversity loss and the rise of zoonotic pathogens. *Clinical Microbiology and Infection* 15, SUPPL. 1, 40–43. <https://doi.org/10.1111/j.1469-0691.2008.02691.x>.
- Packer C, Halabi SF, Hollmeyer H, Mithani, SS, Wilson L, Ruckert A, Labonté, R, Fidler DP, Gostin LO and Wilson K** (2021) A survey of International Health Regulations National Focal Points experiences in carrying out their functions. *Globalization and Health*, 17, 1. <https://doi.org/10.1186/s12992-021-00675-7>.
- Quadrupartite** (2022) Quadrupartite One Health Intelligence Scoping Study.
- Ribot EM, Freeman M, Hise KB and Gerner-Smidt P** (2019) PulseNet: Entering the age of next-generation sequencing. *Foodborne Pathogens and Disease* 16, 7, 451–456. <https://doi.org/10.1089/fpd.2019.2634>.
- Rogers D, Anderson-Berry L, Bogdanova A-M, Fleming G, Gitay H, Kahandawa S, Kootval H, Staudinger M, Suwa M, Tsirkunov V and Wang W** (2020) COVID-19 and lessons from multi-hazard early warning systems. *Advances in Science and Research*, 17. <https://doi.org/10.5194/asr-17-129-2020>.
- Rohr JR, Barrett CB, Civitello DJ, Craft ME, Delius B, DeLeo GA, Hudson PJ, Jouanard N, Nguyen KH, Ostfeld RS, Remais JV, Riveau G, Sokolow SH and Tilman D** (2019) Emerging human infectious diseases and the links to global food production. *Nature Sustainability* 2, 6, 445–456. Nature Publishing Group. <https://doi.org/10.1038/s41893-019-0293-3>.
- Sayers A** (2007) Tips and tricks in performing a systematic review. *The British Journal of General Practice : The Journal of the Royal College of General Practitioners* 57, 545, 999–999. <https://doi.org/10.3399/096016407782604938>.
- Semenza JC** (2015) Prototype early warning systems for vector-borne diseases in Europe. *International Journal of Environmental Research and Public Health* 12, 6, 6333–6351. MDPI AG. <https://doi.org/10.3390/ijerph120606333>.
- Semenza JC and Paz S** (2021) Climate change and infectious disease in Europe: Impact, projection and adaptation. *The Lancet Regional Health - Europe* 9, 100230. <https://doi.org/10.1016/j.lanep.2021.100230>.
- Sirleaf EJ and Clark H** (2021) Report of the Independent Panel for Pandemic Preparedness and Response: making COVID-19 the last pandemic. *The Lancet* 398, 10295, 101–103. [https://doi.org/10.1016/S0140-6736\(21\)01095-3](https://doi.org/10.1016/S0140-6736(21)01095-3).
- Smith KF, Goldberg M, Rosenthal S, Carlson L, Chen J, Chen C and Ramachandran S** (2014) Global rise in human infectious disease outbreaks. *Journal of the Royal Society Interface* 11, 101, 20140950. <https://doi.org/10.1098/rsif.2014.0950>.
- Sokolow SH, Jones IJ, Jocque M, La D, Cords O, Knight A, Lund A, Wood CL, Lafferty KD, Hoover CM, Collender PA, Remais JV, Lopez-Carr D, Fisk J, Kuris AM and de Leo GA** (2017) Nearly 400 million people are at higher risk of schistosomiasis because dams block the migration of snail-eating river prawns. *Philosophical Transactions of the Royal Society B: Biological Sciences* 372, 1722. <https://doi.org/10.1098/rstb.2016.0127>.
- Sondorp E, Ansell C, Stevens RH and Denton E** (2011) *Independent Evaluation of the Global Outbreak Alert and Response Network Executive Summary*. WHO. Available at www.who.int.
- Sudre B, Rossi M, Van Bortel W, Danis K, Baka A, Vakalis N and Semenza JC** (2013) Mapping environmental suitability for malaria transmission. *Greece Emerging Infectious Diseases* 19, 5. <https://doi.org/10.3201/eid1905.120811>.
- Tang X, Feng L, Zou Y and Mu H** (2012) The Shanghai multi-hazard early warning system: Addressing the challenge of disaster risk reduction in an urban megalopolis. In *Institutional Partnerships in Multi-Hazard Early Warning Systems*. Berlin/Heidelberg: Springer. Available at https://doi.org/10.1007/978-3-642-25373-7_7.
- Taylor LH, Latham SM and Woolhouse MEJ** (2001) Risk factors for human disease emergence. *Philosophical Transactions of the Royal Society B: Biological Sciences* 356, 1411, 983–989. <https://doi.org/10.1098/rstb.2001.0888>.
- The White House US Government** (2021) *American Pandemic Preparedness: Transforming Our Capabilities*. Available at <https://www.whitehouse.gov/wp-content/uploads/2021/09/American-Pandemic-Preparedness-Transforming-Our-Capabilities-Final-For-Web.pdf> (accessed 13 September 2023).
- Thomson M, Indekeu M, Connor S, Dille M and Ward N** (2003) Malaria early warning in Kenya and seasonal climate forecasts [6]. *Lancet* 362, 9383, 580. [https://doi.org/10.1016/S0140-6736\(03\)14135-9](https://doi.org/10.1016/S0140-6736(03)14135-9).
- UK Government** (2021) *New Global Partnership Launched to Fight Future Pandemics*. Gov. UK. Available at <https://www.gov.uk/government/news/new-global-partnership-launched-to-fight-future-pandemics> (accessed 13 September 2023).
- UNDRR** (n.d.) *Early Warning System*. Available at <https://www.undrr.org/terminology/early-warning-system> (accessed 24 October 2022).
- Vlieg WL, Fanoy EB, Van Asten L, Liu X, Yang J, Pilot E, Bijkkerk P, Van Der Hoek W, Krafft T, Van Der Sande MA and Liu QY** (2017) Comparing national infectious disease surveillance systems: China and the Netherlands. *BMC Public Health* 17, 1. <https://doi.org/10.1186/s12889-017-4319-3>.

- Weiss RA and McMichael AJ** (2004) Social and environmental risk factors in the emergence of infectious diseases. *Nature Medicine* **10**, 12S, S70–S76. <https://doi.org/10.1038/nm1150>.
- WHO** (2020) *WHO | Global Influenza Surveillance and Response System (GISRS)*. WHO.
- Wildlife Conservation Society** (2022) WCS Input to the Working Draft, on the Basis of Progress Achieved, of a WHO Convention, Agreement or Other International Instrument on Pandemic Prevention, Preparedness and Response. Available at <https://www.wcs.org/our-work/pandemic-prevention-at-source/wcs-input-on-other-related-documents> (accessed 13 September 2023).
- Willets L, Comeau L, Vora N, Horn O, Studer M, Martin K, Lem M, Pétrin-Desrosiers C, Grant L and Webb K** (2023) Health in global biodiversity governance: what is next? *The Lancet* **401**, 10376, 533–536. [https://doi.org/10.1016/S0140-6736\(23\)00130-7](https://doi.org/10.1016/S0140-6736(23)00130-7).
- Willets L, Siege C, Stewart-Ibarra AM, Horn O, Chotthong B, Tanawat T, Omido P, Sharma M, Alqodmani L, Bennett NJ, Golden CD, Wangari Githaiga C and Vora NM** (2023) Advancing integrated governance for health through national biodiversity strategies and action plans. *The Lancet*. [https://doi.org/10.1016/S0140-6736\(23\)01431-9](https://doi.org/10.1016/S0140-6736(23)01431-9).
- World Health Organisation** (n.d.) WHO's Definition of One Health. Available at <https://www.who.int/europe/initiatives/one-health> (accessed 7 March 2023).
- World Meteorological Organization (WMO)** (2022) Early Warnings for All: Executive Action Plan 2023-2027. Available at https://library.wmo.int/index.php?lvl=notice_display&id=22154#.Y_QLzy_P1D8 (accessed 13 September 2023).