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Developing One Health surveillance systems

One Health High-Level Expert Panel (OHHLEP), David T.S. Hayman [a], Wiku B. Adisasmito [b], Salama Almuhairi [c], Casey Barton Behravesh [d,1], Pépé Bilivogui [e], Salome A. Bukachi [f], Natalia Casas [g], Natalia Cediel Becerra [h], Dominique F. Charron [i], Abhishek Chaudhary [j], Janice R. Ciacci Zanella [k], Andrew A. Cunningham [l], Osman Dar [m,n], Nitish Debnath [o,p], Baptiste Dungu [q], Elmoubasher Farag [r], George F. Gao [s], Margaret Khaitsa [t], Catherine Machalaba [u], John S. Mackenzie [v,w], Wanda Markotter [x,*], Thomas C. Mettenleiter [y,*], Serge Morand [z,aa], Vyacheslav Smolenskiy [ab], Lei Zhou [s], Marion Koopmans [ac]

[a] *Molecular Epidemiology and Public Health Laboratory, Hopkirk Research Institute, Massey University, Palmerston North, New Zealand*
[b] *University of Indonesia, West Java, Indonesia*
[c] *National Emergency Crisis and Disasters Management Authority, Abu Dhabi, United Arab Emirates*
[d] *Centres for Disease Control and Prevention, Atlanta, GA, United States of America*
[e] *World Health Organization, Guinea Country Office, Conakry, Guinea*
[f] *Institute of Anthropology, Gender and African Studies, University of Nairobi, Nairobi, Kenya*
[g] *National Ministry of Health, Autonomous City of Buenos Aires, Argentina*
[h] *School of Agricultural Sciences, Universidad de La Salle, Bogotá, Colombia*
[i] *Visiting Professor, One Health Institute, University of Guelph, Guelph Ontario, Canada*
[j] *Department of Civil Engineering, Indian Institute of Technology (IIT) Kanpur, India*
[k] *Brazilian Agricultural Research Corporation (Embrapa), Embrapa Swine and Poultry, Santa Catarina, Brazil*
[l] *Institute of Zoology, Zoological Society of London, United Kingdom*
[m] *Global Operations Division, United Kingdom Health Security Agency, London, United Kingdom*
[n] *Global Health Programme, Chatham House, Royal Institute of International Affairs, London, United Kingdom*
[o] *Fleming Fund Country Grant to Bangladesh, DAI Global, Dhaka, Bangladesh*
[p] *One Health, Bangladesh*
[q] *Afrivet B M, Pretoria, South Africa*
[r] *Qatar Ministry of Public Health (MOPH), Health Protection & Communicable Diseases Division, Doha, Qatar*
[s] *Chinese Center for Disease Control and Prevention, Beijing, People's Republic of China*
[t] *Mississippi State University, Starkville, MS, United States of America*
[u] *EcoHealth Alliance, New York, United States of America*
[v] *Faculty of Health Sciences, Curtin University, Perth, Australia*
[w] *School of Chemistry and Molecular Biosciences, The University of Queensland, Brisbane, Australia*
[x] *Centre for Viral Zoonoses, Department of Medical Virology, University of Pretoria, South Africa*
[y] *Friedrich-Loeffler-Institut, Federal Research Institute for Animal Health, Germany*
[z] *MIVEGEC, CNRS-IRD-Montpellier, Montpellier University, Montpelier, France*
[aa] *Faculty of Veterinary Technology, Kasetsart University, Bangkok, Thailand*
[ab] *Russian Federal Service for Surveillance on Consumer Rights Protection and Human Wellbeing, Moscow, Russian Federation*
[ac] *Erasmus MC, Department of Viroscience, Rotterdam, the Netherlands*

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ABSTRACT

The health of humans, domestic and wild animals, plants, and the environment are inter-dependent. Global anthropogenic change is a key driver of disease emergence and spread and leads to biodiversity loss and ecosystem function degradation, which are themselves drivers of disease emergence. Pathogen spill-over events and subsequent disease outbreaks, including pandemics, in humans, animals and plants may arise when factors driving disease emergence and spread converge. One Health is an integrated approach that aims to sustainably balance and optimize human, animal and ecosystem health. Conventional disease surveillance has been siloed by

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* Corresponding authors.
E-mail addresses: wanda.markotter@up.ac.za (W. Markotter), mettenleiter@fli.de (T.C. Mettenleiter).
[1] Serving in personal capacity.

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sectors, with separate systems addressing the health of humans, domestic animals, cultivated plants, wildlife and the environment. One Health surveillance should include integrated surveillance for known and unknown pathogens, but combined with this more traditional disease-based surveillance, it also must include surveillance of drivers of disease emergence to improve prevention and mitigation of spill-over events. Here, we outline such an approach, including the characteristics and components required to overcome barriers and to optimize an integrated One Health surveillance system.

1. Introduction

The recent series of infectious diseases emerging from wildlife, including Coronavirus disease 2019 (COVID-19), monkeypox, Ebola virus disease (EVD), and Middle East respiratory syndrome (MERS), has led to increased interest in One Health [1]. Parasites, both macro (like ticks, fleas, worms) and micro (viruses, bacteria, protozoa), have evolved to interact with their hosts throughout their existence. While there are generalists, the majority of pathogens, including the majority of mammalian pathogens, lack the capacity to infect people let alone cause human disease, and most host switches, also known as spill-over events, that do occur into human beings or other species, fail to establish persistent infection in the new host populations. However, despite the complex history of zoonotic epidemics, scientific consensus indicates that the rate of infectious disease emergence has been accelerating in recent decades due to external anthropogenic forces resulting in subsequent parasite transmission to new, naïve hosts (i.e., spill-over) [2–4].

In the context of human disease outbreaks, One Health is often only seen as connecting human and animal health. One Health is, however, broader than this, being an integrated and unifying approach to sustainably balance and optimize the health of people, animals, and ecosystems [5,6]. It recognizes that the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and inter-dependent. It demands mobilizing multiple sectors, disciplines, and communities at varying societal levels to collaborate to raise well-being and to tackle health and ecosystem threats, most of which result from human activities. The collective need for clean water, energy and air, safe and nutritious food, and the mitigation of climate change is encompassed by this, enabling sustainable development. The health of all the individual components of our complex systems can be affected through multiple factors, such as demographic growth, international travel and trade, deforestation and other land use change. Translating this holistic definition of One Health into an integrated surveillance approach that includes ecological monitoring is challenging due to a range of issues including: i) historic silos of expertise and sectors; ii) limited surveillance capacity; iii) problems with access to, and quality of, One Health data and information; iv) logistical challenges such as lack of resources, personnel and legal basis for integrated surveillance across different domains (environmental, animal, human health systems), and v) the number of disciplines that need to be involved, including partners currently not routinely involved in disease surveillance (e.g., environmental agencies, ecologists, conservation biologists, social scientists) [7,8].

Further to the COVID-19 pandemic there is renewed interest at the political, scientific and community levels for a One Health approach to disease prevention and surveillance. For example, at the 2020 Paris Peace Forum, the Food and Agricultural Organization (FAO), World Organization for Animal Health (WOAH, then OIE), United Nations Environment Programme (UNEP) and World Health Organization (WHO) (hereon, Quadripartite) were tasked to enhance their collaboration by creating a One Health High-Level Expert Panel (OHHLEP). In 2021, the G7 Carbis Bay declaration charged the Quadripartite with conducting a One Health Intelligence Scoping Study to foster the sharing of One Health information and to strengthen cross-sectoral coordination and collaboration. While these developments were triggered by human health challenges, the reality of the issue, identified by the OHHLEP One Health definition, necessitates that they include plant, domestic and wild animal health and ecosystem function [5,6]. In addition to emerging human health challenges, diseases emerge threatens domestic animals (e.g., African swine fever, Rift Valley fever, influenza), wildlife (e.g., avian influenza, Usutu virus, fish mycobacteriosis), crops (e.g., banana Sigatoka disease, wheat blast) and wild plants (e.g., ash dieback, chestnut blight), with wild animal and plant diseases threatening biodiversity and ecosystem function. For instance, the most devastating animal disease recorded is amphibian chytridiomycosis. This human-induced and -facilitated fungal pandemic has caused catastrophic declines of >500 species and the extinction of at least 90 amphibians (Scheele et al., 2019). Climate change, ecosystem degradation and biodiversity loss are huge challenges in their own right, but increasingly threaten human health and wellbeing through decreased agriculture productivity, loss of ecosystem services and impediments to economic activities and growth; the processes that drive these losses also increase risks of cross-species disease transmission [1,9]. Awareness and mitigation of such drivers of disease emergence and spread is key to the prevention of novel disease threats, with tremendous economic savings when compared to the costs of dealing with a disease once it has emerged [10,11].

A systematic review of One Health surveillance systems (OHSS) produced 53 reports describing 41 different surveillance systems. Although these included some successful, well integrated systems, such as West Nile surveillance in Europe, Canada and the US, which often address human and domestic animals, wildlife and environmental surveillance (including vector surveillance) [12], these few examples barely begin to address global risk, particularly in those biodiverse regions that are currently undergoing most rapid environmental and socioeconomic change [1]. In addition, none of these systems systematically included information on factors driving the emergence and spread of disease. Bordier et al. (2020) provided a framework for characterising systems reported as OHSSs, using a set of criteria that includes the breadth and level of collaboration required across sectors [12]. In addition, they and others have highlighted barriers and enablers of successful OHSSs [8,13,14]. In 2019, the Tripartite organizations – the Food and Agriculture Organization of the United Nations (FAO), the World Health Organization (WHO), and the World Organization for Animal Health (WOAH) – developed the Tripartite Zoonoses Guide (TZG), which was the summation of a global effort of >100 experts worldwide to provide guidance and explain best practices for addressing zoonotic diseases in countries. This includes supporting countries in understanding national contexts and developing capacities for strategic technical areas one of which is surveillance and information sharing. While the focus of this guide is on zoonoses, the guide states that it is relevant to other One Health issues too. It is important to reference this guide and the new Surveillance and Information Sharing Operational Tool (SIS OT) that has been developed by the Tripartite organizations (FAO, WHO, WOAH) and technical experts to support national authorities to establish or strengthen their coordinated, multisectoral surveillance and information sharing for zoonotic diseases. Such a system is essential for early detection of disease events and timely, routine data sharing among all relevant sectors to support coordinated response, prevention, and mitigation of these events. While it provides step-by-step guidance on how to conduct each component of the process, it also provides an instrument for assessing the national coordinated surveillance and information sharing capacity already in place and linking users to a curated set of existing tools and resources that can help develop or improve that capacity.

The barriers to a successful OHSS include differences in awareness and priority between sectors, professional and budgetary silos, lack of capacity and capability to provide high quality data for all components of surveillance and complexity in deciding what to monitor and how to integrate indicators and metrics, siloed decision-making and governance, lack of real-time data sharing, inconsistent communication between sectors, and fragmented community and stakeholder engagement. These are exacerbated by socioeconomic inequalities and other issues, such as greed, corruption, and potentially ignorance or denial by policy makers or politicians (e.g., climate change denial).

Here we describe components needed in integrated disease surveillance systems using a One Health approach to optimize the health of people, animals, and ecosystems. We note that different aspects of each component will necessarily take longer to implement than others, because they have to be newly established, they require (additional) funding and/or because they are more complex to implement.

1.1. Six steps to develop One Health surveillance systems

Based on reviewing OHSSs, identifying challenges and barriers and building from the One Health definition adopted by the Quadripartite in 2021, we identify six steps to overcome barriers and to optimize an integrated One Health surveillance system (Fig. 1).

The first step is for all stakeholders and policy makers to agree on a scope of One Health surveillance that is aligned with and draws from the Quadripartite's One Health definition. This scoping could include system mapping exercises, using tools like causal loop diagrams to ensure all the relevant components (including drivers), stakeholders (including local communities) and key indicators and potential metrics are considered [15,16]. Structured prioritization exercises explicitly considering multiple criteria assist with complex problem decision making, leading to better informed decisions. The costs and appropriate scale can be considered, based on the likely available resources, and indicators ideally include those that demonstrate positive outcomes (including changes in trends) across the sectors. This first step can be repeated at any time and it is good practice to do so in intermittently in order to identify gaps and to ensure optimal risk mitigation.

The second step is to define data collection components and identify which of these are already included within any current initiatives. These data will consist of two types: i) data on the epidemiology of pathogens or diseases, and ii) information on the drivers of disease emergence and spread. While the former is typically included in existing surveillance systems, driver-based surveillance and the inclusion of ecological monitoring is rare, although there are some examples where these are surveilled for vector-borne diseases [17]. Considering the underlying paradigm that disease emergence and spread is driven by changes to human/animal interfaces, including changes in interactions among and between humans, animals and within ecosystems, surveillance for such changes will include environmental, ecological and socio-economic factors in order to inform emerging disease risk. Such surveillance practices would create a risk prediction system that identifies where mitigation measures are required and identify potentially high-risk areas where more-traditional surveillance needs to occur [17,18]. Although some initiatives are exploring how to utilize data on drivers for early warning systems, systematic approaches are also needed to make these widely available and to cover a wide scope of pathogen types and sources.

The third step is the integral system design aspects, starting with drafting an umbrella organisational plan that incorporates the fact that One Health and OHSSs are themselves complex, with multiple interactions occurring through dependent relationships and feedback loops. For example, natural habitats, industrial farming areas and urban environments, as well as the infrastructures (e.g., IT, organisational) and regulatory frameworks that are in place to monitor them, are all complex on their own, with higher levels of complexity when approached as an inter-related system. This 'whole system' approach can identify points of commonality among the components of the system and provide opportunities for interventions. The umbrella plan must allow for flexibility to cope with abrupt changes, such as the emergence of hitherto unknown pathogens (e.g., SARS-CoV-2), or large-scale environmental disasters (e.g. hurricanes, wildfires). While ensuring the basic components are in place, the plan should accommodate technological advances (e.g., whole genome sequencing, citizen science-based surveillance, artificial intelligence, advances in forecasting and modelling) [19,20]. In resource limited settings in particular, reliance may be greater on community-based surveillance [21].

The fourth step is to define the governance system, bearing in mind

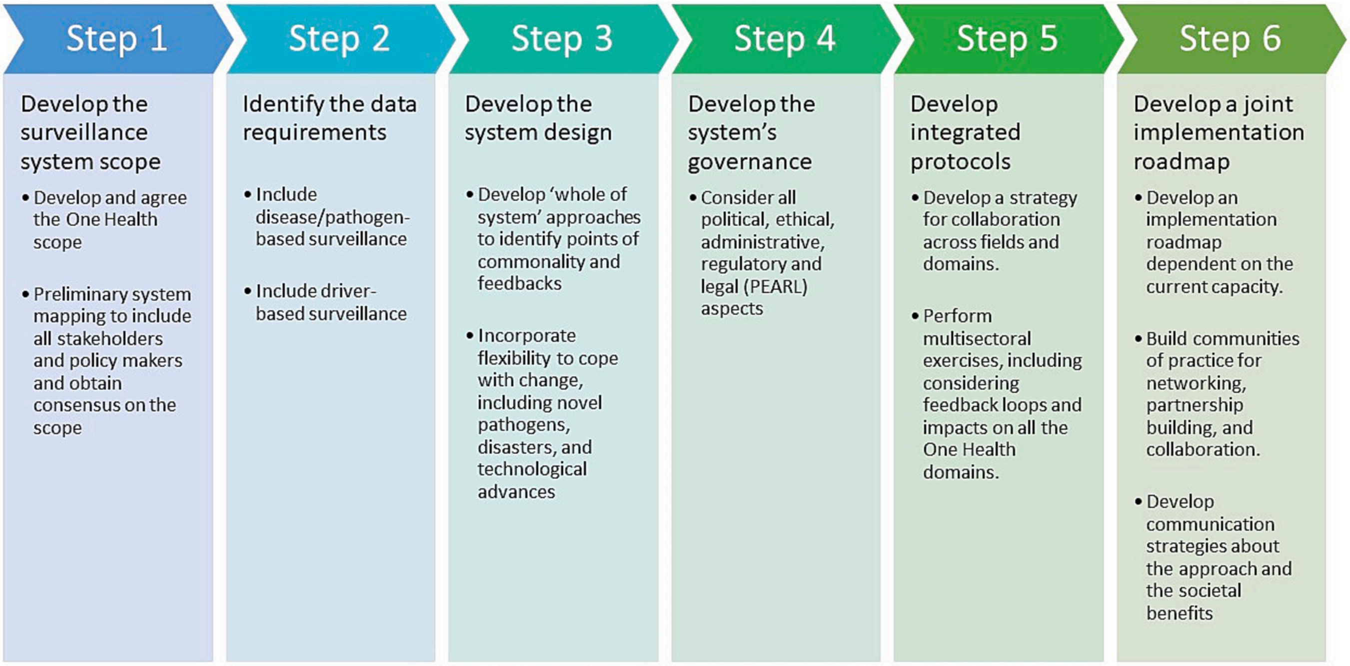

Fig. 1. Six steps that can guide One Health surveillance system development.

political, ethical, administrative, regulatory and legal (PEARL) barriers and enablers. OHSSs require coordination across disciplines, sectors and government departments in order to facilitate and sustain collaboration and partnerships. OHSSs should include integrated steps throughout their process, from planning, data collection, sharing, integration and analyses, to interpretation, visualisation, and results dissemination. OHSSs will require the necessary legal architecture to function, including provisions for fair and equitable access and benefit-sharing from collaborative work, and to ensure sustainable resourcing, including financing. Data feeding into the system can be from multiple sources and ideally need to be of high quality, secure, standardised, and timely, although less well defined and standardised datasets may provide additional information if used carefully. Sufficiently trained and resourced laboratory networks, epidemiological intelligence, as well as alert verification and outbreak response capacity need to be developed equitably around the globe, to allow immediate verification wherever conspicuous signals arise in high-risk areas identified by One Health surveillance of drivers [1,2,18,22]. Laboratories require high operating standards, including appropriate levels of biosecurity and biosafety, with trained workforces able to generate, record, interpret and report suitable data. Integration of laboratories across current human, animal and plant health siloes is required and, as such, funding needs to be appropriate with agreed minimum standards for sustainable development of core capacity and capability across all One Health domains (human, animal, plant, environment), and contingency budgets for signal verification and response actions.

The fifth step is to develop protocols for integrated surveillance overviews and outputs, including a strategy for collaboration with experts across fields and domains to provide evidence-synthesis for science-based risk assessments. This may include the development of exercises to simulate outbreaks or other events that require an integrated action. These exercises should be multisectoral and transdisciplinary and aim to include feedback loops and impacts on all individual sectors within the One Health system. They include training on dealing with uncertainty, which is common in early stages of emerging disease outbreaks. These exercises may help determine if the appropriate indicators and metrics have been included in the system design. Participatory community engagement in such events is most likely to lead to successful community-based surveillance, because it leads to greater acceptability, trust, and engagement due to more collaboration and communication, which builds a sense of ownership [21].The sixth step is to develop a joint roadmap for implementation of the OHSS, bearing in mind that this may be developed with different speeds and priorities in different jurisdictions, depending on decision makers and capacity. Building communities of practice for networking, partnership building, and collaboration is essential [23–25]. Critically, this includes communication about the integrated OHSS approach and the benefits of this to stakeholders and participants [21]. As with the OHSS methodology, communications should include social science experts working in collaboration with natural scientists in a coordinated approach across sectors. This will help ensure that One Health has social licence to succeed.

2. Roles for One Health surveillance implementation

Here, we highlight key components that are either required for, or would facilitate, the implementation of a OHSS.

The implementation of a OHSS should be organised around leadership, communication and coordination, common overall governance and operational application. We take a national perspective for countries that coordinate with the Quadripartite or with any future international One Health agency. However, the framework should be implemented at all levels: international, regional, and local, including within societies [23]. We recognise that implementation at different levels will vary in terms of feasibility and approach, depending on the socioeconomic and political circumstances in each country or other administrative unit. This must all be considered when establishing the following components, that are needed to help achieve the goals of a OHSS.

2.1. National level coordinating role

A senior executive high-level lead (HLL), not necessarily a technical expert, but someone with leadership qualities, may advocate for, and set the strategic direction of, a OHSS, advising government and informing decision making. Operationally, a HLL would be the national counterpart for roadmap development of a OHSS, providing central coordination and oversight for the resourcing, integration, planning and joint reporting among sectors. The HLL determines the relevant institutions required and ensures that the structures and regulatory/legal frameworks are in place. The HLL would assess the joint OHSS plans and evaluations of the OHSS, oversee and review the governance and implementation of the OHSS, and liaise with decision makers across sectors and stakeholders. The HLL should act as an interjurisdictional liaison nationally and internationally and be responsible for the governance of a high-level expert panel.

Communication with the public, policy and decision makers, and the international community (e.g., with the Quadripartite), would be a key role of the HLL, including the communication and reporting of integrated signals from the different sectors. It is key that the HLL provides accountability at government level, providing a level of political representation currently missing. For this, the HLL may be at minister level nationally, yet ideally independent of specific ministries. It is also important that the HLL is able to ensure the allocation of adequate resourcing for the OHSS, including any necessary alterations to laws and regulations, and facilitates the overcoming of challenges in OHSS implementation. Although implementation should start at national level, implementation within sub-administrations, such as provinces, districts and municipalities, must also be aligned.

2.2. High level expert panel

An independent high-level expert panel (HLEP) may help to implement the OHSS. To provide comprehensive and objective advice to the HLL on the operation of the OHSS and responses to key results, the HLEP should include representation from the different

disciplines and sectors, including policy makers, data analysts, logistics and supply chain experts, modellers, social scientists (e.g., medical and social anthropologists), ecologists and climatologists, along with infectious disease experts such as human health experts (clinical and non-clinical), veterinary experts (domestic and wild animal), plant health experts, and molecular and genomic experts [26]. In low resource settings, whether those be financial or small population sizes, regional collaboration might be one way to help ensure that there is adequate funding and expertise across the sectors is available [27]. Under the guidance of, and in collaboration with the HLL, the HLEP can advise on strategies for the implementation of a functional OHSS for a particular jurisdiction. Their role would be to identify best practices and how these should be applied, to conceive appropriate and realistic frameworks to strengthen existing surveillance systems and bring them together with additional surveillance to form a OHSS, and to provide guidance on monitoring drivers of emergence across ecosystems and human society. The HLEP may give purely scientific advice (e.g., OHHLEP) or have a more political role (e.g., Global Leaders Group on Antimicrobial Resistance GLG-AMR). In Germany, for example, the Federal Ministry for Economic Cooperation and Development has established a One Health Advisory board.

Operationally, the HLEP may provide guidance on surveillance targets, monitoring and evaluation processes, help identify best practices, review scientific research relevant to OHSS, support evidence-synthesis activities during outbreak response situations, and comment on cost implications and the feasibility of these systems [10,28–30]. The HLEP also might advise on indicator pathogens and species to monitor within ecosystems and on what type of surveillance should be conducted (e.g., scanning or targeted), help advise on responses to key results arising from the OHSS, and provide connections with different stakeholders and communities. These activities will help keep the HLL & the operational teams informed and effective across their remit, assessing strategy and performance at the national level, while assisting global coordination through aligning One Health surveillance across national and international organizations.

2.3. Operational level

Under the jurisdiction of the HLL, there needs to be an operational team (OT) responsible for the implementation of the OHSS as part of the global network, including assessment of alerts, and risk management, ensuring different components are carried out on time and soliciting stakeholder engagement and management. The OT would also identify surveillance, knowledge and funding gaps (including issues with particular indicators or metrics), bottlenecks and successes, and communicate key results to the HLL, HLEP and other stakeholders. The OT would include emergency warning, emergency response, and resource deployment. As the OT will need to have cross-sectoral and cross-agency reach, a governance and resourcing framework, including the HLL, needs to be devised to avoid politicisation. The setting up of a separate One Health department might be the best way to ensure that this occurs. OT logistics and network management specialists will engage, when required, with other relevant services, such as security services, police, waste management, urban and rural development, and anti-corruption units, whether in the public or private sector.

For settings where community-based surveillance is necessary, participatory community engagement is key, with a recent systematic review finding that clear supervision and training, engagement with community 'informants', using simple and adaptable case definitions, having a quality assurance scheme, effective use of available technology, using data for real-time decision-making showing the utility of the information, and having surveillance workers in close proximity communities are all linked to successful systems [21].

3. Specific disciplines for implementation

3.1. Legal and ethics expertise

A key component is the establishment of multidisciplinary and multisectoral legal expertise with a focus on the different components of a OHSS and the integration of data from multiple sources, including the legal framework for operating during an emergency. This legal expertise will ensure that policy recommendations for implementation of a OHSS are consistent with global governance mechanisms, regional protocols, and national legislation, and develop a governance structure that avoids negative impacts when establishing OHSS structures. A legal team can translate and adapt the integrated governance developed by the Quadripartite for the national situation and this can be used to provide an inclusive framework for stakeholders in order to avoid potential barriers or bottlenecks. Strong and clear jurisdictional legislative and regulatory frameworks are needed in order to ensure One Health approaches are possible, prioritized, and effective. These legal frameworks may take time to develop, however that should not prevent those aspects that can be implemented from being initiated.

The principles of ethics and responsibility relate to all aspects of surveillance, scientific research and policy implementation, including technological and engineering applications, in human medicine, veterinary medicine, agronomy and the environment. They include responsibility to resolve potential conflicts arising from ethical and legal mechanisms developed before the development of a OHSS [31,32]. 'One Ethics' principles should guide navigating the complex 'ethics-scape' of values and responsibilities (rights and justice) in both humanistic and ecocentric views regarding One Health surveillance, disease prediction and prevention. Such ethics cannot be limited to human interests and concerns, but must include nonhuman animals and the environment, and must reflect the needs of justice for individuals, populations and societies that are most exposed to environmental and health crises.

3.2. Data management and data analytics expertise

For a OHSS to be effective and efficient, it is crucial that there is a smooth and iterative flow of data, analyses, communications, knowledge, feedback and ideas between those collecting data and agencies, managers, and data analysts [24,33]. Data management and analysis (including modelling) need to be able to link across sectors and both are essential for the provision of appropriate risk assessment, alerts, informed policy making, and performance evaluation of the OHSS implementation. Crucially, data sharing needs to be possible on jurisdictional, national, and international levels. However, to maintain successful community-based surveillance, it is also necessary to feedback findings to those communities that are engaged with data collection [21].

A platform for sharing surveillance information, potentially requiring cross-sector training, is imperative. It will require IT systems and platforms that can integrate and host these data. Data security, sovereignty and respect of ownership are critical, along with developing user-friendly fair data infrastructures, suited for modern data analysis while balancing the interests of One Health partners who may be hesitant about sharing data openly. Therefore, working with legal, communications, and behaviour teams is required to help overcome these barriers.

These systems and structures lay the foundations for identifying and implementing iterative improvements to the OHSS. Not all components of a OHSS system will have to be developed from scratch as there are several sector specific surveillance platforms already in place that may be incorporated into OHSS systems (e.g., the Joint FAO–OIE–WHO Global Early Warning System for health threats and emerging risks at the human–animal–ecosystems interface [GLEWS], the WHO Global Antimicrobial Resistance and Use Surveillance System [GLASS], The WHO Global Outbreak And Response Network [GOARN], FAO's Global Animal Diseases Surveillance and Early Warning System) and the Quadripartite One Health Joint Plan of Action (OH JPA) [34]. Development of a true OHSS, however, will require modification and expansion beyond these individual components [35]. That also applies to the data analytics and modelling approaches (e.g., statistical, mechanistic models) currently used for risk analyses and forecasting, including phylogenetic and phylodynamic modelling. Integrating data from multiple sources adds complexity, potentially requiring development of new methods that are beyond the capacity of routine surveillance partners, necessitating partnerships between relevant stakeholders, such as academics, public health partners, specialised data scientists among other [27]. These processes should be iterative and final interpretation should be in collaboration with the OT and HLEP experts [24,33]. The development of OHSS data management and analysis functions also need to consider the increasing demand for open data and transparency in modelling parameters and code, and involvement of new stakeholders from disciplines and communities not traditionally involved in surveillance [21,26,36,37].

3.3. Laboratory and bioinformatics expertise

Laboratories can also play important cross-sectoral roles. Resources for laboratories varies widely, both regionally, nationally, within nations, and between and within fields. The identification, isolation, propagation, and in-depth characterization by whole genome sequencing and bioinformatic, genomic, phylogenetic and phenotypic analyses of infectious agents from all species can be performed within the same laboratory system; thus, removing silos and barriers to data sharing, and providing opportunities to increase efficiencies and affordability. How this is structured might vary, but if laboratory diagnostics are separated across the human, plant, animal and environmental sectors, collaboration must be actively managed and coordinated otherwise there is a high risk that patterns of pathogen occurrence or adaptation will be missed or unnecessarily delayed.

Laboratory and bioinformatics expertise and data sharing are key for the detection and identification of agents (e.g., pathogens, strains, vector species); the analysis and interpretation of findings; selecting triggers for alerts; identifying predictive trends and early warning signals; and the tracking effectiveness of responses or other interventions. Fast and accurate pathogen identification is essential, with rapid dissemination of data and information through integrated data systems for alerts and surveillance. For this, laboratories should work closely with, or be integrated within, a 'One Data' model; i.e. data is inputted into common data bases across laboratories within and across jurisdictions in order to allow open and shared access to real-time data. International collaboration is crucial and, for diagnostic laboratories, inter-laboratory comparisons such as proficiency-testing programmes and 'ring tests/trials' are key for harmonisation and quality control of laboratory methods and processes. These can be used to identify where further funding and capacity building is required and what requires prioritization [15,16,27]. Legal and ethical barriers towards this essential function need to be addressed by the One Health ethics experts. These include barriers to data collection and sharing due to privacy concerns, perceived or real commercial interests and blame, concerns about misuse of information, and concerns about equity of access and benefit sharing [32,38].

3.4. *Social sciences and economics expertise*

In addition to legal and ethical expertise, social scientists and economists need to be involved in the operationalisation of a OHSS in order to advise on societal engagement and the economic sustainability of all components of the OHSS within countries, and at supranational level (social sciences and economics team, SET). SET experts can also provide analysis and evidence of any specific socioeconomic burdens of One Health issues within and across countries. Another important role of the SET is to conduct locally appropriate cost-benefit analyses to ensure that both the negative and positive implications of disease control activities are assessed and managed appropriately.

Cross-sectoral social and economic expertise and analyses are needed for identifying changes to disease risks, such as changes in human-animal (domestic or wild) interfaces, in order to identify changes to the disease drivers landscape and, hence, potential new areas of increased disease risk. These areas can then be identified for targeted health and pathogen surveillance in people, animals and plants. Identifying key changes requires knowledge and understanding of human and animal behaviours and activities and the socioeconomic and policy drivers of these. Economic cost-benefit analyses of different actions/mitigations considered in response to the surveillance of pathogens and drivers should preferably be across short-, medium- and long-term time scales, and should include social, economic and environmental impacts. The drivers of the emergence of most infectious diseases today are human/anthropogenic, as are the solutions.

The SET should be well-placed to help identify stakeholders for any given One Health issue and who should participate in monitoring, surveillance or mitigation actions. For example, NGOs, local and indigenous communities, and religious organizations are often neglected stakeholders, yet they are often embedded in society, trusted, have local knowledge and can help design appropriate and practical processes and metrics to deal with One Health hazards across sectors [23]. The SET can advise on context-specific resources for implementation, including the involvement and buy-in of local and indigenous communities alongside the OT. Communications experts within the SET can work with communicators and opinion makers, such as the media and community leaders, to provide information to the public, including finding approaches that engage and motivate the public, e.g., to get tested/examined, or to facilitate necessary behaviour changes, and support the OT in the participatory approaches to community-based surveillance.

3.5. *Clinical expertise*

Clinical institutions have clearly defined roles regarding patient care for humans as well as for livestock, kept wild animals, and companion animals [39–41]. Yet, there are challenges to their integration into a OHSS, due in-part to the historical nature of these silos, the variation from private to public systems, patient data confidentiality, and differences in governance. However, in the context of a OHSS, medical and veterinary clinicians perform front-line, real-time syndromic surveillance and can provide important knowledge of the normal/baseline situation and early warning when changes to this occur. Clinical institutions also help identify pathogens, trends in infectious and non-infectious diseases in people and domestic animals and they form an important interface with the general public and animal owners. The number of clinicians per population varies widely, and with that the potential for clinical surveillance varies greatly [21].

3.6. *Public health expertise*

Public health involves population level analyses and interventions, methods, such as syndromic, active, and passive surveillance, community surveillance, sales data surveillance, along with epidemiological investigations using trace-back of cases (national, regional, local) and other epidemiological tools such as modelling [42,43]. Key for a OHSS is that human health investigations, when appropriate, should be in collaboration with veterinary and environmental (e.g. ecology and wildlife) teams. The public health sector plays a key role in education, capacity building and training, fostering access to data, and appraising data quality. In addition to biological surveillance, behavioural surveillance can help to identify socio-economic and other determinants of disease risk, as well as acceptable safer alternatives and connections to communities, which is essential for successful community engagement.

3.7. *Animal health expertise*

Disease surveillance in animal populations (wild and domestic) and at the animal-human and environmental interfaces is required to monitor, detect and report pathogens in animals. Close collaboration and coordination between the wildlife health, domestic animal health and public health sectors are important for the early detection of pathogen spill-over between species, including identifying the occurrence and source of zoonotic infections. However, different areas of animal health have very different systems and the integration with human surveillance is currently patchy at best. Animal health encompasses (1) companion animals (e.g. domestic cats, horses), which live in close proximity to people in all societies, (2) production animals (e.g. domestic cattle, poultry, fur producing animals) and (3) wild animals including peri-domestic wildlife (e.g. many bat and rodent species). Boundaries between these areas may be fluid, however, with some wild animals being farmed (e.g., masked palm civets, crocodiles) and some domesticated animals living freely (e.g., feral cats). Yet, even though most human pathogens have their origins in other animal species, animal health surveillance systems are generally less well funded than their human counterparts, and surveillance of wild animal health is often extremely limited or absent. While investment in food safety often is significant and technologically advanced, this expertise and investment also varies widely throughout the world, with some countries having only limited veterinary public health services.

Albeit generally poorly monitored, wildlife health is essential for the early detection of infections and identification of pathogens with potential for spill-over to other species, including into humans. The baseline wildlife population and pathogen prevalence data that we need to allow timely detection of changes in pathogen occurrence or disease risk to people, domestic animals or other wild species are poorly known. The limited surveillance in wild animals is partly due to practical, logistical difficulties, and partly prioritization and funding. The practical difficulties include the capture and handling diverse wild species, species identification, obtaining appropriate sample sizes per species, and having validated serological assays for species among many [44]. A unified OHSS needs to include wildlife pathogen and disease surveillance, ideally combined with demographic studies to identify any disease impacts on biodiversity, and provide a channel for the reporting of morbidity and mortality events in wildlife to the other health sectors [36,45]. When disease outbreaks among people or animals are not obviously sector-specific problems (e.g. avian influenza), both wild and domesticated animal health teams should participate in the investigations to help with the identification of pathogen sources, disease risks and their mitigation.

Generation of surveillance data in the animal health system can be through active and passive surveillance of domestic and wild species, including syndromic surveillance, diagnostic investigations, feed and medication sales data, milk- and meat hygiene inspection data. These data can be linked to environmental data, demographic data, and socioeconomic data, and analysed for trends and clustering of events that warrant follow-up. While the goals of surveillance within different animal health sectors may vary, the results can be used across sectors in a OHSS. For example, pairing pathogen surveillance data with risk assessment can help to identify areas where risk of spill-over is highest, such as based on relevant species, interfaces (e.g., markets, extractive industries), and practices . [3,18,46,47]

Finally, engagement with communities about wild and domestic animal health can have other benefits, as these animals can be a conduit for engagement, as they may have cultural, spiritual, and financial value (IPBES) [48,49].

3.8. Environmental expertise

'Environment' is a comprehensive term that for One Health surveillance includes the living and non-living, and natural and artificial (man-made) environmental components. The broader environmental factors that need to be monitored over time include land and water use (in particular, any changes to these), habitat quality and availability [18], biodiversity indicators such as wild animal and plant population abundances and distributions [46], wildlife exploitation [47], along with the monitoring of meteorological and climatic conditions [9,18,46,47]. Integrative laboratory and data analytics functions thread through these. By integrating these data sources with those from other sectors, epidemiological patterns can be identified and assessed, as can environmental and other factors that drive public health, wildlife, and domestic animal threats. The results of these assessments can be used to help understand areas of particular disease risk, helping to inform targeted surveillance efforts and mitigations. They may help to build predictive models, that can help inform mitigation measures to reduce the impact of infectious diseases on people and domestic and wild plants and animals. It is important that these deliberations include international, national, regional, local and indigenous communities in order to include local knowledge and to ensure stakeholder engagement.

4. Conclusion

Here, we lay the foundations for transformational change in the way disease threats to people, domesticated animals, plants and wildlife are identified, surveilled and assessed through the development of a truly integrated One Health Surveillance System; an approach which will improve the prevention, detection and response to disease threats. We focus on infectious diseases, but the framework can be adapted for putative drivers and surveillance of non-infectious disease threats, e.g., chemical contaminants. Governments and other funding agencies must invest in these initiatives, with long-term, sustained funding for public health, domestic and wild animal health, plant health, and environmental agencies as well as for One Health research and teaching to build capacity for future generations.

Declaration of Competing Interest

The authors declare no-conflict of interest.

Data availability

No data was used for the research described in the article.

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