Reshaping surveillance for infectious diseases: less chasing of pathogens and more monitoring of drivers

J.A. Drewe* (1, 2), J. George (3) & B. Häsler (1, 2)

(1) World Organisation for Animal Health Collaborating Centre in Risk Analysis and Modelling, c/o Veterinary Epidemiology, Economics and Public Health Group, Royal Veterinary College, Hawkshead Lane, North Mymms, Hatfield, Hertfordshire, AL9 7TA, United Kingdom

(2) Veterinary Epidemiology, Economics and Public Health Group, Royal Veterinary College, Hawkshead Lane, North Mymms, Hatfield, Hertfordshire, AL9 7TA, United Kingdom

(3) Southern African Centre for Infectious Disease Surveillance Foundation for One Health, Sokoine University of Agriculture, PO Box 3000, Chuo Kikuu, Morogoro, Tanzania

*Corresponding author: jdrewe@rvc.ac.uk

Summary

Animal health surveillance, despite its name, tends to focus on looking for disease. Often this involves searching for cases of infection with known pathogens ('pathogen chasing'). Such an approach is both resource-intensive and limited by the requirement for prior knowledge of disease likelihood. In this paper we propose the gradual reshaping of surveillance towards the systems level, focusing on the processes ('drivers') that promote disease or health, rather than on the presence or absence of specific pathogens. Examples of relevant drivers are land-use change, increasing global interconnectedness, and finance and capital flows. Importantly, we suggest the focus of surveillance should be on the detection of changes in patterns or quantities relating to such drivers. This would generate systems-level risk-based surveillance information to identify areas where additional attention may be needed, and, over time, inform the implementation of prevention efforts. The collection, integration and analysis of data on drivers is likely to require investment in improving data infrastructures. A period of overlap would allow the two systems (traditional surveillance and driver monitoring) to be compared and calibrated. This would also lead to a better understanding of the drivers and their linkages, and thereby generate new knowledge that can improve surveillance and inform mitigation efforts. Since surveillance of drivers may give signals at the level of the system when changes are occurring, which could act as alerts and enable targeted mitigation, this might even enable disease to be prevented before it happens by intervening directly on the drivers themselves. Surveillance focused on drivers such as these would be expected to bring co-benefits because many diseases are promoted by the same drivers. Further, focusing on drivers rather than pathogens should allow for controlling currently unknown diseases, making this approach particularly timely given the increasing risk of emergence of new diseases.

Keywords

Drivers – Health – Infectious disease – Pathogen – Prevention – Surveillance – Systems-level.

Introduction

Infectious disease surveillance is a cornerstone of epidemiology and disease management. It enables us to reveal the amount and distribution of disease(s) in populations; to detect infected individuals or groups in order to target control efforts; to help prevent outbreaks through early detection of pathogen incursion; and to demonstrate specific geographic regions to be free from infection in order to facilitate international travel or trade [1]. Knowledge gleaned from these applications helps us understand where disease occurs (e.g., in which locations and species), how and why diseases spread, and the impact of control measures. Together, these insights should lead to better disease control in the future. But this implies our aim is to remove or prevent disease, actions which are not necessarily synonymous with promoting health. This distinction is important because it will affect how we design and conduct surveillance and, ultimately, what we consider as success.

Health is a social construct, meaning its definition and importance varies with people's personal and social values, and in a dynamic way concurrent with societal change [2]. Further, health is not simply the absence of disease [3] and the meaning of 'in good health' is commonly an opinion (professional or personal) and a relative rather than an absolute condition [4]. Yet, definitions of animal health still largely rely on the absence of disease or the observation of 'normal' behaviour and functioning. It has been said that 'health cannot be measured solely by what is absent but rather by characteristics of (individuals) and their ecosystem that affect their vulnerability and resilience' [5]. This invites us to look more closely at the processes that affect the vulnerability and resilience of living systems, processes that may drive (or protect against) disease emergence.

The majority of current disease surveillance in humans and animals focuses on chasing pathogens: spending effort trying to find known hazards [1]. The problem with this approach is that it usually requires prior knowledge of each pathogen so that you know what to look for and where best to look. It is thus reactive. Surveillance for new pathogens is possible but is by necessity nonspecific and relies on looking for unusual trends. Further, you cannot demonstrate freedom from a disease – which in animal health is often essential for trade purposes, and for human health may also affect permits to travel, as seen in many countries with coronavirus disease 2019 (COVID-19) – if the disease is not yet known to science. Since novel pathogens are constantly emerging, the next pandemic may be caused by a new virus, bacterium, or even a new form of infectious material. Consequently, there is a shared interest across disciplines in targeting surveillance to enable early detection of pathogens in human, animal and plant populations [6]. Limited evidence is available, however, on which factors actually improve early detection [7] and on the usefulness of novel digital surveillance approaches that are increasingly being integrated into public surveillance systems [8]. A possible way to solve some of these challenges might be to conduct surveillance at a systems level, focusing on the processes ('drivers') that promote disease or health, rather than on the presence or absence of specific pathogens. Such an approach would be expected to bring co-benefits because many diseases are promoted by the same drivers. Further, focusing on drivers rather than pathogens has the potential to improve the performance of surveillance by enabling alerts and therefore increasing the likelihood of early detection and response to currently unknown (i.e., un-emerged) diseases.

Drivers of disease emergence

The last two decades have seen an increasing realisation of the importance of major processes driving disease emergence, sometimes called drivers. Drivers of disease can be defined as processes linked to humans, animals, plants and the environment that lead to the necessary conditions for a pathogen to emerge, spread and cause disease in susceptible populations [9, 10, 11]. Most, if not all, are anthropogenic [12]. Examples and some of their impacts include:

– climate change, which may affect geographical distributions of hosts, pathogens and vectors as well as reducing host resilience against infection [13];

– deforestation and habitat disturbance. The risk of outbreaks of zoonotic and vector-borne diseases – as a result of promoting contacts between previously separate viruses and people or animals – has been positively correlated with deforestation, mostly in tropical countries, and with reforestation, mostly in temperate countries [14]. This surprising finding means that reforestation may not be a simple solution because this may in fact increase disease risk if it leads to further biodiversity loss when forest expansion is made at the expense of grasslands, savannas, and open-canopy woodlands [14];

– global interconnectedness, which means an emerging pathogen is increasingly likely to have rapid access to a large number of susceptible hosts, increasing the chances of sparking a pandemic [15].

Focusing surveillance on drivers such as these is attractive because it may give signals at the level of the system when changes are occurring.

In addition to achieving early detection to enable early response, this might enable disease to be prevented before it happens by intervening directly on the drivers themselves.

In 2015, Olson *et al.* proposed a new frontier for infectious disease surveillance focusing on integrated drivers of emerging infectious disease and digital data use [9]. The rationale for this system was to have improved risk-relevant information and thereby provide decision makers with an early alert system at the pre-outbreak stage and help to tailor interventions at the post-outbreak stage. The authors argued that the latter would benefit from an understanding of the local situational context and underlying drivers, which they sourced mainly from three previous studies relating to human infectious diseases [16, 17, 18]. Despite mentioning of the importance of the human-animal interface and many infectious disease events being of animal origin, these drivers did not extend explicitly to animal populations, which seems an important oversight. In other health-related domains, multiple additional drivers have been described; a summary of the main ones across a range of different domains is given in Table I.

Given the large number and diversity of drivers, there is an interest to identify main drivers to pre-empt specific types of disease emergence and be able to target surveillance accordingly. Semenza *et al.* [11] identified five key drivers for infectious disease events out of a total of 17 in Europe, namely: travel and tourism; food and water quality; natural environment; global trade; and climate. Loh *et al.* [19] demonstrated that transmission pathways varied greatly depending on the primary driver (e.g., vector-borne pathways were more important following land-use changes, and oral transmission was more important following food industry changes) – which shows the epidemiological importance of identifying the key drivers. Zhang *et al.* [23] analysed the relationship between introduced alien (i.e., non-native) hosts and over 10,000 zoonosis events across the globe since the 14th century. They showed that the number of zoonosis events has increased with species richness of alien zoonotic hosts across both space and time [23]. Alien hosts may be introduced to new areas deliberately such as for hunting, or accidentally such as in ballast water from cargo ships [24]. Both deliberate and accidental introductions of alien species can be considered as steps on a risk pathway driven by increased global interconnectedness.

Once a disease has emerged, another set of drivers will influence how rapidly it will spread. Perry *et al.* [12] discussed the connectivity of the food systems that create conditions for wide and rapid spread once an outbreak occurs claiming that concentrated livestock trade increases the likelihood of deep and far-reaching impacts as seen during the bovine spongiform encephalopathy crisis. This was corroborated by Tang *et al.* [25] who investigated spatio-temporal patterns of live broiler movements between and within provinces in Guangxi in the People's Republic of China and described high-connectivity patterns that could create conditions for rapid virus spreading. The authors also showed how networks reacted to changes in prices and how risk pathways changed accordingly thereby illustrating the dynamic nature of these drivers.

Economic measures and global capital flows are increasingly being realised as critical underlying drivers of the health of people, animals, plants and the environment. One such example is financialisation which is defined by Bjorkhaug *et al.* [26] as 'the process through which financial actors, logics, and processes exert increasing influence over economic and social life' and has been described as a major influence that shapes all elements of food value chains including production [26]. While a substantial body of literature has focused on financialisation and healthcare, some authors have examined the wider socio-economic conditions created by financialisation and its effects. For example, Gouzoulis and Galanis [27] looked at socio-economic conditions that prevent social distancing in the event of a pandemic and thereby contribute to disease spread. These authors suggest that financialisation leading to worsening housing conditions, financial insecurity in older people due unsafe pensions, and private debt cause risky behaviours of public health relevance, such as indebted employees returning to work while sick. Wallace *et al.* [28, 29, 30] have written extensively about capital flows in global livestock agribusiness and how dysfunctional economies of scale externalise the negative impact (including disease) to consumers, workers, governments, and the environment. This includes the increased vulnerability of people to zoonotic pathogen spillover as a result of austerity programmes undermining public health, and how monoculture plantation fuelled by private interests can lead to land use and labour changes that modifies interactions between people and animals in favour of disease spillover and spread, exemplified by Ebola [31]. A recent report by the Food and Agriculture Organization of the United Nations (FAO), the United Nations (UN) Development Programme, and the UN Environment Programme (UNEP) [32] describes how export and fiscal subsidies as well as import tariffs are promoting unsustainable practices, distorted food prices, damage the health of people, animals and the environment and favour big agri-business over smallholder producers. Together, these examples show a need to go deeper and look at the underlying processes that shape other drivers – such as structural drivers causing land use changes, inequality, and changed human-animal interactions.

Turning the attention of surveillance away from pathogens and onto drivers

Tempting as it might be to call for the drivers of disease emergence to be prevented (e.g., Kock and Caceres-Escobar [33]), the diversity and global span of many drivers means the prevention of drivers is likely to be impossible. Instead, we are likely to have more success if we aim to modify rather than prevent such drivers. Accordingly, we suggest more attention should be paid to monitoring changes in these drivers of disease emergence. This would include changes in the connectivity of systems, which affect the likelihood of disease spread once it has emerged. In doing so, the scope of what is detectable would be broadened to include known and unknown causes of disease, since *a priori* specification of pathogens would no longer be necessary. Because many pathogens and other health challenges share common drivers that are not population specific, information on many diseases and health risks would be generated from fewer surveillance programmes and thereby promote economic efficiency. We hypothesise that such surveillance would also be cost-effective and therefore attractive to policymakers, but formal economic studies are needed to generate evidence to test this.

In the short to medium term we suggest drivers are considered on a sector-by-sector basis to make use of existing structures, data and capacities. Thus, we propose that the animal health sector incorporates into surveillance data on drivers for animal and zoonotic disease. This includes both drivers that are influenced directly by the animal sector as well as drivers that are animal-relevant, but predominantly influenced by other sectors (e.g., activities for human benefits or impact that have an influence on the animal sector). Their selection should be informed by considerations of surveillance to generate better knowledge for disease prevention, alert, and management.

Table II describes the sorts of drivers that could be monitored to capture large-scale changes at the level of the system. Drivers are categorised as being proximal if they directly affect health (e.g., provision of animal health-related infrastructure and services), or distal if they indirectly affect health (e.g., policy changes such as subsidies or taxes which are intended to change behaviour). This classification is well established in the health sciences although it is not without contention [34]. Notwithstanding, we consider that both proximal and distal drivers could lead to the necessary conditions for pathogen emergence. For example, a drop in market prices for livestock may lead to producers rearing more animals to recover the shortfall; the resulting increase in stocking density may then be a necessary condition for a pathogen to emerge, spread or cause disease. Importantly, we suggest the focus of driver monitoring should be on the detection of changes in patterns/quantities relating to each driver, as opposed to simply measuring the status quo. This represents a reshaping of surveillance, from the current focus on pathogen detection towards detection and documentation of changes within drivers combined with relevant algorithms to generate alerts and decision structures to discuss and use the information produced by the system. Consequently, the primary function will be to generate systems-level risk-based surveillance information to identify areas where additional attention may be needed from decision makers and their technical staff/advisors and, over time, inform the implementation of prevention efforts. Like other surveillance systems, good knowledge on the drivers will facilitate the designing of high-performance (e.g., sensitive, timely) surveillance components. Thus, the data collected will also allow the generation of essential information to better understand the drivers and their linkages, and thereby generate new knowledge that can improve surveillance and inform mitigation efforts. This is particularly important in the animal health sector, where there is a dearth of large-scale studies analysing drivers of animal disease. Consequently decision-makers and technical advisors working in surveillance do not currently know which drivers to prioritise. Additionally, several drivers are general so would need unpacking for different animal populations and their characteristics. For example, animal health concerns, trade flows and contact patterns will differ widely depending on the purpose of the animals (e.g., livestock, companion, zoo), species, and the production system in use (e.g., extensive, intensive, backyard).

In the following section we present three case studies from around the world which exemplify the links between drivers and disease emergence. Collectively these case studies illustrate the need for surveillance of key drivers.

Case study 1: agricultural land use change in the United Kingdom

A major rethink is currently underway in the United Kingdom (UK) to determine how agricultural land is used to produce food and bioenergy in a more sustainable way [44]. This is primarily being driven by climate change concerns, specifically the need to drastically reduce greenhouse gas emissions and increase carbon capture to limit global warming, alongside the need to produce higher agricultural yields. Such targets will not be achieved without significant changes in land use [45]. The Committee on Climate Change has recommended releasing around one-fifth of agricultural land in the UK for actions that reduce emissions or sequester carbon [46]. This could involve:

– planting 30,000 hectares (90–120 million trees) of woodland each year – a relative increase in forest cover of 30% or about one million hectares over the next 30 years [47, 48]. A recent analysis suggests that two million hectares (one-twelfth of the UK) is potentially available for new woodland [48]: careful consideration is needed as to how this reforestation is implemented since the choice of tree species, locations and sizes of land parcels is expected to affect disease emergence risk;

– expanding the planting of energy crops (those grown solely for energy production rather than for food) by 53,000 hectares each year, a relative increase of 750% in land used for energy crops over the next 30 years [47, 49];

– restoring 25–50% of UK peatlands [47, 48];

– reducing the numbers of cattle and sheep farmed by 20%, thereby freeing up land currently used to raise livestock for the other land uses listed above [46].

Such large changes in agricultural land use are likely to bring concomitant changes in the risks of emergence and spread of infectious diseases. This is because land use changes alter habitats which affect wild and domestic host abundance and diversity, as well as interactions between species, and hence surveillance of such land-use changes is needed. The outputs of such surveillance would be useful to inform land-use change policies which are currently being formulated in England [50]; specifically to help determine which combinations of land uses are most effective at reducing or limiting infectious disease risks, and so influence decisions made to mitigate such risks.

Case study 2: pig production in Thailand

In the past few decades, pig production systems in many Asian countries have changed dramatically with the rise of intensive systems. The advantages of these systems are said to include higher efficiency, productivity, hygiene and biosecurity; disadvantages include concerns over pig welfare; barriers to entry for smallholders (with effects on livelihoods), waste production and generation of hazards (e.g., antibiotic residues) [51, 52, 53]. Nonetheless, traditional or backyard small-scale production systems continue to exist in many countries. In Thailand, farms are classified as smallholdings when they have fewer than 50 pigs, but these can be backyard or commercial [54]. In 2018, smallholders constituted 94% of all pig producers, but they only hold about 25% of the total pig population [54]. Key reasons for their persistence are of socio-economic nature, as they offer sources of income, livelihoods, food security as well as socio-cultural value [55]. Moreover, industrialised, large-scale farms are expanding rapidly with a growth rate of almost 9% between 2014 and 2018 [54].

Since backyard, commercial small-scale and commercial large-scale production systems have distinct characteristics, they require different disease prevention, surveillance and management approaches. They also cause different forms of disease risks. Consequently, it is important to monitor the landscape of production systems (including types, numbers, locations and their trade channels) to be able to react to changes in these production systems or, in other words, the changes in conditions that allow pathogens to emerge, spread and cause disease. These changes may be very dynamic depending on a wide variety of external factors. For example, more smallholders may emerge when other livelihood options dry up (such as hospitality and tourism during the COVID-19 pandemic) or numbers may decrease rapidly when epidemics like African swine fever hit a country (in such cases they may be replaced by other livestock holdings).

In Thailand, smallholders are homogenously distributed throughout the country covering all geographic areas [56]; this places demands on infrastructure and animal health service provision, and poses challenges for early detection and response. Pig smallholders in Thailand react dynamically and quickly to changes in market prices by adjusting the number of pigs produced; these fluctuations are magnified through disease outbreaks [56]. Formal registration systems may struggle to keep up with these dynamic patterns. Thus, innovation may be required in the way data are collected and analysed to be able to identify changes that may be of epidemiological interest. Possible avenues may be to monitor local market prices for pigs, market sales volumes of production inputs such as feed, or market movement data gathered from smartphone applications. Since these same metrics may indicate either increased risk of disease incursion or the impact of disease that is already present, any alerts triggered will likely need to be combined with an increase in surveillance efforts and epidemiological investigations to determine what, if any, additional disease prevention or control action is required.

Case study 3: animal health surveillance in Tanzania

Tanzania's animal health surveillance is coordinated by the Ministry of Livestock and Fisheries through the epidemiology unit in the Directorate of Veterinary Services. To date, this surveillance has tended to focus on understanding disease distribution, the introduction of new strains, risks of disease introduction, and vaccination efficiency [57]. Challenges include the diverse nature of the country in terms of agroecological zones and livestock production systems, its interconnectedness with neighbouring countries, and many national parks and game reserves which are home to wild animals who may, in addition to livestock, act as reservoirs of zoonotic diseases [58]. Such complex systems have made disease surveillance very expensive and mismatched with Tanzania's budget for veterinary services and human resources, which compromises its ultimate goal [57].

In order to address such challenges, the country is now moving into integration of surveillance systems and activities by capitalising on existing multiple sources of data [59] while leveraging technological innovation. Tanzania's current animal health surveillance strategy (2019–2024) advocates for monitoring of animal health instead of solely focusing on diseases. It has provisions for capturing drivers such as animal movements, rangeland health, antimicrobial purchases, and production parameters. New technological interventions to strengthen the capacity of the animal health surveillance system for early detection and response include the introduction of digital surveillance tools and web-based information systems such as Event Mobile Application called EMA-i, AfyaData, laboratory information management system and Agricultural Routine Data System [57]. There are also ongoing efforts to make such systems interoperable while integrating early warning indicators and alert functions such as floods, drought, and unusual migration of wildlife or movement of livestock that may signal adverse health events. These surveillance information systems may improve interoperability and the data spectrum from community to national level and across sectors for improving early detection. Nevertheless, such intervention has to go hand in hand with strengthening of community-level reporting and animal health stakeholder involvement to ensure ongoing data generation and usage.

Unlike conventional disease surveillance, monitoring of multiple drivers and animal health and production parameters implies different data sources which in most cases contain heterogenous data. Therefore, it will be important to identify and build expertise in fundamental analytical skills in order to make sense of the data and efficiently produce systems that can generate signals for early detection and response.

Reshaping surveillance: implications and conclusions

For many years, the field of veterinary public health has protected the health of humans and animals through food safety, zoonotic disease risk assessments and surveillance, and, more recently, antimicrobial resistance monitoring and management. Increasingly, dimensions of environmental health are being incorporated to better understand disease emergence, inform mitigation measures, and capture the environmental impact of animal food and feed systems. In the future, a fully integrated One Health surveillance approach incorporating drivers of disease would be expected to bring many benefits, since drivers overlap in their effects and have impact on the health of humans, animals, plants, and the environment (as well as individuals, groups, populations and ecosystems). We envisage that focusing on drivers rather than pathogens will generate valuable evidence that will inform prevention measures that could take the form of shaping healthier environments where the likelihood of disease emergence or spillover is reduced. But this is likely to be a massive task that is beyond current capability (or at least beyond current will) and so, for now, we propose a simpler solution focusing a selected drivers with direct or indirect impact on animal health. In the future, further evidence will become available on the key drivers of health challenges and will inform decisions on what drivers to include in surveillance systems. For example, the One Health high-level expert panel to the Quadripartite (comprising the FAO, the World Organisation for Animal Health, the UNEP, and the World Health Organization) has compiled a list of drivers of zoonotic disease spillover and is now exploring methods to identify where mitigation efforts would make the biggest impact [60].

Many relevant datasets are available already and could be incorporated into driver surveillance. There are national and international databases available on health, disease and related factors, often supported by relevant regulations such as the International Health Regulations, the Codex Alimentarius or the Animal Health Codes. Assessment tools exist to support the development of relevant health systems, such as the Performance of Veterinary Services assessment. However, new analyses, algorithms, interpretation and decision processes would need to be generated. Such a shift in or expansion of surveillance focus can only work if appropriate resources (human, intellectual, financial) are made available and supported through long-term commitments and the necessary infrastructure and performance (e.g., digital databases, computing power, accessibility, interoperability). Driver surveillance can take advantage of big data and artificial intelligence: big data analytics are used to understand health risks and minimise the impact of adverse animal health issues through identifying high-risk populations, combining data or processes acting at multiple scales. Epidemiological modelling approaches and harnessing high-velocity data help to monitor animal health trends and detect emerging health threats [61]. Because of the cross-border nature of many diseases and cross-border trade and movement patterns, regional collaboration in driver surveillance is likely to be required.

In 2019, a global map of food systems sustainability was published which illustrates how data from multiple indicators may be aggregated into a single output [21]: this approach could act as a blueprint for driver surveillance. Of 192 potential indicators, 27 were chosen spanning five dimensions: environment (air, water, soil and land, biodiversity, energy); economic (financial performance, employment rate, and economic distribution); social (gender equality and inclusion); and food and nutrition (food security, food safety, food waste and use, and nutrition) [21]. The unavoidability of trade-offs was highlighted by the authors and opportunities highlighted in terms of comparing across geographies, documenting change over time, evaluating progress towards objectives, informing policy strategies, and assessing the effects of drivers. This experience suggests that, when designing surveillance for multiple drivers, the animal health sector may look to food systems monitoring to learn about relevant experiences and to identify opportunities.

It should not be forgotten that people matter in health surveillance and that no one should be left behind or excluded. It is people who shape the systems we are operating in, it is people who react to changes in the system, and it is people who socially construct health [2]. Thus, people need to be central in the surveillance of disease drivers and there may be opportunities for innovation in terms of measuring people's behaviour as proxies for key drivers. Identification and engagement of all stakeholders in a whole-of-society approach and capacity building in health surveillance are essential. This will allow surveillance actors to be more proactive in identifying and understanding the drivers of diseases and other disasters instead of relying on the reporting of suspicions and clinical signs which sometimes is too late. Also, the public collectively spans most environments, they can be a valuable (and economic) source of information. For example, during a recent 'Invasive Species Week' in the UK, river users and local communities were encouraged to look for and report non-native flora and fauna that could be harming the Broads National Park, a regional network of rivers and lakes [62].

Because of the variety of indicators used, the collation, interpretation and use of information is not straightforward and will require input from a diverse set of professionals. When it comes to policy making, eventual trade-offs need to be discussed and priorities negotiated; for this to be effective, collaboration will be needed within and potentially across sectors. From One Health experience we know that cross-sectoral surveillance faces many barriers such as siloed thinking, lack of coordination, unequal representation and power struggles, among others [63]. Thus, it can be expected that a new form of surveillance spanning multiple domains will face similar obstacles. It has been suggested that more and better facilitators for integration can help to promote collaboration, communication and coordination [63].

In conclusion, the reshaping of animal disease surveillance away from its current focus on pathogens and onto the monitoring of drivers has real potential to deliver better results and wider benefits. Because of the co-benefits spanning multiple diseases (both old and new, known and unknown), this approach is expected to be cost-effective. Since surveillance of drivers may give signals at the level of the system when changes are occurring, it may even enable disease to be prevented before it happens by intervening directly on the drivers themselves. In due course, we envisage a transition from chasing pathogens and recording diseases, towards a new focus on identifying and promoting healthy systems.

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Table I

Examples of key health and disease-related drivers grouped by domain

Domain	Drivers	Reference
Infectious disease of people	Human susceptibility to infection, climate and weather, human demographics and behaviour, economic development, land use and ecosystem changes, technology and industry, human-wildlife interaction, breakdown of public health measures, poverty and social inequality, war and famine, lack of political will, and international travel and commerce	[9]
Zoonoses emergence	Land-use change, agricultural industry change, and international travel and commerce	[19]
	Increasing demand of people for animal protein, unsustainable agricultural intensification, over-exploitation and use of wildlife, unsustainable use of natural resources negatively impacted by urbanisation, change to land use and extraction, travel and transport, food supply chains, and climate change	[20]
Food system change	Population growth, rise in income, urbanisation and a growing awareness of topics related to diet and health, technological innovation, agricultural intensification, homogenisation, access to infrastructure, urban markets, and the supermarketisation of food supply, policies enabling national and international trade, internationalisation of private investments	[21]
Environmental change	Land-use change, climate change, pollution, natural resource use and exploitation, and invasive species driven more distantly by socio-economic and demographic factors, technological innovation, and societal drivers (e.g., culture, government)	[22]
Infectious disease threats events	Globalisation and environment, climate, natural environment, human-made environment, travel and tourism, migration, global trade, demographic, social inequality, vulnerable groups, prevention, lifestyle, occupational, terrorism, healthcare system, animal health, food and water quality, surveillance and reporting failure	[11]
Infectious disease of animals	Ecosystem change (e.g., 'deforestation, infrastructure, irrigation, or urban sprawl'), ecosystem incursion (e.g., Lyme disease caused by recreational exposure to ticks, movements of people and animals with more distal drivers being demographic dynamics and higher demand for livestock products, urbanisation, livestock kept nearby in low-income areas (and often in unhygienic conditions), food system connectivity and concentrated livestock	[12]
Emerging issues in animal and plant health	Habitat encroachment and alteration; resource extraction; intensified food production; movement of animals, people and products; changing food production, distribution and consumption – all of these made worse by climate change and human population displacements	[10]

Table II

Examples of proposed drivers of disease to be monitored by the animal health sector

Driver	Type	Aspects to be monitored	Rationale	Possible data sources
1. Amount, location, and species of animals	Proximal and distal	Geo-spatial data on changes in number of animals, density of animals, location of animals, and species compositions monitored over time	Time series analysis allows capturing major shifts in animal populations including new sites of animal production, concentration, homogenisation, and expansion into new habitats	Government ministries, livestock industry, wildlife population surveys
2. Movements of animals and animal products, and resultant changes to connectivity	Proximal and distal	Changes in animal and product movement data, trade statistics, network connectivity; both legal and illegal	Description and quantification of flows of animals and animal products, and changes in network connectivity, can show where new trade channels open, and capture cross-border activities at national and international levels	FAOSTAT trade data [35], national (government) trade statistics, government animal movement databases (e.g., TRACES [36]), open-source databases of animal tracking (e.g., Movebank [37])
3. Land-use change	Proximal	Conversion of natural habitats to agriculture, changes within agricultural land use (e.g., intensification of animal production); replacement of grazing with tree planting	Land use change will alter the host species composition and abundance, and interactions between species, and therefore potential for pathogen transmission	Government agencies, open-source satellite imagery
4. Location and quantity of animal health-related infrastructure and services	Proximal	Changes in animal markets, feed processors, abattoirs, animal workers (e.g., slaughterers, official veterinarians), veterinarians, animal health advisors, diagnostic laboratories	Change in the infrastructure and services is an indicator of a shifting system (e.g., a reaction to more animals in an area or a change in production system or a change in disease or a change in investment)	Government/private industry/professional association records (e.g., EU approved food establishments [38], WOAH PVS reports/Veterinary workforce surveys [39])

5. Finance and capital flows	Distal	Capital flow data in relation to animal production, asset data (e.g., global corporations), subsidies, tariffs, and private and public investment projects	A change in the financing leading to structural changes in the system indicates where shifts may occur in relation to animals (e.g., expansion of vertical poultry production in countries to date diversified; shift towards more extensive production with subsidies favouring biodiversity)	International Monetary Fund balance of payments data [40], investments, private equity and venture capital databases [41]
6. Relevant policy changes	Distal	Subsides and taxes promoting or disincentivising the production or consumption of animal products	Policy changes can be used to alter the behaviour of producers and consumers (e.g., Common Agricultural Policy and import taxes). Recently there has been a proposal to introduce a meat and zoonotic tax to fund pandemic prevention [42, 43]	Government policy documents, national and international data on consumption; can be stratified (e.g., urban *versus* rural; local *versus* international)

EU: European Union
FAOSTAT: Food and Agriculture Organization Corporate Statistical Database
PVS: Performance of Veterinary Services
TRACES: European Commission's online platform for sanitary and phytosanitary certification required for the importation of animals, animal products, food and feed of non-animal origin and plants into the European Union, and the intra-EU trade and EU exports of animals and certain animal products
WOAH: World Organisation for Animal Health