Emerging infectious disease risk: shared drivers with environmental change

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Summary

Outbreaks of emerging infectious diseases (EIDs) seemingly appear without warning, severely exacerbating public and animal health burdens and spreading across borders. Since 1940, the rate of infectious disease emergence events has risen. Given the considerable economic and other societal costs associated with EIDs, understanding the specific drivers of these diseases and developing concrete measures to prevent and mitigate their spread is urgently needed in both health security and sustainable development discussions. Human modification of the environment serves as an underlying driver in EID risk: environmental change thus warrants consideration in surveillance and outbreak investigations to identify the origin of the disease and contribute to the development of effective actions to prevent, prepare for or reduce the risk of future events. Coordinated approaches to address the underlying and, in some cases, overlapping causes of both disease emergence and global environmental change may yield benefits for sustainable and healthy solutions to meet or reshape the demands of a growing global population and contribute to global health security.

Keywords

Disease emergence – Drivers – Emerging infectious disease – Environment – Global health security – Risk – Risk reduction.

Introduction

Emerging infectious disease (EID) events often seem to appear without warning, creating local public and/or animal health disasters and posing a threat to global health security through their international spread. Since 1940, the rate of EID events has increased beyond improved reporting, peaking in the 1980s with the human immunodeficiency virus (HIV) pandemic leading to acquired immunodeficiency syndrome (AIDS) – a disease of zoonotic origin which, to date, is responsible for over 30 million human deaths, with continued epidemics in developing and developed nations alike (1, 2).

Outbreaks of Nipah virus, avian influenzas, severe acute respiratory syndrome (SARS) and many others have followed, including the West African Ebola outbreak which has claimed over 11,300 lives since its start in December of 2013 (3, 4). While the particular context shaping each of these epidemics may vary, they share a common factor – original spillover events from animals as a consequence of human activity.

Human modification of the environment serves as an underlying driver for EID risk. In particular, the processes associated with environmental change warrant examination to identify disease origin and inform effective policy responses. Most environmental degradation, such as deforestation or the contamination of water supplies, is immediately apparent at the local level. Yet, broader-scale (macro) impacts also exist and influence local dynamics, which both contribute to and are affected by global environmental change (5). Such impacts include changes in species abundance and pathogen prevalence, novel exposure to pathogens through increased or new types of exposure, selection pressures for rapid pathogen evolution, enabling factors for disease spread and, ultimately, the potential for an increased associated human health burden and economic consequences. A 'One Health' understanding of the connections between human, animal and ecosystem health, together with a changing global environment,

doi: 10.20506/rst.36.2.2664

is required to fully grasp these dynamics and develop solutions.

Microbes and emerging infectious diseases

Infectious disease emergence can be considered on both the micro and macro level to inform targeted prevention and control strategies. On the micro level (or single pathogen level), emergence events may have complex mechanisms, prompting various theories about the different factors that could lead to disease emergence and spread and their relation to changes in biodiversity or species composition in an ecosystem (6, 7).

At the macro level, emergence is driven by the many anthropogenic impacts that are altering ecological dynamics on a large scale, leading to environmental change. For example, land conversion for agricultural use, livestock production and other anthropogenic activities has increased or led to new types of human or domestic animal contact with wildlife, thereby facilitating pathogen 'spillover' to humans (1, 8). At the same time, the rapid expansion in trade and travel in recent decades has also established new pathways for the spread of dangerous pathogens (sometimes to immunologically naïve populations). These new pathways include the introduction of invasive species and the climatic, vegetation and other habitat conditions that support their establishment.

Not all microbes are pathogenic to a given species – in fact, the majority are not, and many are even beneficial (such as humans' commensal bacteria, which may protect against illness – for example, see research from studies of the human microbiome). However, those that are benign or mildly pathogenic in their natural host may have potentially severe health consequences in other species. EIDs can be further categorised, such as the first detection of a novel agent (for example, the coronavirus that causes SARS, which was first reported in 2003), a re-emerging (reappearing) disease, or one that emerges in a new region or new host. Infectious agents may evolve sufficiently to come under an entirely new pathogen classification (as with gene segment re-assortment events in the influenza virus, or the development of antibiotic-resistant bacterial strains, e.g. methicillin-resistant *Staphylococcus aureus*, or MRSA). Finally, EIDs may be classified by their transmission source to humans, such as vector-borne diseases (e.g. dengue, malaria, Zika virus); environmental (e.g. anthrax in soil spores, histoplasmosis); human diseases (e.g. measles, smallpox and poliomyelitis); or zoonotic diseases (animal-borne, such as the rabies virus), which potentially have multiple routes of infection (e.g. Rift Valley fever is maintained in mosquitoes but exposure to infected animals is the common route of human infection).

The majority (61%) of known infectious agents that are pathogenic to humans are zoonotic, with an original or recurring animal source (9). Of the zoonoses that emerged between 1940 and 2004, nearly three-quarters originated in wildlife, including HIV/AIDS, SARS and Ebola virus, all of which involved animal-to-human contact during at least the initial stage of transmission (1).

The source of an EID that transmits the pathogen to a human is either a reservoir (the natural source of the pathogen in nature; typically one that harbours the pathogen with a low or non-existent fitness burden), or an incidental host (one that does not naturally carry it but is susceptible to infection, with or without necessarily exhibiting clinical manifestations). While reservoir species are not always readily identified, this distinction between host types can help to target optimal prevention or control strategies: interventions may prove ineffective or inefficient if they mistakenly target incidental hosts rather than the ongoing source(s). For example, some index cases of Ebola virus disease in humans have been linked to contact with great apes, yet the severe illness that apes can suffer when infected with some strains of the virus, as well as the current lack of evidence linking them to the maintenance cycle, suggests that they are probably incidental hosts. Research points to certain species of fruit bats as the actual reservoir (10, 11).

The basic pathogen-host(s) interaction is a natural process, and can have beneficial outcomes in terms of regulating plant, animal and wildlife population(s) within an ecosystem, in the same way that resource availability may keep plant and animal population numbers balanced. Pathogen adaptation promotes pathogen survival; thus, exploiting new niches, such as a new host species, is logical. What has changed over recent decades, however, is the macro-level context as a result of human activity, particularly the increased and changing opportunities for human and animal contact that may lead to pathogen spillover, as well as other factors promoting pathogen movement and adaptation (8, 12).

Human and ecological costs

Given the considerable human costs associated with EIDs, understanding the specific drivers of these diseases and developing concrete measures to prevent and curtail their spread is urgently needed in both health security and sustainable development discussions. Endemic and enzootic (zoonoses maintained in animal populations) diseases alone account for approximately 1 billion human cases and millions of deaths each year (8).

While some EID events have fortunately been short-term, others have become a persistent health burden, with the potential to become pandemics. HIV/AIDS has wide societal consequences in parts of sub-Saharan Africa and other areas where it remains firmly entrenched. The Zaire Ebola virus outbreak in West Africa, where it had never previously been reported, caused exceedingly high morbidity (>28,000 human cases) and mortality, and financial impacts estimated at a loss of approximately 12% in the gross domestic product of each of the three most heavily affected countries (Guinea, Liberia and Sierra Leone) (13).

In addition to direct health burdens, their associated costs and the loss of productivity, there are wide-ranging indirect costs, due to societal disruption, that affect commercial sectors such as hospitality and tourism, transportation, education, the provision of public health services for other diseases (e.g. reduced access to malaria treatment, interruptions in vaccination campaigns), and have a severe effect upon the workers and users that rely on these sectors. Mexico suffered a trade deficit in its pork industry from reduced demand during the H1N1 influenza pandemic, plus tourism losses estimated at US$ 1.2 billion from a full million fewer visitors (14). Even emerging diseases that produce a relatively low incidence of cases or fatalities can be catastrophic; the 2003 SARS outbreak, with around 800 reported deaths, cost the global economy an estimated US$ 30+ billion (15), disrupting international tourism and commerce as well as local markets in China.

The burden of EIDs is not exclusive to human health; there is ample evidence that disease spillover can pose serious threats to food security and the conservation of non-human species (16, 17). For example, past Ebola outbreaks have led to major declines in endangered chimpanzee populations (11). As of June 2015, the United States (US) had reported the deaths of over 48 million birds from highly pathogenic avian influenza infection or culling as an infection control measure. Cases were primarily found in areas with major North American wild bird flyways, though specific sources of introduction into and between poultry farms have not been reported. Even without any associated human cases, financial impacts were seen across the value chain, including compensation to affected farms and the high response costs of government intervention (estimated at US$ 950 million) (18).

In addition to zoonoses, emerging diseases that are not transmissible to humans (such as white-nose syndrome in bats or chytridiomycosis in amphibians) may threaten human health and agricultural production through the loss of health-supporting ecosystem services, such as pest control and pollination services for agriculture. Furthermore, they may also pose species endangerment or extinction risks (17, 19). Infectious disease impacts may add to pressures caused by other effects of global environmental change (such as extreme weather events, pollution or the introduction of invasive alien species) on food security and species survival.

Emerging infectious diseases and global environmental change: interrelated drivers

The conventional scope of public health typically focuses on human transmission dynamics, with little attention to environmental factors, such as interactions between species, ecological dynamics and climate and weather. This limits a potential full understanding of the mechanisms leading to disease emergence and their possible predictive value (20). Factors such as seasonality (which may involve weather, migration, reproductive cycles, resource availability, etc.) may affect viral prevalence and shedding (21, 22). Similarly, practices that may facilitate pathogen spillover and spread may also have seasonal determinants (e.g. reliance on hunted wild meat for nutrition may increase during periods of lean agricultural yield) (23). These integral and complex connections take on increasing importance as we face widespread global environmental changes.

Global environmental change involves a wide range of processes and factors that are altering ecosystem dynamics. Human-induced environmental change has been broadly associated with globalisation (24), and anthropogenic activities are contributing to a new phase in endemic and emerging zoonotic diseases by changing the natural histories of pathogens (8). The hundreds of outbreaks of emerging zoonotic diseases detected in the past half-century have been linked to specific practices that enabled new pathways for transmission, created more frequent transmission opportunities, or increased the prevalence in host species (thus increasing opportunities for infection of humans).

The authors highlight how land-use or habitat change, agricultural developments, international trade and travel, climate and weather, and the hunting or consumption of wildlife contribute to biothreat risks. These and other leading drivers of EIDs may be closely related and occur in tandem with other societal trends (e.g. urbanisation) (12). However, they are part of the global pattern of environmental change, and provide opportunities for upstream risk mitigation through future development decisions (8, 25).

Land-use change

Driven largely by economic development and population pressures, anthropogenic land-use change is introducing fundamental and rapid changes in ecological dynamics and threatening biodiversity. Land conversion may be commonly associated with the expansion or establishment of new agricultural plots or plantations (witnessed in the explosion in palm-oil plantations in Asia and elsewhere); natural resource extraction such as the timber, mining or oil industries; road-building; and human settlements, among other causes. The mechanism and timescale of conversion may differ from situation to situation, ranging from scenarios with managed forests in which timber extraction is carefully planned to reduce environmental impact to slash-and-burn practices. Changes in habitat can affect ecosystems in many ways that may have disease implications, such as altering the species present and their relative abundance, movement, interactions with other species, access to resources, and immune responses (26).

Land conversion projections raise alarms for EID risks on the horizon. With rising agricultural demands, a total of 120 million hectares of expansion is expected in developing countries, accompanied by the conversion of a portion of arable land in developed nations for other uses (27). Some 25 million kilometres of roads are estimated for development by 2050, with 90% occurring in developing nations, primarily in areas of high biodiversity (28). In addition to altering natural habitat, these corridors may allow unprecedented human access to such parts of the world and the pathogens present there.

Land-use change is the primary driver associated with recent emerging zoonotic disease events (25). The effects of disease transmission from land-use change are not widely understood or acknowledged, partly due to a lack of 'before and after' incidence or prevalence studies across landscapes undergoing significant alteration. A review of the studies published on land use and infectious disease reported that an increase in disease transmission was observed in more than half of these studies, though there are many factors shaping such disease outcomes; notably, the degree and type of land disturbance as well as the type of habitat and species present (26).

Agricultural developments

Smallholder farming is still common in some parts of the world, while livestock production has vastly intensified in others. Animal agriculture is growing to meet increased demand, and contributes to global environmental change. While some agricultural developments have increased efficiency, it has been estimated that agricultural activity – including both subsistence and industrial practices – is responsible for approximately one-sixth of global greenhouse gas emissions. Livestock production, in particular, makes up a large share of this, thereby further exacerbating climate change pressures (29). In some cases, adequate biosecurity has not accompanied agricultural intensification. For example, in moderately intensive backyard poultry operations, wild birds may come into contact with domesticated birds, enabling pathogen transmission (as observed with some avian influenzas). If supported by strong Veterinary Services, large-scale animal agriculture may operate within more controlled and contained conditions, reducing the potential for disease introduction (30). Yet, the scale of intensified production may result in high stocking density, often with limited genetic variability and reduced immune function from stress. The animal value chain may also present opportunities for so-called pathogen 'pollution', as different species and populations mix in market and other settings, if not paired with sufficient biosecurity.

While antimicrobials have valuable benefits for human and animal health, injudicious use – such as for non-therapeutic growth promotion in agriculture – threatens their efficacy. A significant amount (i.e. up to 90%) of antimicrobial agents, mostly un-metabolised, may be excreted by livestock, potentially contaminating the environment without proper waste management (31). The finding of colistin-resistant bacterial strains in pigs in China in 2015 and evidence of transmission to their handlers (with subsequent detection of intercontinental spread) demonstrate how agricultural use can exert selection pressures for resistant strains in animal stocks with the potential for a biothreat to humans (32, 33).

Pathogens can also find their way into livestock settings, and then potentially to people, through a range of routes, such as feed contamination, the introduction of disease via new animal stocks, or insufficient biosecurity. The latter drove the emergence of the first human Nipah virus outbreak in Malaysia between 1998 and 1999 via sick pigs, themselves infected by Pteropid fruit bat reservoirs. The pigs were probably infected by feeding on fruit contaminated by bat saliva or urine from bats roosting at an orchard overhanging the pig housing. Dense stocking conditions and respiratory shedding of the virus enabled efficient transmission among pigs and spillover to humans, with more than 100 human deaths and long-term disability from encephalitis (34). Over a million pigs were culled as part of the control measures, devastating much of Malaysia's pig industry (35).

International trade and travel

The speed and volume of modern trade and travel provide the unprecedented potential for pathogens to spread. Modern transport systems that move humans around the world in less than 24 hours also move 'exotic' diseases across wide geographic areas. The 2003 SARS outbreak, first detected in mainland China (and later thought to have been transmitted by horseshoe bats) (36), spread to 29 countries in less than a year, resulting in interventions aimed at promoting 'social distance' to limit the spread of the respiratory illness (37). In response to the Zika virus emergence and epidemic in Latin America in 2015, air passenger movements became cause for concern in the potential international spread and establishment of the disease.

The international trade in animals also plays a role in the cross-border movement of biothreats. The accidental introduction of monkeypox into the US in 2003, the first recorded occurrence in humans outside the disease's endemic range in Africa, is attributed to infection through prairie dogs housed with and infected by legally imported African rodents (38). Illegal wildlife trafficking exacerbates the challenges of traceability and identification of unknown potential disease threats. Wildlife movement may also facilitate the purposeful or accidental introduction of invasive alien species, and suitable climate and ecological factors may allow their establishment. Long known to be in other regions of the world, West Nile virus is thought to have been introduced into the US in 1999 via international travel.

Climate and weather

Climate change from anthropogenic pressures is often mentioned as a likely contributor to some known and future outbreaks of zoonotic disease, but the relationships are complex (39). Climate may have a significant role, as changing climatic conditions may cause shifts in host ranges. For example, Daszak *et al.* examined varying projections of the contraction and expansion of host ranges for suitable host species of Nipah virus under different climate scenarios (40). However, even accelerated climate change will likely take decades before relevant ecological effects become apparent. More immediate factors (e.g. the daily flow of air passengers) probably pose higher risks for the appearance of biothreats in a new region or species.

Temporal and spatial trends indicate increased reporting of certain diseases, including some vector-borne and waterborne diseases, with the evidence suggesting that changing temperature, humidity and rainfall patterns have already altered the distribution of some waterborne illnesses and disease vectors (39, 41). The suitable habitat for Lyme disease, the emergence of which is thought to be associated with reforestation, which supported increased populations of the tick vector, is projected to expand by over 200% in Canada by the 2080s, under changing climate scenarios (42). Over all, the impacts of climate change on pathogens may be best considered on both the micro and macro levels. On the micro level, climate change may affect the basic reproductive rate (R_0) of pathogens or their vectors whose development cycles depend on temperature and precipitation, thus determining pathogen survival and spread in a population. Moreover, it may similarly affect the suitable habitat range of its competent host(s). On a macro level, EIDs are dependent on a wide range of factors, and climate cannot be viewed in isolation when assessing risks.

Wildlife hunting, butchering and consumption

The hunting, butchering and/or consumption of certain wild animals in the tropics ('bushmeat') has also been linked to significant public health threats. Most notably, the detection in humans of human immunodeficiency virus (HIV), whose precursor, simian immunodeficiency virus (SIV), is found in non-human primates, was linked to the hunting of chimpanzees in sub-Saharan Africa (43). The hunting or butchering of non-human primates has also been associated with outbreaks of Ebola virus (44). Some studies have estimated the annual consumption of bushmeat at approximately 1 billion kilos in Central Africa alone (45).

Bushmeat hunting is a means of subsistence for some populations in developing countries, and may make an important contribution to their micro- and macronutrient requirements (46). At the same time, a significant amount of wildlife may be harvested for urban demand, sometimes as a specialty food or for non-food use (e.g. the exotic pet trade, traditional medicine); some destined for other countries or continents. Unsustainable harvesting puts pressure on wild species and may provide pathways for possible zoonotic disease spillover, particularly from certain taxonomic groups (e.g. bat species and non-human primates) (45, 47).

Solutions and recommendations

The numerous relationships between global environmental change and disease emergence offer opportunities to develop harmonised, coherent and sustainable policies and strategies that promote the benefits of both biodiversity and ecosystem conservation (and restoration) and public health (5). They also provide opportunities to address public health challenges associated with climate change and to jointly improve public and planetary health outcomes (48).

The leading causes of disease emergence overlap with the main drivers of biodiversity loss, including habitat loss, degradation and fragmentation; the overexploitation of biological resources (e.g. wildlife trade); unsustainable production and consumption; introductions of invasive species; and compounding pressures, such as climate change and ocean acidification (49). These shared drivers provide common ground for the health and biodiversity sectors to gain mutual benefits. Policy measures aimed at reducing environmental risk from land conversion, changing agricultural practices and climate change also yield benefits for disease prevention, by reducing ecological pressures, increasing social and ecological resilience and avoiding new pathways for human exposure to infectious disease transmission (39). Health impact assessments (HIAs) can be used proactively to anticipate health externalities and any disproportionate impacts on vulnerable populations before development projects are approved (50). Meanwhile, EID risk assessment can be enhanced by integrating environmental impact information into HIAs, which can also help to identify appropriate safeguards to benefit multiple sectors.

Knowledge gained from ecological niche modelling, hazard identification (such as surveys of wildlife on the sites of production premises and human practices that could elevate transmission risk), the assessment of exposure pathways, and potentially ongoing active or passive surveillance, as well as strategic environmental assessment, could add significant information about the levels of both ecological and public health risk and point to opportunities for potential risk mitigation. The added value of comprehensive or integrated assessment more fully informs preventive action. In addition, it can create synergies and complementarity with broader policies, such as energy policies, which may help to generate stakeholder support.

Responses to disease outbreaks can be highly resource-intensive. As demonstrated by the recent Ebola crisis in West Africa and the Zika epidemic in Latin America, the rapid mobilisation of resources may prove challenging. Economic optimisation projections suggest that taking mitigation measures against pandemic threats could save costs of more than US$ 300 billion over the next century, when compared to adaptation programmes (51). Such projections estimate a high return on investment – with global benefits valued at US$ 30 billion per year through avoided pandemic costs – through the annual investment of US$ 3.4 billion into strengthened animal and public health capacities in low- and middle-income countries. This is based on the assumption that a once-a-century pandemic could cost as much as 4.8% of global gross domestic product (15).

While benefits from avoided EID events may be conferred across several sectors (e.g. health, agriculture, tourism), to date health security investments into this potential local and global public good have been limited. EID impact analyses at the country level may help to inform national decisions on resource optimisation across multiple public sectors for multiple gains. Similarly, given the role of some industry practices in the macro drivers of EIDs, as well as the economic losses that industries face from epidemics, the private sector may also have a key role and vested interest in multi-sectoral partnerships for health security. These non-traditional partnerships are especially important since progress on some of the Sustainable Development Goals may not be compatible with the achievement of others, requiring innovative and pragmatic approaches. The Livestock Global Alliance, a partnership between the Food and Agriculture Organization of the United Nations (FAO), the International Fund for Agricultural Development (IFAD), the International Livestock Research Institute (ILRI), the World Organisation for Animal Health (OIE) and the World Bank, intends to take an active role in offering operational solutions for the private sector. It is an initiative that, by constructively acknowledging and tackling sustainable development trade-offs in livestock production, hopes to optimise broad development benefits.

Conclusion

Significant technological advances now enable rapid pathogen screening, with the compilation of the 'global virome' potentially in reach. Yet the trajectory of recent EID epidemics demonstrates our insufficient capacity for their prevention. Addressing the underlying drivers of disease emergence and global environmental change may yield benefits by preventing negative impacts in both realms. To do so requires our public and animal health systems to work with broader development partners for health security gains. With global commitment to the Sustainable Development Agenda, concerted partnerships may turn shared drivers into shared solutions, paving the way for a sustainable and healthy population.

Acknowledgements

This paper benefited from intellectual developments from the United States Agency for International Development PREDICT project for Global Health Security and Emerging Pandemic Threats.

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Les risques d’émergence de maladies infectieuses : facteurs déclenchants communs avec le changement environnemental

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Résumé

Les foyers de maladies infectieuses émergentes semblent surgir sans signes annonciateurs préalables, ce qui aggrave considérablement leur impact sur la santé publique et la santé animale ainsi que leur capacité de propagation transfrontalière. Depuis 1940, le taux d’émergence des maladies infectieuses n’a cessé de croître. Compte tenu des coûts économiques et sociétaux au sens large associés à l’émergence de maladies infectieuses, la nécessité de mieux comprendre les facteurs déclenchants spécifiques de ces maladies et de mettre en œuvre des mesures concrètes pour prévenir et atténuer leur propagation fait partie des impératifs de la sécurité sanitaire et du développement durable. Les modifications de l’environnement dues à l’action de l’homme constituent un facteur sous-jacent du risque d’émergence de maladies infectieuses. Par conséquent, le changement environnemental doit être pris en compte lors de la surveillance d’une maladie et des enquêtes sur les foyers, afin de retracer l’origine de la maladie et de contribuer à la conception de mesures efficaces visant à prévenir les risques de nouveaux épisodes, à s’y préparer ou à les atténuer. L’adoption de méthodes concertées pour faire face aux causes sous-jacentes respectives (et parfois imbriquées) de l’émergence des maladies et du changement environnemental à l’échelle mondiale peut se révéler bénéfique pour concevoir des solutions durables et saines permettant de satisfaire ou de remodeler les exigences d’une population mondiale croissante, et de contribuer à la sécurité sanitaire mondiale.

Mots-clés

Émergence de maladies – Environnement – Facteur déclenchant – Maladies infectieuses émergentes – Réduction des risques – Risque – Sécurité sanitaire mondiale.

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El riesgo de enfermedades infecciosas emergentes: factores inductores en común con el cambio ambiental

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Resumen

Los brotes de enfermedades infecciosas emergentes parecen surgir sin previo aviso, propagándose allende las fronteras e imponiendo un duro tributo a la salud pública y la sanidad animal. El ritmo de aparición de enfermedades infecciosas viene acelerándose desde el decenio de 1940. Para toda reflexión sobre cuestiones de seguridad sanitaria y desarrollo sostenible, y habida cuenta de los considerables costes económicos y de otra índole que las enfermedades infecciosas emergentes entrañan para la sociedad, es urgente profundizar en los factores específicos que dan origen a estas enfermedades y definir medidas concretas para prevenir y contener su propagación. La modificación del medio por obra del hombre es un factor subyacente que acrece el riesgo de enfermedades infecciosas emergentes: por ello, al efectuar labores de vigilancia o investigar un brote con el fin de descubrir el origen de la enfermedad y ayudar a definir medidas eficaces para prevenirla, prepararse para nuevos episodios o reducir el riesgo de que se produzcan, merece la pena tener en cuenta la función que cumple en esa dinámica el cambio ambiental. El uso de planteamientos coordinados para abordar los factores subyacentes y, en ciertos casos, superpuestos que provocan tanto la aparición de enfermedades como el cambio ambiental planetario puede resultar provechoso para dar con soluciones saludables y duraderas que permitan satisfacer o modular las demandas de una población mundial cada vez más numerosa y contribuir a la seguridad sanitaria del planeta.

Palabras clave
Aparición de enfermedades – Enfermedad infecciosa emergente – Factor inductor – Medio ambiente – Reducción del riesgo – Riesgo – Seguridad sanitaria mundial.

References

1. Jones K.E., Patel N.G., Levy M.A., Storeygard A., Balk D., Gittleman J.L. & Daszak P. (2008). – Global trends in emerging infectious diseases. *Nature,* **451** (7181), 990–993. doi:10.1038/nature06536.

2. Joint United Nations Programme on HIV/AIDS (UNAIDS) (2013). – 2013 global fact sheet. UNAIDS, Geneva. Available at: www.unaids.org/en/resources/campaigns/globalreport2013/factsheet (accessed on 28 June 2017).

3. Baize S., Pannetier D., Oestereich L., Rieger T., Koivogui L., Magassouba N., Soropogui B., Sow M.S., Keita S., De Clerck H., Tiffany A., Dominguez G., Loua M., Traore A., Kolie M., Malano E.R., Heleze E., Bocquin A., Mely S., Raoul H., Caro V., Cadar D., Gabriel M., Pahlmann M., Tappe D., Schmidt-Chanasit J., Impouma B., Diallo A.K., Formenty P., Van Herp M. & Gunther S. (2014). – Emergence of Zaire Ebola virus disease in Guinea. *N. Engl. J. Med.*, **371** (15), 1418–1425. doi:10.1056/NEJMoa1404505.

4. World Health Organization (WHO) (2016). – Ebola situation report, 17 February 2016. WHO, Geneva. Available at: http://apps.who.int/iris/bitstream/10665/204418/1/ebolasitrep_17Feb2016_eng.pdf?ua=1&ua=1 (accessed on 28 June 2017).

5. World Health Organization (WHO) & Convention on Biological Diversity (2015). – Connecting global priorities: biodiversity and human health, a state of knowledge review. WHO, Geneva, & Secretariat of the Convention on Biological Diversity, Montreal. Available at: www.cbd.int/health/SOK-biodiversity-en.pdf (accessed on 28 June 2017).

6. Keesing F., Holt R.D. & Ostfeld R.S. (2006). – Effects of species diversity on disease risk. *Ecol. Letters*, **9** (4), 485–498. doi:10.1111/j.1461-0248.2006.00885.x.

7. Randolph S.E. & Dobson A.D. (2012). – Pangloss revisited: a critique of the dilution effect and the biodiversity-buffers-disease paradigm. *Parasitol.,* **139** (7), 847–863. doi:10.1017/S0031182012000200.

8. Karesh W.B., Dobson A., Lloyd-Smith J.O., Lubroth J., Dixon M.A., Bennett M., Aldrich S., Harrington T., Formenty P., Loh E.H., Machalaba C.C., Thomas M.J. & Heymann D.L. (2012). – Ecology of zoonoses: natural and unnatural histories. *Lancet,* **380** (9857), 1936–1945. doi:10.1016/S0140-6736(12)61678-X.

9. Taylor L.H., Latham S.M. & Woolhouse M.E. (2001). – Risk factors for human disease emergence. *Philos. Trans. Roy. Soc. Lond., B, Biol. Sci.*, **356** (1411), 983–989. doi:10.1098/rstb.2001.0888.

10. Olival K.J. & Hayman D.T. (2014). – Filoviruses in bats: current knowledge and future directions. *Viruses,* **6** (4), 1759–1788. doi:10.3390/v6041759.

11. Rouquet P., Froment J.M., Bermejo M., Kilbourn A., Karesh W., Reed P., Kumulungui B., Yaba P., Delicat A., Rollin P.E. & Leroy E.M. (2005). – Wild animal mortality monitoring and human Ebola outbreaks, Gabon and Republic of Congo, 2001–2003. *Emerg. Infect. Dis.*, **11** (2), 283–290. doi:10.3201/eid1102.040533.

12. Richardson J., Lockhart C., Pongolini S., Karesh W.B., Baylis M., Goldberg T., Slingenbergh J., Gale P., Venturini T., Catchpole M., de Balogh K., Pautasso M., Broglia A., Berthe F., Schans J. & Poppy G. (2016). – Drivers for emerging issues in animal and plant health. *EFSA J.*, **14** (Suppl. 1), s0512. doi:10.2903/j.efsa.2016.s0512.

13. Thomas M.R., Smith G., Ferreira F.H.G., Evans D., Maliszewska M., Cruz M., Himelein K. & Over M. (2015). – The economic impact of Ebola on sub-Saharan Africa: updated estimates for 2015. Working paper. World Bank, Washington, DC. Available at: http://documents.worldbank.org/curated/en/541991468001792719/The-economic-impact-of-Ebola-on-sub-Saharan-Africa-updated-estimates-for-2015 (accessed on 28 June 2017).

14. Rassy D. & Smith R.D. (2013). – The economic impact of H1N1 on Mexico’s tourist and pork sectors. *Hlth Econ.,* **22** (7), 824–834. doi:10.1002/hec.2862.

15. World Bank (2012). – People, pathogens and our planet: the economics of One Health. World Bank, Washington, DC. Available at: http://documents.worldbank.org/curated/en/612341468147856529/People-pathogens-and-our-planet-the-economics-of-one-health (accessed on 28 June 2017).

16. Nabarro D. & Wannous C. (2014). – The potential contribution of livestock to food and nutrition security: the application of the One Health approach in livestock policy and practice. *In* Coordinating surveillance policies in animal health and food safety 'from farm to fork' (S.A. Slorach, ed.). *Rev. Sci. Tech. Off. Int. Epiz*, **33** (2), 475–485. doi:10.20506/rst.33.2.2292.

17. Daszak P., Cunningham A.A. & Hyatt A.D. (2000). – Emerging infectious diseases of wildlife – threats to biodiversity and human health. *Science,* **287** (5452), 443–449. doi:10.1126/science.287.5452.443.

18. United States Department of Agriculture (USDA) Animal and Plant Health Inspection Service Veterinary Services (2016). – 2016 HPAI Preparedness and Response Plan. USDA, Washington, DC, 20 pp. Available at: www.aphis.usda.gov/animal_health/downloads/animal_diseases/ai/hpai-preparedness-and-response-plan-2015.pdf (accessed on 1 July 2017).

19. Boyles J.G., Cryan P.M., McCracken G.F. & Kunz T.H. (2011). – Conservation. Economic importance of bats in agriculture. *Science*, **332** (6025), 41–42. doi:10.1126/science.1201366.

20. Machalaba C.C. & Karesh W.B. (2015). – Envisioning a world without emerging disease outbreaks. *Solutions*, **6** (2), 63–71. Available at: www.ecohealthalliance.org/wp-content/uploads/2016/02/Envisioning-a-world-without-emerging-disease-outbreaks.pdf (accessed on 1 July 2017).

21. Ip H.S., Flint P.L., Franson J.C., Dusek R.J., Derksen D.V., Gill R.E. Jr, Ely C.R., Pearce J.M., Lanctot R.B., Matsuoka S.M., Irons D.B., Fischer J.B., Oates R.M., Petersen M.R., Fondell T.F., Rocque D.A., Pedersen J.C. & Rothe T.C. (2008). – Prevalence of influenza A viruses in wild migratory birds in Alaska: patterns of variation in detection at a crossroads of intercontinental flyways. *Virol. J.*, **5**, 71. doi:10.1186/1743-422X-5-71.

22. Amman B.R., Carroll S.A., Reed Z.D., Sealy T.K., Balinandi S., Swanepoel R., Kemp A., Erickson B.R., Comer J.A., Campbell S., Cannon D.L., Khristova M.L., Atimnedi P., Paddock C.D., Crockett R.J., Flietstra T.D., Warfield K.L., Unfer R., Katongole-Mbidde E., Downing R., Tappero J.W., Zaki S.R., Rollin P.E., Ksiazek T.G., Nichol S.T. & Towner J.S. (2012). – Seasonal pulses of Marburg virus circulation in juvenile *Rousettus aegyptiacus* bats coincide with periods of increased risk of human infection. *PLoS Pathog.*, **8** (10), e1002877. doi:10.1371/journal.ppat.1002877.

23. Schulte-Herbruggen B., Cowlishaw G., Homewood K. & Rowcliffe J.M. (2013). – The importance of bushmeat in the livelihoods of West African cash-crop farmers living in a faunally-depleted landscape. *PloS ONE,* **8** (8), e72807. doi:10.1371/journal.pone.0072807.

24. Saker L., Lee K., Cannito B., Gilmore A. & Campbell-Lendrum D.H. (2004). – Globalization and infectious diseases: a review of the linkages. World Health Organization (WHO), Geneva. Available at: www.who.int/tdr/publications/documents/seb_topic3.pdf (accessed on 1 July 2017).

25. Loh E.H., Olival K.J., Zambrana-Torellio C., Bogich T.L., Johnson C.K., Mazet J.A.K., Karesh W.B. & Daszak P. (2015). – Targeting transmission pathways for emerging zoonotic disease surveillance and control. *Vector Borne Zoon. Dis.,* **15** (7), 432–437. doi:10.1089/vbz.2013.1563.

26. Gottdenker N.L., Streicker D.G., Faust C.L. & Carroll C.R. (2014). – Anthropogenic land use change and infectious diseases: a review of the evidence. *Ecohealth,* **11** (4), 619–632. doi:10.1007/s10393-014-0941-z.

27. Food and Agriculture Organization of the United Nations (FAO) (2009). – How to feed the world in 2050. FAO, Rome. Available at: www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf (accessed on 20 April 2017).

28. Laurance W.F., Clements G.R., Sloan S., O'Connell C.S., Mueller N.D., Goosem M., Venter O., Edwards D.P., Phalan B., Balmford A., Van Der Ree R. & Arrea I.B. (2014). – A global strategy for road building. *Nature,* **513** (7517), 229–232. doi:10.1038/nature13717.

29. Gerber P.J., Steinfeld H., Henderson B., Mottet A., Opio C., Dijkman J., Falcucci A. & Tempio G. (2013). – Tackling climate change through livestock – a global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations, Rome, 115 pp. Available at: www.fao.org/3/i3437e.pdf (accessed on 1 July 2017).

30. Hosseini P.R., Fuller T., Harrigan R., Zhao D., Arriola C.S., Gonzalez A., Miller M.J., Xiao X., Smith T.B., Jones J.H. & Daszak P. (2013). – Metapopulation dynamics enable persistence of influenza A, including A/H5N1, in poultry. *PLoS ONE,* **8** (12), e80091. doi:10.1371/journal.pone.0080091.

31. Marshall B.M. & Levy S.B. (2011). – Food animals and antimicrobials: impacts on human health. *Clin. Microbiol. Rev*., **24** (4), 718–733. doi:10.1128/CMR.00002-11.

32. Liu Y.Y., Wang Y., Walsh T.R., Yi L.X., Zhang R., Spencer J., Doi Y., Tian G., Dong B., Huang X., Yu L.F., Gu D., Ren H., Chen X., Lv L., He D., Zhou H., Liang Z., Liu J.H. & Shen J. (2016). – Emergence of plasmid-mediated colistin resistance mechanism MCR-1 in animals and human beings in China: a microbiological and molecular biological study. *Lancet Infect. Dis*., **16** (2), 161–168. doi:10.1016/S1473-3099(15)00424-7.

33. Skov R.L. & Monnet D.L. (2016). – Plasmid-mediated colistin resistance (MCR-1 gene): three months later, the story unfolds. *Eurosurveillance*, **21** (9), 30155. doi:10.2807/1560-7917.ES.2016.21.9.30155.

34. Chua K.B. (2003). – Nipah virus outbreak in Malaysia. *J. Clin. Virol.*, **26** (3), 265–275. doi:10.1016/S1386-6532(02)00268-8.

35. Food and Agriculture Organization of the United Nations (FAO) (2002). – The emergence of Nipah virus. Chapter 1. *In* Manual on the diagnosis of Nipah virus infection in animals. FAO Regional Office for Asia and the Pacific, Bangkok. Available at: ftp://ftp.fao.org/docrep/fao/005/ac449e/ac449e00.pdf (accessed on 1 July 2017).

36. Ge X.Y., Li J.L., Yang X.L., Chmura A.A., Zhu G., Epstein J.H., Mazet J.K., Hu B., Zhang W., Peng C., Zhang Y.J., Luo C.M., Tan B., Wang N., Zhu Y., Crameri G., Zhang S.Y., Wang L.F., Daszak P. & Shi Z.L. (2013). – Isolation and characterization of a bat SARS-like coronavirus that uses the ACE2 receptor. *Nature,* **503** (7477), 535–538. doi:10.1038/nature12711.

37. Ahmad A., Krumkamp R. & Reintjes R. (2009). – Controlling SARS: a review on China's response compared with other SARS-affected countries. *Trop. Med. Int. Hlth*, **14** (Suppl. 1), 36–45. doi:10.1111/j.1365-3156.2008.02146.x.

38. Bernard S.M. & Anderson S.A. (2006). – Qualitative assessment of risk for monkeypox associated with domestic trade in certain animal species, United States. *Emerg. Infect. Dis.*, **12** (12), 1827–1833. doi:10.3201/eid1212.060454.

39. Machalaba C., Romanelli C., Stoett P., Baum S.E., Bouley T.A., Daszak P. & Karesh W.B. (2015). – Climate change and health: transcending silos to find solutions. *Ann. Glob. Hlth*, **81** (3), 445–458. doi:10.1016/j.aogh.2015.08.002.

40. Daszak P., Zambrana-Torrelio C., Bogich T.L., Fernandez M., Epstein J.H., Murray K.A. & Hamilton H. (2013). – Interdisciplinary approaches to understanding disease emergence: the past, present, and future drivers of Nipah virus emergence. *Proc. Natl Acad. Sci. USA*, **110** (Suppl. 1), 3681–3688. doi:10.1073/pnas.1201243109.

41. Watts N., Adger W.N., Agnolucci P., Blackstock J., Byass P., Cai W., Chaytor S., Colbourn T., Collins M., Cooper A., Cox P.M., Depledge J., Drummond P., Ekins P., Galaz V., Grace D., Graham H., Grubb M., Haines A., Hamilton I., Hunter A., Jiang X., Li M., Kelman I., Liang L., Lott M., Lowe R., Luo Y., Mace G., Maslin M., Nilsson M., Oreszczyn T., Pye S., Quinn T., Svensdotter M., Venevsky S., Warner K., Xu B., Yang J., Yin Y., Yu C., Zhang Q., Gong P., Montgomery H. & Costello A. (2015). – Health and climate change: policy responses to protect human health. *Lancet*, **386** (10006), 1861–1914. doi:10.1016/S0140-6736(15)60854-6.

42. Brownstein J.S., Holford T.R. & Fish D. (2005). – Effect of climate change on Lyme disease risk in North America. *Ecohealth,* **2** (1), 38–46. doi:10.1007/s10393-004-0139-x.

43. Faria N.R., Rambaut A., Suchard M.A., Baele G., Bedford T., Ward M.J., Tatem A.J., Sousa J.D., Arinaminpathy N., Pepin J., Posada D., Peeters M., Pybus O.G. & Lemey P. (2014). – HIV epidemiology. The early spread and epidemic ignition of HIV-1 in human populations. *Science,* **346** (6205), 56–61. doi:10.1126/science.1256739.

44. Leroy E.M., Rouquet P., Formenty P., Souquiere S., Kilbourne A., Froment J.M., Bermejo M., Smit S., Karesh W., Swanepoel R., Zaki S.R. & Rollin P.E. (2004). – Multiple Ebola virus transmission events and rapid decline of central African wildlife. *Science,* **303** (5656), 387–390. doi:10.1126/science.1092528.

45. Wilkie D.S. & Carpenter S.F. (1999). – Bushmeat hunting in the Congo Basin: an assessment of impacts and options for mitigation. *Biodivers. Conserv.*, **8**, 927–955. doi:10.1023/A:1008877309871.

46. Golden C.D., Fernald L.C., Brashares J.S., Rasolofoniaina B.J. & Kremen C. (2011). – Benefits of wildlife consumption to child nutrition in a biodiversity hotspot. *Proc. Natl Acad. Sci. USA*, **108** (49), 19653–19656. doi:10.1073/pnas.1112586108.

47. Smith K.M., Anthony S.J., Switzer W.M., Epstein J.H., Seimon T., Jia H., Sanchez M.D., Huynh T.T., Galland G.G., Shapiro S.E., Sleeman J.M., McAloose D., Stuchin M., Amato G., Kolokotronis S.O., Lipkin W.I., Karesh W.B., Daszak P. & Marano N. (2012). – Zoonotic viruses associated with illegally imported wildlife products. *PLoS ONE,* **7** (1), e29505. doi:10.1371/journal.pone.0029505.

48. Whitmee S., Haines A., Beyrer C., Boltz F., Capon A., de Souza Dias B.F., Ezeh A., Frumkin H., Gong P., Head P., Horton R., Mace G., Marten R., Myers S.S., Nishtar S., Osofsky S.A., Pattanayak S.K., Pongsiri M.J., Romanelli C., Soucat A., Vega J. & Yach D. (2015). – Safeguarding human health in the Anthropocene epoch: report of the Rockefeller Foundation–Lancet Commission on planetary health. *Lancet*, **386** (10007), 1973–2028. doi:10.1016/S0140-6736(15)60901-1.

49. Secretariat of the Convention on Biological Diversity (SCBD) (2014). – Global biodiversity outlook 4: a mid-term assessment of progress towards the implementation of the Strategic Plan for Biodiversity 2011–2020. SCBD, Montreal, 155 pp. Available at: www.cbd.int/gbo/gbo4/publication/gbo4-en-hr.pdf (accessed on 1 July 2017).

50. Seifman R., Kornblet S., Standley C., Sorrell E., Fischer J. & Katz R. (2015). – Think big, World Bank: time for a public health safeguard. *Lancet Glob. Hlth,* **3** (4), e186–187. doi:10.1016/S2214-109X(15)70012-4.

51. Pike J., Bogich T., Elwood S., Finnoff D.C. & Daszak P. (2014). – Economic optimization of a global strategy to address the pandemic threat. *Proc. Natl Acad. Sci. USA*, **111** (52), 18519–18523. doi:10.1073/pnas.1412661112.