Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

Emerging challenges of infectious diseases as a feature of land systems

Sophie O Vanwambeke[1], Catherine Linard[2,3] and Marius Gilbert[4,5]

The association of infectious diseases to the environment, and in particular land use, has long been known but has regained interest in the late 20th century in relation to global environmental change. We identify four major challenges, for which disease ecologists and land use scientists should collaborate further to understand how land systems affect health. First, the multifactorial determinants of the complex ecological systems of infectious diseases should be better acknowledged. Second, new challenges appear in urban areas in relation to their dynamics. Third, livestock raising, as a component of land systems, creates specific types of ecological interfaces. Fourth, tensions discussed in the land use community regarding conservation must account for issues related to the health of human, livestock and wildlife. We use those four illustrations to show how disease ecologists and land use scientists could tighten their collaboration.

Addresses
[1] Georges Lemaître Centre for Earth and Climate Research, Earth & Life Institute, UCLouvain. Place Pasteur 3, 1348 Louvain-la-Neuve, Belgium
[2] Institute of Life-Earth-Environment (ILEE), Université de Namur, Rue de Bruxelles 61, 5000 Namur, Belgium
[3] Namur Research Institute for Life Sciences (Narilis), Université de Namur, Rue de Bruxelles 61, 5000 Namur, Belgium
[4] Spatial Epidemiology Lab, Université Libre de Bruxelles, CP264/03, Av. F. Roosevelt, 50, 1050 Brussels, Belgium
[5] Fonds National de la Recherche Scientifique, Brussels, Belgium

Corresponding author:
Vanwambeke, Sophie O (Sophie.vanwambeke@uclouvain.be)

Current Opinion in Environmental Sustainability 2018, **38**:31–36

This review comes from a themed issue on **Sustainability governance and transformation**

Edited by **Rinku Roy Chowdhury**, **Darla K Munroe**, and **Ariane de Bremond**

Received: 15 January 2019; Accepted: 13 May 2019

https://doi.org/10.1016/j.cosust.2019.05.005

Introduction

Global environmental changes, including land use changes, are associated to changes in the prevalence and distribution of infectious diseases in humans, livestock, and wildlife. While environmental degradation and human encroachment have generally been assumed associated with increased pathogen transmission [1•], pathogens form part of complex human-ecological systems. Land use change may favor or disfavor pathogen circulation. Numerous studies have been improving our understanding of this association, but some questions remain — in relation to the broader set of ecological relationships involved, and as the prominence of land use changes varies through time. We present examples of associations between land use and pathogen circulation and emergence that highlight the potential complexity of these human-ecological systems. We identify areas in which disease ecologists and land use scientists could collaborate to further and broaden our understanding of how land-use changes affect infectious diseases.

Arthropod vectors, animal and human hosts, and pathogens, as they interact in the environment, can give rise to endemic or epidemic disease circulation in susceptible species. The conceptualization of infectious diseases as ecological systems is often quoted back to Sorre [2], May [3] and Pavlovsky [4]. All three, coming from different disciplinary angles (geography, medicine, and ecology, respectively), argued that disease transmission can only happen in places where a set of environmental conditions are met, including ecological interactions and human-environment interfaces. The late 20th century gave researchers two major incentives to revisit those ideas. Most importantly, the realization that unprecedented human-induced global change was affecting environment-sensitive pathogens [7] drove an impetus into disease ecology research. The advent of remote sensing provided disease ecologists with effective tools to monitor environmental determinants of infectious disease in a systematic way [5,6]. Patz *et al.* [8] and Reisen [9••] identified pathways through which landscape changes affect disease (re-)emergence, including direct effects of land cover conversion and indirect effects such as habitat fragmentation. Along other researchers (e.g. in Refs. [10,11]), they advocated for furthering this research, with the support of interdisciplinary teams and robust conceptual backgrounds.

Since these publications, much effort has gone into studying infectious disease dynamics in diverse land systems across the globe and in response to environmental change. We present four areas of research on pathogens as features of human-environment systems that illustrate areas where our knowledge of the effect of land use has progressed, associating a broad diversity of land use and land use changes to diseases but uncovering complex relationships. These examples illustrate how land use trade-offs in the context of health may not be arbitrated easily. Disease ecologists study environmental questions that are in direct connection with central debates in land system sciences, such as land use changes and biodiversity losses. However, health has been generally absent from land system studies. There is therefore significant scope for collaborative research in this area. We further propose concrete areas of collaboration between disease ecologists and land use scientists in this context.

Beyond direct effects on a single species at the frontier

Since the advent of remote sensing, numerous studies have looked into associations between land use and land use changes and infectious pathogens, reservoir hosts, and vectors, at a range of spatial scales [6,12•,13,14] have reviewed such studies. Gottdenker *et al.* [12•] identified biases, toward certain pathogens (e.g. vector-borne), certain environments (with higher Net Primary Productivity), and toward the effects of land use changes on host or vector community composition. The authors emphasized that many studies failed to provide details on mechanisms involved in associations observed mostly empirically but rarely experimentally.

We want to highlight two further lessons from the past few decades of research. First, land use classes may be imperfect representations of vector and host habitats and of human spaces of activities relevant to pathogen exposure. Second, land use changes may relate to health risk in complex, multidimensional ways.

Land use classes as perceived by humans must be considered with nuances. Empirical studies classically consider land use or land cover classes appropriate proxies for a species' habitat. This may be inappropriate for understanding vector-borne and zoonotic pathogens distribution, because no environmental proxy may encompass the full set of resources the species need from the environment, and because pathogen circulation relies on the presence and interaction of multiple species, including pathogen, vector, and (potentially multiple) host [15]. Land use classes may affect species involved in disease circulation in opposing directions [16]. This includes the issue of land use as a proxy for human exposure [17], considering the immaterial character of some land features (e.g. attractivity), the fine scale of others (e.g. use of bednet or screening), and the temporally dynamic character of human, vector, and host activity.

A second lesson points at better consideration for the human processes at stake when land use changes. Randolph [18] synthesized the complexity of the human-environmental factors of tick-borne encephalitis emergence in Eastern Europe in the 1990s: environmental factors, including land use and climate, colluded with massive socio-economic changes to produce a major increase of disease incidence. However, land-use changes have also been associated to disease incidence decreases. Ijumba and Lindsay [19] early on identified this as 'paddies paradox', suggesting that increases in wealth and access to healthcare can counter-balance increases in malaria-carrying *Anopheles*. Other human coping factors may have the same effect, such as the familiarity with protection measures. Baeza *et al.* [20••], using simulation models, show the diversity of trajectories of malaria incidence that can follow land conversion at the forest frontier, if socio-economic and demographic processes are modelled alongside mosquito population dynamics. This is not only relevant in frontier regions.

The sheer societal and ecological complexity of infectious disease circulation requires researchers to think of land use systems as affecting many aspects of pathogen transmission, and formulate hypothesis that reflect all possible ways in which a given landscape may affect transmission.

Urban ecology of diseases

Urbanization is a key environmental and demographic change of the 21st century [21]. This is not without consequences for health [22,23]. We highlight two specific, related, processes: the adaptation of pathogens to niches new to them, and the appearance of new niches in the urban environment.

Some diseases previously restricted to forests, such as dengue, are now fully reliant on the urban and peri-urban environment [24]. Others, such as malaria, were long thought primarily rural. However, the evolution of both land use and malaria transmission raise the question of the epidemiological weight of urban areas. Both the extent of cities and the fraction of population living in them have grown significantly over the past decades. And while, globally, malaria incidence is decreasing [25], and likely so also in cities [26], *Anopheles* mosquitoes [27] and malaria transmission [28] are observed in cities. Strong spatial heterogeneity and urban heat islands reinforce the specificity of the urban environment [29].

Cities create new types of human-wildlife interfaces, growing into previously rural land, because of counter-urbanization, abandonment or 'greening' in city planning, or because wild species adapt to the urban environment. Bradley and Altizer [30] identify key processes relevant here as changes in the type and distribution of resources, in species composition, in contact rates and in stress, all of which can be associated to increases, as well as decreases, in pathogen circulation. Urban growth has drawn a lot of attention [31], and so have the benefits of 'greening' urban areas [32,33]. How greener urban environments may negatively affect health, or broadly speaking ecosystem disservices [34], has been much less studied. This is particularly true in the context of de-urbanization/ counter-urbanization [35,36]. Cities grow but also evolve in ways that affect, positively or negatively, human and animal health.

These examples illustrate the diverse processes in which urbanization can drive pathogen circulation, and underline the many forms human-wildlife interfaces can take, including in densely built and populated landscapes.

Livestock as pathogen mixing vessels

Recent major disease emergence events such as Highly Pathogenic Avian Influenza (HPAI), SARS, and Nipah virus underline the role of livestock in pathogen emergence. Livestock is a major source of livelihood globally, and a major component of land systems. Global livestock production is undergoing major changes, predominantly intensification [37]. Intensive livestock production and its industrialization create unique ecosystems, with large numbers of genetically similar animals in close contact [38,39••], providing suitable conditions for evolution of low pathogenic into highly pathogenic strains, and where biocontainment is impossible. In fact, the large majority of novel HPAI (i.e. conversion of a low pathogenic avian influenza into HPAI) emerged in high-income countries [40]. Intensive systems often specialize infrastructure and concentrate certain types of activities (e.g. breeding, maturing, slaughtering), resulting in important movements of flocks and herds, sometimes over long distances, providing opportunities for pathogen spread. While the control of HPAI epidemics may be easier in high-income countries, due to better financial and human resources for disease control, the coexistence of intensive and small-scale poultry farming makes HPAI control difficult in middle-income countries where the disease can become endemic. Another spatial feature of intensified systems is the proximity to urban centers, where demand is located. While many land use relevant issues of industrialized production can be highlighted, intensive, small-scale agriculture also provides opportunities for pathogen emergence as was the case for Nipah virus emergence. The combination of fruit and pig production, at the edge of the habitat of frugivorous bats naturally hosting Nipah virus, permitted the spillover of the virus into pigs, and eventually into humans [41]. Extensive smallholders may not represent the primary hotspots of disease emergence, but poor use of medicines, lack of veterinary services and disease control may also place those systems at health risk [42].

Conservation and degradation affect disease emergence

The challenge of feeding the world population in a sustainable way is a question at the heart of current land use science [43]. As a land use issue, this questions translates, in part, to spatial organization [44]. One of the major trade-offs identified in this context is biodiversity [45]. Landscape structure and biodiversity relate directly to high-stakes questions in the field of infectious diseases. The first issue pertains to edges, an issue mentioned above, and landscape structure as the support of interaction networks [46]. Spillover from wildlife to human or livestock punctuate our history (e.g. HIV, Ebola virus [47], and SARS [48] represent only a few recent examples). Of concern to conservation, spillover from humans and livestock is also observed (e.g. *Toxoplasma gondii* from felines, including domestic cats, to sea otters [49], giardia, pneumonia, *Escherichia coli* and others to primates [50]). Biodiversity is much discussed in the context of health [51••,52]. The idea that preserving biodiversity leads to positive health outcomes is very endearing. However, biodiversity can play two opposite roles in infectious disease dynamics: dilution and amplification. Overall, even concerning pathogens for which this question has been focal, such as *Borrelia burgdorferi* spp. (pathogenic agent of Lyme disease) [53], researchers underline the uncertainties persisting on the role of biodiversity [54]. Recent studies underline the fact that biodiversity should be dealt with in combination with land use changes [55•,56].

What do these examples tell us? Emerging tools for disease ecology

The cases outlined here do not seek to exhaustively review instances of land use affecting diseases. They identify the challenges that appear when associating infectious diseases to land systems, advocate to expand existing frames and the strong connection between the two fields of research. We formulate three areas in which disease ecologists and land use scientists can collaborate to produce finer and more generalizable knowledge of pathogen dynamics as a feature of land systems: i) conceptual frameworks must allow to explore mechanisms of emergence at the landscape scale; ii) knowledge integration should be pursued; iii) data opportunities and weaknesses should be identified.

Conceptual frameworks

Conceptual models of disease emergence as a feature of human-environment interactions exist, and some have been used successfully to drive fundamental and applied research, such as the Ecohealth framework [57], but many empirical studies lack a robust conceptual backbone. Hypotheses on the effects of environmental variables and on biological and ecological processes are lacking in completeness. Because many pathogen systems are multi-species, an environmental factor may reflect habitat of any species [15]. Weak hypotheses, in the absence of a theoretical framework, do not allow to draw conclusions on the ecological mechanisms of spillover [1]. Many studies linking land use to disease events are correlational and their underlying conceptual framework is not always clear [58]. The issue here is not to produce new theoretical frameworks but to identify more finely knowledge gaps, also in the context of land processes. A clear opportunity concerns land and livestock management [59] and human exposure to infectious landscape [60]. Land use scientists and disease ecologists would benefit from finer, more nuanced views of disease ecology and land use, respectively. Both communities also need to acknowledge the beneficial and detrimental effects that the environment can have on health — sometimes simultaneously.

Pursuing knowledge integration

Disease modelers have produced an abundance of studies and models over the past two decades, and while many argue that their model can help in risk reduction, the number of such successes is conspicuously small [61]. Keeling *et al.* [62] warned against the misleading impression of accuracy that models can give. While such efforts were carried out in the past [63], and have more recently been done with a focus on climate [64], integration from the expanding body of empirical studies of land use and diseases is scant. A clear path for integration, in the absence of standardized study protocols facilitating formal data analysis, would be to better use integration of modelling tools. Empirical studies tend to produce somewhat idiosyncratic results, and simulation models tend to simplify systems — in order to explore very specific questions. The potential of combining them, including in the context of land use systems is great. Considering the challenges of experimental studies when considering both ecological and human dynamics, this combination appears crucial to furthering our understanding of complex dynamics such as those outlined above.

Identifying data caveats and opportunities

Environmental monitoring data are getting ever more available, and their ease of access and use can obscure the caution required in using them, as is the case with any dataset [65]. The interest of collaborating with land use and remote sensing scientists, familiar with the production of environmental monitoring data and with land systems is clear for disease ecologist, most of whom are simply environmental data users. Use of environmental monitoring data in the context of disease ecology must acknowledge that they represent proxies for various processes. Effects captured by a single variable may be in opposing directions for different species involved in disease transmission. Environmental proxies chosen to represent animal (host, vector) ecology may also reflect human exposure. Efficient use of data also requires acknowledging its nature as imperfect representations of spatial processes that occur across multiple scales. Poor explanatory power of a dataset may relate more to its inability to represent the process rather than to the relevance of the ecological process it is trying to capture. Many parallels exist with health-related data, which may give an incomplete picture of the phenomenon studied, as is illustrated by zoonotic vector-borne diseases. Researchers often have to compromise between resolution and extent when monitoring vectors or hosts, as the resource-intensiveness of field work limits what can be monitored in space and in time. Spatially exhaustive datasets, such as records of human cases of a notifiable disease only record what has been described as the tip of the iceberg of zoonotic circulation [66]. The zoonotic iceberg idea underlines the fact that most datasets on zoonotic pathogens only capture a fraction of zoonotic circulation. These vantage points combined, environmental data and health data, show that deeper insight will be gained if the strengths and weaknesses of the datasets are accounted for thoroughly.

Conclusion

Various environmental processes affect infectious disease circulation, including climate, land cover and land use, and ecological interactions. Land use however is a valuable entry point from the societal point of view as it is more 'actionable' for communities than are many abiotic and biotic factors. Landscapes connect vectors, hosts, and humans, including activities exposing them to pathogens. Disease ecologists and land use scientists should collaborate further in the study of health as a feature of land systems in contexts not restricted to land use conversions. Just like in the field of land science, recognition that these are complex ecological issues where normativity plays a role will help researchers identify trade-offs and producing knowledge relevant to society.

Conflict of interest statement

Nothing declared.

Acknowledgements

This paper was written as SOV was hosted by the Center for International Earth Science Information Network (CIESIN), The Earth Institute, at Columbia University, New York (USA).

References

1. • Faust CL, McCallum HI, Bloomfield LSP, Gottdenker NL, Gillespie TR, Torney CJ, Dobson AP, Plowright RK: **Pathogen spillover during land conversion**. *Ecol Lett* 2018, **21**:471-483.
This paper uses simulation models to explore the effects of land conversion at different stages on pathogens circulating across multiple species. It shows that transmission is most intense at intermediate stages of conversion. While not specific to a landscape or a pathogen, it highlights current shortcomings of empirical research and gaps in knowledge on the effect of land use changes on pathogen transmission.

2. Sorre M: **Complexes pathogènes et géographie médicale**. *Ann Géographie* 1933, **42**:1-18.

3. May JM: *History, Definition, and Problems of Medical Geography: A General Review*. International Geographical Union; 1952.
4. Pavlovsky E: *Natural Nidality of Transmissible Diseases in Relation to the Landscape Epidemiology of Zooanthroponoses*. Peace Publishers; 1966.
5. Hay SI, Randolph SE, Rogers DJ (Eds): *Remote Sensing and Geographical Information Systems in Epidemiology*. Academic Press; 2000.
6. Herbreteau V, Salem G, Souris M, Hugot J-P, Gonzalez J-P: **Thirty years of use and improvement of remote sensing, applied to epidemiology: from early promises to lasting frustration**. *Health Place* 2007, **13**:400-403.
7. Rapport D, Costanza R, McMichael AJ: **Assessing ecosystem health**. *Trends Ecol Evol* 1998, **13**:397-402.
8. Patz JA, Daszak P, Tabor GM, Aguirre AA, Pearl M, Epstein J, Wolfe ND, Kilpatrick AM, Foufopoulos J, Molyneux D *et al.*: **Unhealthy landscapes: policy recommendations on land use change and infectious disease emergence**. *Environ Health Perspect* 2004, **112**:1092-1098.
9. •• Reisen WK: **Landscape epidemiology of vector-borne diseases**. *Annu Rev Entomol* 2010, **55**:461-483.
Excellent review of the main aspects of landscape epidemiology with a focus on vector-borne diseases.
10. Wilcox BA, Aguirre AA, Daszak P, Horwitz P, Martens P, Parkes M, Patz JA, Waltner-Toews D: **EcoHealth: a transdisciplinary imperative for a sustainable future**. *EcoHealth* 2004, **1**:3-5.
11. Wilcox BA, Colwell RR: **Emerging and reemerging infectious diseases: biocomplexity as an interdisciplinary paradigm**. *EcoHealth* 2005, **2**:244-257.
12. • Gottdenker NL, Streicker DG, Faust CL, Carroll CR: **Anthropogenic land use change and infectious diseases: a review of the evidence**. *EcoHealth* 2014, **11**:619-632.
Recent review of studies of anthropogenic land use changes and infectious diseases, highlighting recurring themes, main findings and neglected areas.
13. Herbreteau V, Salem G, Souris M, Hugot J: **Sizing up human health through remote sensing: uses and misuses**. *Parassitologia* 2005, **47**:63-79.
14. Tran A, Kassié D, Herbreteau V: **Applications of remote sensing to the epidemiology of infectious diseases: some examples**. *Land Surface Remote Sensing*. Elsevier; 2016:295-315.
15. Hartemink N, Vanwambeke SO, Purse BV, Gilbert M, Van Dyck H: **Towards a resource-based habitat approach for spatial modelling of vector-borne disease risks: resource-based habitats for vector-borne diseases**. *Biol Rev* 2015, **90**:1151-1162.
16. Vanwambeke SO, Zeimes CB, Drewes S, Ulrich RG, Reil D, Jacob J: **Spatial dynamics of a zoonotic orthohantavirus disease through heterogenous data on rodents, rodent infections, and human disease**. *Sci Rep* 2019, **9**:2329.
17. Zeimes CB, Olsson GE, Hjertqvist M, Vanwambeke SO: **Shaping zoonosis risk: landscape ecology vs. landscape attractiveness for people, the case of tick-borne encephalitis in Sweden**. *Parasit Vectors* 2014, **7**:370.
18. Randolph SE: **Tick-borne encephalitis virus, ticks and humans: short-term and long-term dynamics**. *Curr Opin Infect Dis* 2008, **21**:462-467.
19. Ijumba JN, Lindsay SW: **Impact of irrigation on malaria in Africa: paddies paradox**. *Med Vet Entomol* 2001, **15**:1-11.
20. •• Baeza A, Santos-Vega M, Dobson AP, Pascual M: **The rise and fall of malaria under land-use change in frontier regions**. *Nat Ecol Amp Evol* 2017, **1**:0108.
Focusing on the case of malaria at the frontier of forest conversion, this study uses a simulation model to show how the entomological as well as human aspects of the system can affect the outcome of disease transmission and prevalence.
21. United Nations Department of Economic and Social Affairs: *World Urbanisation Prospects: The 2018 Revision*. United Nations; 2018.
22. Dye C: **Health and urban living**. *Science* 2008, **319**:766-769.
23. Alirol E, Getaz L, Stoll B, Chappuis F, Loutan L: **Urbanisation and infectious diseases in a globalised world**. *Lancet Infect Dis* 2011, **11**:131-141.
24. Gubler DJ: **Dengue viruses: their evolution, history and emergence as a global public health problem**. In *Dengue and Dengue Hemorrhagic Fever*. Edited by Gubler DJ, Ooi EE, Vasudevan S, Farrar J. CABI; 2014:1-29.
25. Tatem AJ, Gething PW, Smith DL, Hay SI: **Urbanization and the global malaria recession**. *Malar J* 2013, **12**:133.
26. Mudhune SA, Okiro EA, Noor AM, Zurovac D, Juma E, Ochola SA, Snow RW: **The clinical burden of malaria in Nairobi: a historical review and contemporary audit**. *Malar J* 2011, **10**:138.
27. Gadiaga L, Machault V, Pagès F, Gaye A, Jarjaval F, Godefroy L, Cissé B, Lacaux J-P, Sokhna C, Trape J-F *et al.*: **Conditions of malaria transmission in Dakar from 2007 to 2010**. *Malar J* 2011, **10**:312.
28. Klinkenberg E, McCall PJ, Wilson MD, Akoto AO, Amerasinghe FP, Bates I, Verhoeff FH, Barnish G, Donnelly MJ: **Urban malaria and anaemia in children: a cross-sectional survey in two cities of Ghana**. *Trop Med Int Health* 2006, **11**:578-588.
29. LaDeau SL, Allan BF, Leisnham PT, Levy MZ: **The ecological foundations of transmission potential and vector-borne disease in urban landscapes**. *Funct Ecol* 2015, **29**:889-901.
30. Bradley CA, Altizer S: **Urbanization and the ecology of wildlife diseases**. *Trends Ecol Evol* 2007, **22**:95-102.
31. Frumkin H: **Urban sprawl and public health**. *Public Health Rep* 2002, **117**:201-217.
32. Hartig T, Mitchell R, de Vries S, Frumkin H: **Nature and health**. *Annu Rev Public Health* 2014, **35**:207-228.
33. Hartig T, Kahn PH: **Living in cities, naturally**. *Science* 2016, **352**:938-940.
34. Lyytimäki J, Sipilä M: **Hopping on one leg – the challenge of ecosystem disservices for urban green management**. *Urban For Urban Green* 2009, **8**:309-315.
35. Eskew EA, Olival KJ: **De-urbanization and zoonotic disease risk**. *EcoHealth* 2018, **15**:707-712.
36. Gulachenski A, Ghersi B, Lesen A, Blum M: **Abandonment, ecological assembly and public health risks in counter-urbanizing cities**. *Sustainability* 2016, **8**:491.
37. Gilbert M, Conchedda G, Van Boeckel TP, Cinardi G, Linard C, Nicolas G, Thanapongtharm W, D'Aietti L, Wint W, Newman SH *et al.*: **Income disparities and the global distribution of intensively farmed chicken and pigs**. *PLoS One* 2015, **10**:e0133381.
38. Mennerat A, Nilsen F, Ebert D, Skorping A: **Intensive farming: evolutionary implications for parasites and pathogens**. *Evol Biol* 2010, **37**:59-67.
39. •• Gilbert M, Xiao X, Robinson TP: **Intensifying poultry production systems and the emergence of avian influenza in China: a •One Health/Ecohealth' epitome**. *Arch Public Health* 2017, **75**.
This paper discusses the emergence of novel avian influenza viruses in the context of the 'livestock revolution'. It puts zoonotic pathogens in perspective with intensification and industrialization of production globally and with other externalities of livestock production, including for ecosystem health.
40. Dhingra MS, Artois J, Dellicour S, Lemey P, Dauphin G, Von Dobschuetz S, Van Boeckel TP, Castellan DM, Morzaria S, Gilbert M: **Geographical and historical patterns in the emergences of novel Highly Pathogenic Avian Influenza (HPAI) H5 and H7 viruses in poultry**. *Front Vet Sci* 2018, **5**.
41. Pulliam JRC, Epstein JH, Dushoff J, Rahman SA, Bunning M, Jamaluddin AA, Hyatt AD, Field HE, Dobson AP, Daszak P *et al.*: **Agricultural intensification, priming for persistence and the emergence of Nipah virus: a lethal bat-borne zoonosis**. *J R Soc Interface* 2012, **9**:89-101.

42. Perry BD, Grace D, Sones K: **Current drivers and future directions of global livestock disease dynamics**. *Proc Natl Acad Sci U S A* 2013, **110**:20871-20877.

43. Ramankutty N, Mehrabi Z, Waha K, Jarvis L, Kremen C, Herrero M, Rieseberg LH: **Trends in global agricultural land use: implications for environmental health and food security**. *Annu Rev Plant Biol* 2018, **69**:789-815.

44. Grau R, Kuemmerle T, Macchi L: **Beyond 'land sparing versus land sharing': environmental heterogeneity, globalization and the balance between agricultural production and nature conservation**. *Curr Opin Environ Sustain* 2013, **5**:477-483.

45. Tscharntke T, Clough Y, Wanger TC, Jackson L, Motzke I, Perfecto I, Vandermeer J, Whitbread A: **Global food security, biodiversity conservation and the future of agricultural intensification**. *Biol Conserv* 2012, **151**:53-59.

46. Real LA, Biek R: **Spatial dynamics and genetics of infectious diseases on heterogeneous landscapes**. *J R Soc Interface* 2007, **4**:935-948.

47. Leroy EM: **Multiple Ebola virus transmission events and rapid decline of central African wildlife**. *Science* 2004, **303**:387-390.

48. Wang L-F, Eaton BT: **Bats, civets and the emergence of SARS**. In *Wildlife and Emerging Zoonotic Diseases: The Biology, Circumstances and Consequences of Cross-Species Transmission.* Edited by Childs JE, Mackenzie JS, Richt JA. Berlin Heidelberg: Springer; 2007:325-344.

49. Burgess TL, Tim Tinker M, Miller MA, Bodkin JL, Murray MJ, Saarinen JA, Nichol LM, Larson S, Conrad PA, Johnson CK: **Defining the risk landscape in the context of pathogen pollution: *Toxoplasma gondii* in sea otters along the Pacific Rim**. *R Soc Open Sci* 2018, **5**:171178.

50. Dunay E, Apakupakul K, Leard S, Palmer JL, Deem SL: **Pathogen transmission from humans to great apes is a growing threat to primate conservation**. *EcoHealth* 2018, **15**:148-162.

51. •• Randolph SE, Dobson ADM: **Pangloss revisited: a critique of the dilution effect and the biodiversity-buffers-disease paradigm**. *Parasitology* 2012, **139**:847-863.

This paper examines various pathways through which biodiversity may affect pathogen transmission dynamics. It constitutes a good introduction to this broad question.

52. Wood CL, Lafferty KD, DeLeo G, Young HS, Hudson PJ, Kuris AM: **Does biodiversity protect humans against infectious disease?** *Ecology* 2014, **95**:817-832.

53. Wood CL, Lafferty KD: **Biodiversity and disease: a synthesis of ecological perspectives on Lyme disease transmission**. *Trends Ecol Evol* 2013, **28**:239-247.

54. Kilpatrick AM, Dobson ADM, Levi T, Salkeld DJ, Swei A, Ginsberg HS, Kjemtrup A, Padgett KA, Jensen PM, Fish D *et al.*: **Lyme disease ecology in a changing world: consensus, uncertainty and critical gaps for improving control**. *Philos Trans R Soc B Biol Sci* 2017, **372**:20160117.

55. • Faust CL, Dobson AP, Gottdenker N, Bloomfield LSP, McCallum HI, Gillespie TR, Diuk-Wasser M, Plowright RK: **Null expectations for disease dynamics in shrinking habitat: dilution or amplification?** *Philos Trans R Soc B Biol Sci* 2017, **372**:20160173.

This paper uses simulation models to explore various configuration in terms of habitat, biodiversity and type of pathogen transmission (density dependent or frequency dependent) that may lead to dilution and amplification. Their results indicate that dilution is not generalizable.

56. Hosseini PR, Mills JN, Prieur-Richard A-H, Ezenwa VO, Bailly X, Rizzoli A, Suzán G, Vittecoq M, García-Peña GE, Daszak P *et al.*: **Does the impact of biodiversity differ between emerging and endemic pathogens? The need to separate the concepts of hazard and risk**. *Philos Trans R Soc B Biol Sci* 2017, **372**:20160129.

57. Charron DF (Ed): *Ecohealth Research in Practice: Innovative Applications of an Ecosystem Approach to Health*. International Development Research Centre; Springer; 2012.

58. Escobar LE, Craft ME: **Advances and limitations of disease biogeography using ecological niche modeling**. *Front Microbiol* 2016, **07**.

59. Cecchi G, Slingenbergh J: *World Livestock 2013: Changing Disease Landscapes*. Food and Agriculture Organization of the United Nations; 2013.

60. Lambin EF, Tran A, Vanwambeke SO, Linard C, Soti V: **Pathogenic landscapes: Interactions between land, people, disease vectors, and their animal hosts**. *Int J Health Geogr* 2010, **9**:54.

61. Purse BV, Golding N: **Tracking the distribution and impacts of diseases with biological records and distribution modelling**. *Biol J Linn Soc* 2015, **115**:664-677.

62. Keeling MJ: **Models of foot-and-mouth disease**. *Proc R Soc B Biol Sci* 2005, **272**:1195-1202.

63. Smolinski MS, Hamburg MA, Lederberg J: In *Microbial Threats to Health: Emergence, Detection, and Response.* Edited by Institute of Medicine (U.S.). National Academies Press; 2003.

64. Watts N, Amann M, Ayeb-Karlsson S, Belesova K, Bouley T, Boykoff M, Byass P, Cai W, Campbell-Lendrum D, Chambers J *et al.*: **The Lancet Countdown on health and climate change: from 25 years of inaction to a global transformation for public health**. *Lancet* 2018, **391**:581-630.

65. Olofsson P, Foody GM, Herold M, Stehman SV, Woodcock CE, Wulder MA: **Good practices for estimating area and assessing accuracy of land change**. *Remote Sens Environ* 2014, **148**:42-57.

66. Randolph SE, umilo D: **Tick-borne encephalitis in Europe: dynamics of changing risk**. *Emerging Pests and Vector-borne Disease in Europe*. Wageningen Academic Publishers; 2007:187-206.