



The ethics of isolation, the spread of pandemics, and landscape ecology

João C. Azevedo · Sandra Luque · Cynnamon Dobbs · Giovanni Sanesi · Terry C. H. Sunderland

Received: 29 July 2020 / Accepted: 5 August 2020 / Published online: 11 August 2020
© Springer Nature B.V. 2020

Introduction

The debate around the SARS-CoV-2 pandemic has raised multiple and incompletely answered questions regarding how zoonoses are transmitted from wild populations to humans, how they spread within human communities, over regions and across continents, how countries and societies can fight or counter pandemics and how landscapes will have to be effectively

managed for limiting the spread of diseases keeping communities safe and healthy.

A broader long-standing debate on the (un)sustainability of ongoing development models where biodiversity, climate, and socio-economic crises are central, both as causes and effects, has received additional attention in the context of the current pandemic. This has stressed the urgency of changing development paradigms to reduce pressures on ecosystems and biodiversity, increase investments in ecosystem and landscape restoration and integrate natural capital and ecosystem services valuation into decision-making processes, also at the urban scale.

Inspired in Forman's 1987 book chapter "The Ethics of Isolation, the Spread of Disturbance, and Landscape Ecology" (Forman 1987).

J. C. Azevedo (✉)
Centro de Investigação de Montanha, Instituto Politécnico de Bragança, Campus de Santa Apolónia,
5300-253 Bragança, Portugal
e-mail: jazevedo@ipb.pt

S. Luque
TETIS, Univ Montpellier, CNRS, INRAE,
34090 Montpellier, France
e-mail: sandra.luque@inrae.fr

C. Dobbs
Centro de Modelacion y Monitoreo de Ecosistemas,
Escuela de Ingenieria Forestal, Universidad Mayor, Jose
Toribio Medina 29, Santiago, Chile
e-mail: cynnamon.dobbs@umayor.cl

G. Sanesi
Department of Agro-Environmental and Territorial
Sciences, University of Bari Aldo Moro, Via Amendola
165/A, 70126 Bari, Italy
e-mail: giovanni.sanesi@uniba.it

T. C. H. Sunderland
Faculty of Forestry, University of British Columbia, 2424
Main Mall, Vancouver V6T 1Z4, Canada
e-mail: terry.sunderland@ubc.ca

The SARS-CoV-2 pandemic has also highlighted a third debate on the epistemology of science and the discipline of landscape ecology. There is clearly a need to acknowledge the increasing need for holistic, integrative, and inter and transdisciplinary conceptual frameworks and research methods in science and broader applications such as human health.

There has been a convergence between environmental and health disciplines over recent years highlighting the importance of the human–environment relationship in all aspects of human life, from economic, ecological, social and political perspectives, and the need for integrative and transdisciplinary approaches in science and practice (Jia et al. 2019; Spano et al. 2020). In general, human diseases spread by insects and other vectors, water, and food, and/or transmitted within groups through other processes (respiratory droplets, contact routes), are best understood by considering the environment as a whole. A holistic vision, using landscapes as a framework to gain a spatial understanding of human diseases and their spread, has previously been described in the literature (e.g. Cumming et al. 2015; Lambin et al. 2010; Paull et al. 2012; Reisen 2010). A landscape epidemiological approach calls for interdisciplinary cooperation and, as such, needs to be complemented by knowledge from other fields such as climatology, biology, medical anthropology, archeology and environmental economic history, among others, to understand processes from the past that influence the present (Ziegler 2016). We have to recognize the importance of the human–environment relationship in all aspects of human life from economic, ecological, social and political perspectives (Jia et al. 2019; Spano et al. 2020).

‘All in all’, medical science alone provides insufficient grounds to fully understand and deal with complex epizootics and only an interdisciplinary approach will be able to do so. Multi and interdisciplinary approaches such as landscape epidemiology, disease ecology or disease biogeography, require that a whole set of new factors and pressures interconnected to landscape patterns and processes, the core of landscape ecology, is taken into the study of the spread of diseases. At the same time, landscape ecology, as a consolidated but evolving scientific discipline, is able to respond to these emerging challenges based on its theoretical grounds as well as on a wide range of methods and tools representative of the multi and

interdisciplinarity of landscape ecology, that are essential to prevent, avoid and reduce the impact of both known and emerging diseases. This can contribute significantly to the One Health approach of the World Health Organization, of designing and implementing political, technical, legislative and research initiatives at different scales through communication and common work across sectors (WHO 2019).

This editorial is motivated by a webinar organized by the IUFRO (International Union of Forest Research Organizations) Forest Landscape Ecology Working Group (<https://iufrole-wp.weebly.com/>) held on June 24th, 2020. We discuss here what landscape ecology has to learn from this unprecedented crisis generated by the coronavirus pandemic and, simultaneously, demonstrate how this discipline can be useful to support integrated solutions to minimize the spread of diseases and to create increasingly safer, and sustainable landscapes.

Diseases and landscapes

Nearly two-thirds of human infectious diseases arise from pathogens shared with wild or domestic animals (Karesh et al. 2012). Natural habitat destruction is one of the main drivers, not just of species loss but also of spread of diseases. Physical changes in habitats and in the environment can affect populations of disease-related organisms through changes in climatic conditions and the creation of new breeding sites for disease vectors, favoring the emergence of zoonotic diseases. Changes in habitat type can have both positive and negative effects on the prevalence of infectious diseases. Industrial agriculture, road building, mining pits, and logging can all create new breeding habitats for insect vectors as well as paths for their proliferation. Human workers in these areas can also work as vectors. MacDonald and Mordecai (2019) found that deforestation significantly increases malaria transmission in the Amazon. Another study in the Peruvian Amazon showed that the biting rate of the malaria vector *Anopheles darlingi* was proportional to the area of land use modification and inversely proportional to the area of remaining forest (Vittor et al. 2006). In western Uganda, Bloomfield et al. (2020) found that fragmentation around households (edge density) and human behaviors (collection of small trees for construction, foraging and hunting for food) in forested

habitat increased the likelihood of contacts between humans and wild nonhuman primates. Changes caused by deforestation (habitat loss, road building, etc.) on landscape patterns, namely in terms of the extension of forest edge, increase the chance of emergence of infectious diseases exponentially.

Encouraged by trade, bushmeat increases contacts between forest animals, domestic animals and humans (Baudron and Liegeois 2020). Encroachment into forest lands is thought to have been a relevant factor in the emergence of several viral diseases, including Ebola, Marburg, Nipah and Ross River Viruses (Chua et al. 2002). In addition, road building and the associated increase in bushmeat hunting and trade are thought to have played a part in the original zoonosis of HIV and simian foamy virus (Wolfe et al. 2004). The present coronavirus crisis has brought renewed calls to stop the trading of wildlife, opening up a long conflict and rumbling tensions between those who want to conserve species, and those pushing for their sustainable use. This crisis provides evidence on the lack of awareness of the impact that human activities can have on nature, and of the nexus between human health and biodiversity.

Besides, the recent emergence of the devastating SARS-CoV-2 is thought to have originated in cave-dwelling bats that have increasingly come into contact with both humans and other possible mammalian hosts (Hu et al. 2017). As deforestation has increased, so have the incidences of zoonotic transfer to human populations - it is estimated that 50% of all zoonotic diseases have emerged since 1940, correlated with vast increases in forest loss and encroachment (Jones et al. 2008).

Despite the recognized importance of forests, we continue suffering record losses of these ecosystems across the world. Fires are creating astonishing impacts in primary and other forests in Europe (Ceccherini et al. 2020) but most noticeably in tropical regions in countries like Bolivia and Brazil where fires are strongly connected to deforestation and commodity-based farming practices. Worldwide, primary forest loss in 2019 was 2.8% higher than the previous years and the third highest loss since the turn of the century, after 2016 and 2017, equivalent to the loss of a football pitch every six seconds according to the latest Global Forest Watch Report (WRI, 2020 <https://www.wri.org/>).

Deforestation and landscape homogenization driven by industrial agriculture/forestry intensification have triggered a wave of extinction, threat, and local population declines that may be comparable in both rate and magnitude with the five previous mass extinctions of Earth's history (Barnosky et al. 2011). Indeed, patterns of “defaunation”, produced by humans in the past 500 years, as presented by Dirzo et al. (2014), extend across taxonomic groups, but are also selective, with some taxonomic groups and regions being particularly affected more than others (Cardillo et al. 2008; Di Marco et al. 2015). Losses and degradation of forest habitat, changes in landscape configuration, and impoverishment of ecosystems due to local extinctions increase the potential for the emergence and spread of zoonotic diseases and the causes for this degradation needs to be addressed within efforts to prevent both current and future pandemics.

The landscape ecology legacy

Landscape ecology, both conceptually and methodologically, can play an active role in explaining, describing, modeling and forecasting the emergence and spread of zoonosis diseases and in informing decision-making to minimize spread and to foster disease-safe landscapes. Landscape ecology has inspired health related disciplines such as landscape epidemiology (Kitron 1998; Reisen 2010), approaches to achieve nutrition-sensitive landscapes (Kennedy et al. 2017) and the interactions between pathology and landscape ecology are growing rapidly (e.g. Cumming et al. 2015, Morandeira et al. 2019). There is, nevertheless, much more that landscape ecology can offer to a comprehensive scientific and technical effort to deal with the pandemics and to find solutions for the problems it produces. The holistic approach followed in landscape ecology to address structure and processes (and their interactions) can accommodate the integration of factors and effects of the spread of diseases. These, operating at different scales, both spatially and temporally, are required to analyze and model interactions of pathogens with complex socio-ecological systems. Hierarchy theory (O'Neill 1986) underpins this perspective by providing the conceptual framework for structuring complex systems such as multi-functional landscapes, fundamental in

formalizing research and practical applications. Relevant theoretical models and developments emerging from or applied in landscape ecology with interest for epidemiology include the conceptual landscape structure model (patch-corridor-matrix) of Forman and Godron (1987) and patch theory (Wiens 1995), percolation theory (O'Neill et al. 1988), and graph theory (Pascual-Hortal and Saura 2006), among others. These provide the conceptual background to the definition of entities of interest, their spatial and temporal scales, articulation among them, definition and description of processes related to the spread of diseases and the mechanistic or statistical formulation of models directed to the study or forecast of behavior and distribution of pathogens.

Correspondingly, there is a diversity of models used in landscapes (Scheller and Mladenoff 2007, Synes et al. 2016) conceived for and operating at several levels of complexity, from individual organisms (Boyce et al. 2017) to metapopulations (Levins 1970) and from predator-prey, consumer-resources systems, species distribution models (Zurrell et al. 2018) to spread of disturbances (Perera et al. 2015) and landscape change dynamics models (Baker 1989; Houet et al. 2010), just to mention a few with direct links to the context of epidemics. Remotely sensed data and remote sensing technology have been pivotal for the early development of landscape ecology. As such, landscape ecology today can provide key applications to derive spatially explicit operational territorial answers and systems understanding for use in disease risk and spatial dynamics assessment, management and monitoring. In addition, landscape ecology applications in fields such as forestry, land planning, hydrology, urban planning, conservation, climate change, adaptive management, and others are adaptable to tackle societal problems that can be put at the service of prevention and fighting epidemic diseases.

The consolidation of landscape (socio)ecology in the time of pandemics

As Ziegler (2016) pointed out, epidemics are a product of landscapes shaped by humans to fit our purposes, if not always optimally our needs, and are therefore not entirely 'pristine' (Barrett and Armelagos 2013). In the context of the Anthropocene, we encounter

growing uncertainties, but we need to better understand and improve the dynamic relationship of humans and landscape elements necessary to maintain biodiversity and ecological functions, while supporting human well-being. In that vein, landscape ecology can have an important role given the discipline has evolved towards an integrated and multidisciplinary scientific field. The adoption of concepts, research frameworks and methods from social sciences in addition to biology, ecology, technology (remote sensing and GIS), make landscape ecology a promising transdisciplinary field. Similarly, landscape sustainability science (LSS), has grown as a place-based, use-inspired science (Opdam et al. 2018; Liao et al. 2020), providing important insights to planning and managing sustainable landscapes, and for supporting the implementation of the UN Sustainable Development Goals (SDGs). The widening of the scope of landscape ecology has brought it closer to problems that contemporary societies face. Similarly, the landscape ecology community is increasingly engaged in the detection and implementation of solutions to these current socio-ecological problems. The following three key aspects are essential to understand the evolution of landscape ecology and the emergence of a transdisciplinary, integrated science directed to solutions, which is being stressed by the current covid-19 pandemics

Landscape ecology as a socio-ecological science

Landscapes are recognized as a combination of natural structures/processes and anthropogenic pressures modeled by individual and collective decision making, dependent on socioeconomic conditions, including economic markets (especially food markets), but also on contrasting components such as cultural or historical legacies. Landscapes are intrinsically socio-ecological systems (Sunderland et al. 2017) and landscape ecology is increasingly recognized as a socio-ecological science (Helfenstein et al. 2014; Frazier et al. 2019).

Ecosystem services and landscape ecology

The rapid evolution of landscape ecology as a socio-ecological science is related to the ecosystem services (ES) concept and framework. ES has boosted the importance of landscape ecology given that most

ecosystem services depend on landscape scale pattern/processes or are even landscape services (Iverson et al. 2014). ES highlight the importance of assessing ecological processes further from discrete events and looking at ecological phenomenon as continuous events. Landscape ecology tools and methods can then be used to understand, at different scales, where ecosystem services are produced, how those change over time and how the supply of ecosystem services relates to its demand.

Active involvement of landscape ecologists in solutions

Related to the previously mentioned changes, landscape ecology has been more than ever involved in the development of solutions for evolving societal problems. Landscape ecology research and its applications have been more frequently used in the assessment of risk and effects of disturbances at larger scales (Loehman et al. 2017), land planning for conservation (Karimi and Hockings 2018; Solmundson et al. 2020) and adaptive management (Chacón-Moreno et al. 2020) determining spatially explicit vulnerability to climate change (Mayer et al. 2016).

The definitive recognition of urban landscapes

Considering that a large proportion of the world population lives in urban areas and that urban populations, due to their high density, are more vulnerable to infection but also contribute the most to disease transmission within and between cities, urban landscapes require particular attention in times of pandemics at least in two ways. Firstly, urban landscapes, as a habitat for humans, with their green infrastructure (UGI) provide ecosystem services, food production, and other benefits that maintain human physical and mental health, especially during lockdown periods. A non-secondary aspect in improving human health is linked to the improvement of the psychological status of urban populations determined by the presence of green spaces close to the place of ‘social confinement’ during lockdown. Lockdown has shown, however, inequities in the provision of UGI in most countries around the world, with more profound inequities occurring for economies with larger Gini index, a popular measure of income inequality in a nation

(Ceriani and Verme 2012). By using landscape approaches to assess the quality, quantity and distribution of green spaces and eventually UGI, we can create cities that are more resilient and better prepared to provide ecosystem services and positively improve human well-being and health for all city inhabitants under complete lockdown or semi-lockdown (Ramirez-Rubio et al. 2019). Secondly, urban landscapes, as barriers, buffers, or low contagion spatial systems, can contribute to halt or slow down the spread of diseases. Improving urban green infrastructure and green spaces accessibility and distribution can aid in changing the mobility patterns that have led to higher rates of contagion and incidence of the pandemic. Urban landscape planning should consider mobility, not only of people, but of other components of the ecosystem. Understanding the dispersion of plants and animals in urban landscapes and how those connect to the surrounding natural might help in detecting possible zoonosis expansion and can aid in designing cities that are capable of providing a safer environment for urban dwellers. Moreover, biodiversity rich landscapes and UGI work as prevention for zoonosis dispersion (Zhao et al. 2020). A scientific approach in organizing UGI with multiple species and strata, and diverse green patches can prevent mobility of hazardous biological vectors, which can contribute to understand as different urban growth patterns appear to have significantly amplified the exposure of urban populations to health risks (e.g. zoonoses) (Connolly et al. 2020).

Final remarks

Landscape ecology as an established scientific discipline with a relatively recent evolution towards socio-ecological science, is a source of theoretical frameworks, models and applications suitable to face challenges posed by emergent pandemics. The holistic and integrative vision of landscape ecology will help to better understand the notion that nature is not everlasting and that the society, including scientists, should rethink and reshape economic growth and revolutionize the way development is put in place and assessed, replacing the mistakenly perception that natural resources on which we depend — from forests to fossil fuels — will always be there, by a sustainable perspective based on the limits of natural capital. This

vision not only requires new approaches and perhaps also new languages to be implemented but also requires a greater involvement of citizens and professionals in diverse sectors that are aware of the complexity of the problems and how these require balanced and fair solutions. The need to rethink development models, food production and distribution systems, urban planning, mobility and transportation systems is a priority in the context of sustainability and epidemics within a nexus thinking approach facilitating cross-scale and cross-sectoral planning (Fürst et al. 2017; Luque et al. 2017). At the same time, there is an urgent need to rethink policy and governance to protect habitats and avoid zoonotic spillover. Landscape ecology makes the realization of the consequences of decision making more real for politicians and decision makers.

Analysis at different scales to gain a holistic understanding of landscapes coupled to a landscape ecology framework and methods allows us to realize the impact of local decisions on the surrounding environment, helps realize the spillover effects of climate change and helps us communicate the importance of certain areas or patches for maintaining the resilience or sustainability of a landscape. For cities, it can help us not only to identify critical areas to maintain connectivity for dispersion, ecosystem services and human mobility, but also to know how we can achieve higher levels of resilience.

References

- Baker WL (1989) A review of models of landscape change. *Landscape Ecol* 2:111–133
- Barnosky A, Matzke N, Tomiya S, Wogan GOU, Swartz B, Quental TB, Marshall C, McGuire JL, Lindsey EL, Maguire KC, Mersey B, Ferrer EA (2011) Has the Earth's sixth mass extinction already arrived? *Nature* 471:51–57
- Barrett R, Armelagos G (2013) An unnatural history of emerging infections. Oxford University Press, Oxford, p 160
- Baudron F, Liegeois F (2020) Fixing our global agricultural system to prevent the next COVID-19. *Outlook Agric* 45(2):111–118
- Bloomfield LSP, McIntosh TL, Lambin EF (2020) Habitat fragmentation, livelihood behaviors, and contact between people and nonhuman primates in Africa. *Landscape Ecol* 35:985–1000
- Boyce MS, Mallory CD, Morehouse AT, Prokopenko CM, Scraftford MA, Warbington CH (2017) Defining landscapes and scales to model landscape–organism interactions. *Curr Landsc Ecol Rep* 2:89–95
- Cardillo M, Mace GM, Gittleman JL, Jones KE, Bielby J, Purvis A (2008) The predictability of extinction: biological and external correlates of decline in mammals. *Proc Biol Sci* 275(1641):1441–1448
- Ceccherini G, Duveiller G, Grassi G, Lemoine G, Avitabile V, Pilli R, Cescatti A (2020) Abrupt increase in harvested forest area over Europe after 2015. *Nature* 583:72–77
- Ceriani L, Verme P (2012) The origins of the Gini index: extracts from *VariabilitA e MutabilitA* (1912) by Corrado Gini. *J Econ Inequal* 10(3):421–443
- Chacón-Moreno E, Olivares I, Navarro G, Albarrán AJ, Paredes Y, Aranguren CI, Nagy GJ (2020) Landscape ecology and conservation for building resilience and adaptation to global change in Venezuela. In: Leal Filho W, Nagy G, Borga M, Chávez Muñoz P, Magnuszewski A (eds) *Climate change, hazards and adaptation options. Climate change management*. Springer, Cham, pp 147–160
- Chua KB, Chua BH, Wang CW (2002) Anthropogenic deforestation, El Nino and the emergence of Nipah virus in Malaysia. *Malays J Pathol* 24(1):15–21
- Connolly C, Keil R, Ali SH (2020) Extended urbanisation and the spatialities of infectious disease: demographic change, infrastructure and governance. *Urban Stud*. <https://doi.org/10.1177/0042098020910873>
- Cumming GS, Abolnik C, Caron A, Gaidet N, Grewar J, Hellard E, Henry DAW, Reynolds C (2015) A social–ecological approach to landscape epidemiology: geographic variation and avian influenza. *Landscape Ecol* 30(6):963–985
- Di Marco M, Collen B, Rondinini C, Mace GM (2015) Historical drivers of extinction risk: using past evidence to direct future monitoring. *Proc Biol Sci* 282(1813):20150928
- Dirzo R, Young HS, Galetti M, Ceballos G, Isaac NJB, Collen B (2014) Defaunation in the Anthropocene. *Science* 345(6195):401–406
- Forman RTT (1987) The ethics of isolation, the spread of disturbance, and landscape ecology. In: Turner MG (ed) *Landscape Heterog Disturb*. Springer, New York, pp 213–229
- Frazier AE, Vadjunc JM, Kedron P, Fagin T (2019) Linking landscape ecology and land system architecture for land system science: an introduction to the special issue. *J Land Use Sci* 14:123–134
- Fürst C, Luque S, Geneletti D (2017) Nexus thinking: how ecosystem services can contribute to enhancing the cross-scale and cross-sectoral coherence between land use, spatial planning and policy-making. *Int J Biodivers Sci Ecosyst Serv Manage* 13(1):412–421
- Helfenstein J, Bauer L, Claluna A, Bolliger J, Kienast F (2014) Landscape ecology meets landscape science. *Landscape Ecol* 29:1109–1113
- Houet T, Verburg PH, Loveland TR (2010) Monitoring and modelling landscape dynamics. *Landscape Ecol* 25:163–167
- Hu B, Zeng LP, Yang XL, Ge XY, Zhang W, Li B, Xie JZ, Shen XR, Zhang YZ, Wang N, Luo DS, Zheng XS, Wang MN, Daszak P, Wang LF, Cui J, Shi ZL (2017) Discovery of a rich gene pool of bat SARS-related coronaviruses provides new insights into the origin of SARS coronavirus. *PLOS Pathog* 13(11):e1006698

- Iverson L, Echeverria C, Nahuelhual L, Luque S (2014) Ecosystem services in changing landscapes: an introduction. *Landscape Ecol* 29(2):181–186
- Jia P, Lakerveld J, Wu J, Stein A, Root ED, Sabel CE, Vermeulen R, Remais JV, Chen X, Brownson RC, Amer S, Xiao Q, Wang L, Verschuren WMM, Wu T, Wang Y, James P (2019) Top 10 research priorities in spatial life-course epidemiology. *Environ Health Perspect* 127:7
- Jones KE, Patel NG, Levy MA, Storeygard A, Balk D, Gittleman JL, Daszak P (2008) Global trends in emerging infectious diseases. *Nature* 451:990–993
- Karesh WB, Dobson A, Lloyd-Smith JO, Lubroth J, Dixon MA, Bennett M, Aldrich S, Harrington T, Formenty P, Loh EH, Machalaba CC, Jason TM, Heymann DL (2012) Ecology of zoonoses: natural and unnatural histories. *Lancet* 380(9857):1936–1945
- Karimi A, Hocking M (2018) A social-ecological approach to land-use conflict to inform regional and conservation planning and management. *Landscape Ecol* 33:691–710
- Kennedy G, Raneri J, Termote C, Nowak V, Groot RRR, Thilsted S (2017) Nutrition-sensitive landscapes: approach and methods to assess food availability and diversification of diets. In: Obern I, Vanlauwe B, Phillips M, Thomas R, AttaKrah K, Brooijmans W (eds) Sustainable intensification in smallholder agriculture: an integrated systems research approach. Taylor and Francis, London, pp 247–258
- Kitron U (1998) Landscape ecology and epidemiology of vector-borne diseases: tools for spatial analysis. *J Med Entomol* 35(4):435–445
- Lambin EF, Tran A, Vanwambeke SO, Linard C, Soti V (2010) Pathogenic landscapes: interactions between land, people, disease vectors, and their animal hosts. *Int J Health Geogr* 9(1):54
- Levins R (1970) Extinction. In: Gerstenhaber M (ed) Some mathematical questions in biology. American Mathematical Society, Providence, pp 75–107
- Liao C, Qiu J, Chen B, Chen D, Fu B, Georgescu M, He C, Jenerette GD, Li X, Li X, Xin Bading Q, Shi P, Wu J (2020) Advancing landscape sustainability science: theoretical foundation and synergies with innovations in methodology, design, and application. *Landscape Ecol* 35:1–9
- Loehman RA, Keane RE, Holsinger LM, Wu Z (2017) Interactions of landscape disturbances and climate change dictate ecological pattern and process: spatial modeling of wildfire, insect, and disease dynamics under future climates. *Landscape Ecol* 32:1447–1459
- Luque S, Fürst C, Geneletti D (2017) Nexus thinking—how ecosystem services concepts and practice can contribute balancing integrative resource management through facilitating cross-scale and cross-sectoral planning. *Int J Biodivers Sci Ecosyst Serv Manag* 13(2):i–iii
- MacDonald AJ, Mordecai EA (2019) Amazon deforestation drives malaria transmission, and malaria burden reduces forest clearing. *Proc Natl Acad Sci USA* 116(44):22212–22218
- Mayer AL, Buma B, Davis A, Gagné SA, Loudermilk LE, Scheller RM, Schmiegelow FKA, Wiersma YF, Franklin J (2016) How landscape ecology informs global land-change science and policy. *Bioscience* 66(6):458–469
- Morandeira NS, Castesana PS, Cardo MV, Salomone VN, Vadell MV, Rubio A (2019) An interdisciplinary approach to assess human health risk in an urban environment: a case study in temperate Argentina. *Heliyon* 5(10):e02555
- O’Neill RV, Deangelis DL, Waide JB, Allen TFH (1986) A hierarchical concept of ecosystems. Princeton University Press, Princeton
- O’Neill RV, Milne BT, Turner MG, Gardner RH (1988) Resource utilization scales and landscape pattern. *Landscape Ecol* 2:63–69
- Opdam P, Luque S, Nassauer J, Verburg PH, Wu J (2018) How can landscape ecology contribute to sustainability science? *Landscape Ecol* 33(1):1–7
- Pascual-Hortal L, Saura S (2006) Comparison and development of new graph-based landscape connectivity indices: towards the prioritization of habitat patches and corridors for conservation. *Landscape Ecol* 21:959–96
- Paull SH, Song S, McClure KM, Sackett LC, Kilpatrick AM, Johnson PTJ (2012) From super-spreaders to disease hotspots: linking transmission across hosts and space. *Front Ecol Environ* 10(2):75–82
- Perera AH, Sturtevant BR, Buse LJ (eds) (2015) Simulation modeling of forest landscape disturbances. Springer International Publishing, Cham
- Ramirez-Rubio O, Daher C, Fanjul G, Gascon M, Mueller N, Pajin L, Plasencia A, Rojas-Rueda D, Thondoo M, Nieuwenhuijsen MJ (2019) Urban health: an example of a “health in all policies” approach in the context of SDGs implementation. *Glob Health* 15(1):87
- Reisen WK (2010) Landscape epidemiology of vector-borne diseases. *Annu Rev Entomol* 55(1):461–483
- Scheller RM, Mladenoff DJ (2007) An ecological classification of forest landscape simulation models: tools and strategies for understanding broad-scale forested ecosystems. *Landscape Ecol* 22:491–505
- Solmundson K, Bowman J, Adey E, Baici JE, Dillon R, Dupuis AE, Marrotte RR, Morin SJ, Newar SL, O’Brien P, Scott L (2020) The currency of conservation: how is landscape extent applied in conservation planning? *Curr Landscape Ecol Rep* 5:1–11
- Spano G, Giannico V, Elia M, Bosco A, Laforteza R, Sanesi G (2020) Human health–environment interaction science: an emerging research paradigm. *Sci Total Environ* 704:20
- Sunderland TR, Abdoulaye R, Ahammad R, Asaha S, Baudron F, Deakin E, Duriaux J-Y, Eddy I, Foli S, Gumbo D, Khatun K, Kondwani M, Kshatriya M, Leonald L, Rowland D, Stacey N, Tomsha S, Yang K, Gergel S, Vianen JV (2017) A methodological approach for assessing cross-site landscape change: understanding socio-ecological systems. *For Policy Econ* 84:83–91
- Synes NW, Brown C, Watts K, White SM, Gilbert MA, Travis JMJ (2016) Emerging opportunities for landscape ecological modelling. *Curr Landscape Ecol Rep* 1:146–167
- Vittor AY, Gilman RH, Tielsch J, Glass G, Shields T, Lozano WS, Pinedo-Cancino V, Patz JA (2006) The effect of deforestation on the human-biting rate of *Anopheles darlingi*, the primary vector of *Falciparum* malaria in the Peruvian Amazon. *Am J Trop Med Hyg* 74(1):3–11
- WHO (2019) Taking a multisectoral, one health approach: a tripartite guide to addressing zoonotic diseases in countries. World Health Organization, Food and Agriculture

- Organization of the United Nations & World Organisation for Animal Health. WHO Press, Geneva
- Wiens JA (1995) Landscape mosaics and ecological theory. In: Hansson L, Fahrig L, Merriam G (eds) Mosaic landscapes and ecological processes. Springer, Dordrecht
- Wolfe N, Switzer WM, Carr JK, Bhullar VB, Shanmugam V, Tamoufe U, Prosser AT, Torimiro JN, Wright A, Mpoudi-Ngole E, McCutchan FE, Birx DL, Folks TM, Burke DS, Heneine W (2004) Naturally acquired simian retrovirus infections in central African hunters. *The Lancet* 363(9413):932–937
- Zhao J, Tang T, Wang X (2020) Effects of landscape composition on mosquito population in urban green spaces. *Urban For Urban Gree* 49:126626
- Ziegler M (2016) Landscapes of disease. *Landscapes* 17(2):99–107
- Zurrell D, Pollock L, Thuiller W (2018) Do joint species distribution models reliably detect interspecific interactions from co-occurrence data in homogenous environments? *Ecography* 41:1812–1819

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations