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Examining the paradox of urban disease ecology by linking the perspectives of Urban One Health and Ecology with Cities

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Abstract

The ecology of zoonotic, including vector-borne, diseases in urban social-ecological systems is influenced by complex interactions among human and environmental factors. Several characteristics contribute to the emergence and spread of infectious diseases in urban places, such as high human population densities, favorable habitat for vectors, and humans' close proximity to animals and their pathogens. On the other hand, urban living can contribute to the improvement of public health through better access to health services and creation of ecological and technological infrastructure that reduces disease burdens. Therefore, urbanization creates a disease ecology paradox through the interplay of urban health penalties and advantages for individual and community outcomes. To address this contradiction, we advocate a holistic Urban One Health perspective for managing urban systems, especially their green spaces and animal populations, in ways that more effectively control the spread of zoonotic diseases. This view should be coupled with an Ecology with Cities approach which emphasizes actionable science needed for urban planning, management and policymaking; developing disease and vector surveillance programs using citizen and community science methods; and improving education and communication actions that help diverse stakeholders understand the complexities of urban disease ecology. Such measures will enable scholars from many disciplines to collaborate with professionals, government officials, and others to tackle challenges of the urban disease paradox and create more sustainable, health-promoting environments.

Keywords Urban disease ecology · Infectious diseases · Vectors · Zoonosis · Public health · Community science

Introduction

The emergence and spread of zoonotic diseases in social-ecological systems are determined by many variables including those of human populations, infrastructure, public health systems, and pathogens (Morse et al. 2012; Johnson et al. 2015a; Plowright et al. 2017; Gibb et al. 2020). Further, because zoonotic diseases are transmitted directly to humans from vertebrate animals (livestock, pets, and wildlife), and through vectors such as ticks, mosquitoes and rats, disease dynamics are strongly determined by many ecological characteristics of animals' populations (abundance, distribution, behaviors, movement, etc.), communities (species richness, interspecific interactions, etc.), and interactions with people (Karesh et al. 2012; Johnson et al. 2015b; McMahon et al. 2018; Keesing and Ostfeld 2021). Urbanization alters these variables and other environmental conditions (e.g., climate, food and habitat availability; landscape structure; waste accumulation; water flow), all of which interact to affect disease risk for human and non-human residents (Bradley and Altizer 2007; Gottdenker et al. 2014; Lõhmus and Balbus 2015; Hassell et al. 2017; McMahon et al. 2018; Combs et al. 2022). Because urbanization continues to increase around the world, securing urban public health is a growing societal priority, especially in context of preventing future pandemics (Alirol et al. 2011; Neiderud 2015; de Leeuw 2020; Connolly et al. 2021).

Zoonotic disease dynamics in urban systems are particularly complex because of the multivariate host-pathogen-environment-human interactions occurring across

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spatiotemporal scales in highly heterogeneous landscapes (Douglas 2012; LaDeau et al. 2015; Hassell et al. 2017; Santiago-Alarcon and MacGregor-Fors 2020; Combs et al. 2022). Further, various characteristics of urban systems may have contrasting influences on biodiversity, disease risk, and human health, leading to management tradeoffs and localized, site-specific dynamics that are difficult to generalize and predict (Douglas 2012; Gottdenker et al. 2014; LaDeau et al. 2015; Lõhmus and Balbus 2015; Rothenburger et al. 2017; Marselle et al. 2021; Combs et al. 2022). Cities, in particular, have traditionally been considered as facilitating the spillover and spread of zoonotic pathogens due to higher density of large human populations living closely with zoonotic reservoirs (Alirol et al. 2011; Neiderud 2015; Hassell et al. 2017; Rothenburger et al. 2017). Sanitation problems, social inequalities in health care, and lack of local knowledge can increase the risk of infectious disease transmission (Alirol et al. 2011; Krystosik et al. 2020). At the same time, urban living often provides better access to health services and health-promoting social interactions (Johnson 2006; Hotez 2017). Abundance of disease-causing agents may be reduced in urban areas due to adequate sanitation systems, more effective disease surveillance, and management afforded by urban economies and governments (Alirol et al. 2011). Also, urbanization can reduce human contact with wildlife and their pathogens, limiting the risk of spillover events. On the other hand, unplanned urbanization or de-urbanization (i.e., abandonment of urbanized areas) can favor the proliferation of disease vectors such as mosquitoes and urban-adapted rodents (Bradley and Altizer 2007; Lõhmus and Balbus 2015; Eskew and Olival 2018). Reconciling these contrasting effects of urbanization on disease vectors and human health, i.e., urban health penalties *versus* urban health advantages (Vlahov et al. 2005; Segurado et al. 2016), exemplifies the challenge of unraveling, much less reducing, the causes of zoonotic disease burdens in diverse urban systems around the globe.

Deeper understanding of this complex urban disease ecology paradox will be facilitated by a holistic view of disease dynamics in urban social-ecological systems. Such a perspective is provided by One Health, which emphasizes that human, animal and environmental factors need to be simultaneously considered in a unified way to effectively understand, prevent, and control the emergence and spread of zoonotic infectious diseases (Cunningham et al. 2017; CDC 2018; Ellwanger et al. 2021). The objective of this article is to discuss urban health penalties and advantages, and develop an Urban One Health approach to examine the paradoxical complexity of urban zoonotic disease ecology (de Leeuw 2020). Further, because actions at local (e.g., city, neighborhood) levels are crucial for managing social-ecological variables affecting animal populations and disease risk, we advocate linking Urban One Health to an Ecology with Cities perspective which promotes collaborative activities with a diverse audience, including decision-makers, teachers, scientists, and other community members, to study, improve and communicate about urban environments (Byrne 2022). By adopting and coupling these two perspectives, we suggest that urban ecologists, scholars from other disciplines, and diverse professionals will be better able to examine the complexities of disease ecology in urban settings and help communities create healthier and more sustainable urban social-ecological systems. This will be particularly relevant to environmental justice programs that seek to address the disproportionate health burdens too often experienced by marginalized residents and developing regions (Bowser and Cid 2020; Lindahl and Magnusson 2020; Schell et al. 2020; Gruetzmacher et al. 2021).

Urban health penalties

A key cause of urban health penalties is increased transmission of zoonotic diseases due to the close coexistence of humans and zoonotic species (Reolon et al. 2004; Sormunen et al. 2020). Many disease-carrying animals thrive in urban settings and transmit diverse pathogens to humans that cause diseases such as cryptococcosis (from pigeons), leptospirosis (from rats), leishmaniasis (from dogs/sandflies), and hydatidosis (from dogs) (Kobayashi et al. 2005; Pimentel et al. 2015; Minter et al. 2019; Ribeiro et al. 2019a; Saldanha-Elias et al. 2019; Cociancic et al. 2020; Desvars-Larrive et al. 2020). Increased pathogen and vector densities are often facilitated by poor infrastructure and deficient sanitation of trash and sewage (Bradley and Altizer 2007; Eskew and Olival 2018; Ellwanger et al. 2021). For example, in Brazil, the proliferation of urban-adapted mosquitoes (e.g., *Aedes aegypti*) associated with high human density exacerbated the 2015–2016 Zika epidemic, and increased the circulation of chikungunya, West Nile, dengue, and yellow fever viruses (Lima-Camara 2016; Marcondes and Ximenes 2016; Hotez 2017; Kotsakiozi et al. 2017). One study found infection rates of pigeons by the zoonotic fungus *Cryptococcus neoformans* as high as 100% in many public squares of Porto Alegre (southern Brazil), evidencing a high risk of human infection by this pathogen, especially for immunosuppressed individuals (Reolon et al. 2004).

Another way urban areas can facilitate disease involves alteration of biodiversity patterns (Pongsiri et al. 2009; Everard et al. 2020; Keesing and Ostfeld 2021). Increased species richness has been observed to reduce the pathogen load in reservoirs and vectors, thus protecting human health, a phenomenon known as the dilution effect (Keesing et al. 2006; Lõhmus and Balbus 2015). When biodiverse landscapes are urbanized and species richness and population sizes are reduced, some urban-adapted (synanthropic) animals that more effectively carry zoonotic pathogens may proliferate more easily than non-synanthropic species (McFarlane et al. 2012; Han et al. 2015; Keesing and Ostfeld 2021). In this sense, arthropod vectors, rodents, and other small animals found in urban environments in high number and with reduced biodiversity usually host a higher diversity and load of pathogens, contributing to more transmission of zoonotic infections (Keesing et al. 2006; Ostfeld 2009; Hassell et al. 2017).

In addition to increased spread of common zoonotic diseases, urbanization can facilitate the emergence of new pathogens. The expansion of markets where wild species are easily marketed to the public enables more interactions between wildlife and humans, increasing the probability of new pathogen introduction into humans, such as SARS-CoV-2, the causative agent of COVID-19 (Woo et al. 2006; Lee et al. 2020; Ellwanger and Chies 2021). Further, sprawling urbanization increases urban-wildland interfaces which favors novel interactions among species and can increase spillover risk, including through direct human contact with wildlife (Patz et al. 2004; Bevins et al. 2012; Heylen et al. 2019; Hendy et al. 2020; Sormunen et al. 2020).

Finally, health penalties of urban life, especially in dense cities, include chronic exposure to air, soil, water, thermal, and noise pollutants, crowded living situations, and many other stressors. Stress can increase susceptibility to infections and facilitate the circulation of pathogens in animal populations and between humans and other animals (Bradley and Altizer 2007). As a result, urban residents, especially ones living in poverty and without adequate health care, may be more susceptible to zoonotic diseases (Fig. 1).

Urban health advantages

Despite many urban health penalties, Wood et al. (2017) found that, at a global scale, urbanization has created net positive outcomes for human health, especially through reducing infectious disease burden. Such urban health advantages include more access to education, employment, recreation, medical care, and financial resources, which directly and indirectly enhance health outcomes, including protection from and treatment of zoonotic disease. Cities also facilitate economic and scientific development which benefits public health (Vlahov et al. 2005; Johnson 2006; Segurado et al. 2016; Hotez 2017; Wood et al. 2017). Urbanization can reduce human contact with livestock, wildlife, and their potential pathogens compared to living in rural areas, providing a direct health advantage (Hassell et al. 2017; Eskew and Olival 2018). At the same time, the presence of well-managed biodiversity can benefit human health, including through improvements in immune systems and mental health; access to outdoor recreation; reduction of pollution exposure (e.g., through filtration, retention, and remediation); and biological control of disease vectors by predators (Ostfeld and Holt 2004; Douglas 2012; Mills et al. 2019; Flies et al. 2020; Marselle et al. 2021).

Of course, the health benefits of urban living depend on proper, ongoing maintenance of infrastructure and services, such as clean water provision, sanitation, and, as needed, anthropogenic control of synanthropic disease vectors (Hotez 2017; Ellwanger et al. 2021). Given such advantages, effective urban planning that addresses the tradeoffs of the urban disease ecology paradox can be seen as a form of preventative medicine (*sensu* Corburn 2015) that should be embraced as essential to public health initiatives and related ecological research (Lõhmus and Balbus 2015). For example, programs that focused on preventing disease vectors from entering homes, and campaigns aimed at reducing mosquito breeding sites in residential areas have significantly improved vector-borne disease prevention, limiting undesirable effects of urbanization on human health (Tusting et al. 2017; WHO 2017).

Urban One Health and Ecology with Cities

Effective urban planning is necessary but insufficient for creating healthier urban places and people. Many other factors affect the emergence and spread of pathogens and their vectors, including vaccines, personal hygiene, literacy levels, and public health programs, alongside many biological and ecological factors determining disease dynamics (Acharya et al. 2021; Ellwanger et al. 2021). Thus, in any given urban system, the net health outcomes of the urban disease ecology paradox are modulated by specific combinations and tradeoffs of anthropogenic and environmental variables interacting at multiple scales, from individually owned parcels through cities and entire urbanized regions (Fig. 1) (Douglas 2012; Lõhmus and Balbus 2015; Santiago-Alarcon and MacGregor-Fors 2020; Combs et al. 2022). Given such spatiotemporal and social-ecological complexity, new approaches to better examine and communicate about the interplay of social, technological, biological and environmental variables of the urban disease ecology paradox are needed to help communities and individuals navigate zoonotic disease risk (Douglas 2012; Corburn 2015; Hassell et al. 2017; Combs et al. 2022). Such an integrated strategy characterizes the One Health approach, in which multidisciplinary teams collaborate to understand, prevent, and solve human and wildlife health problems using a complex systems perspective (Cunningham et al. 2017; CDC 2018;

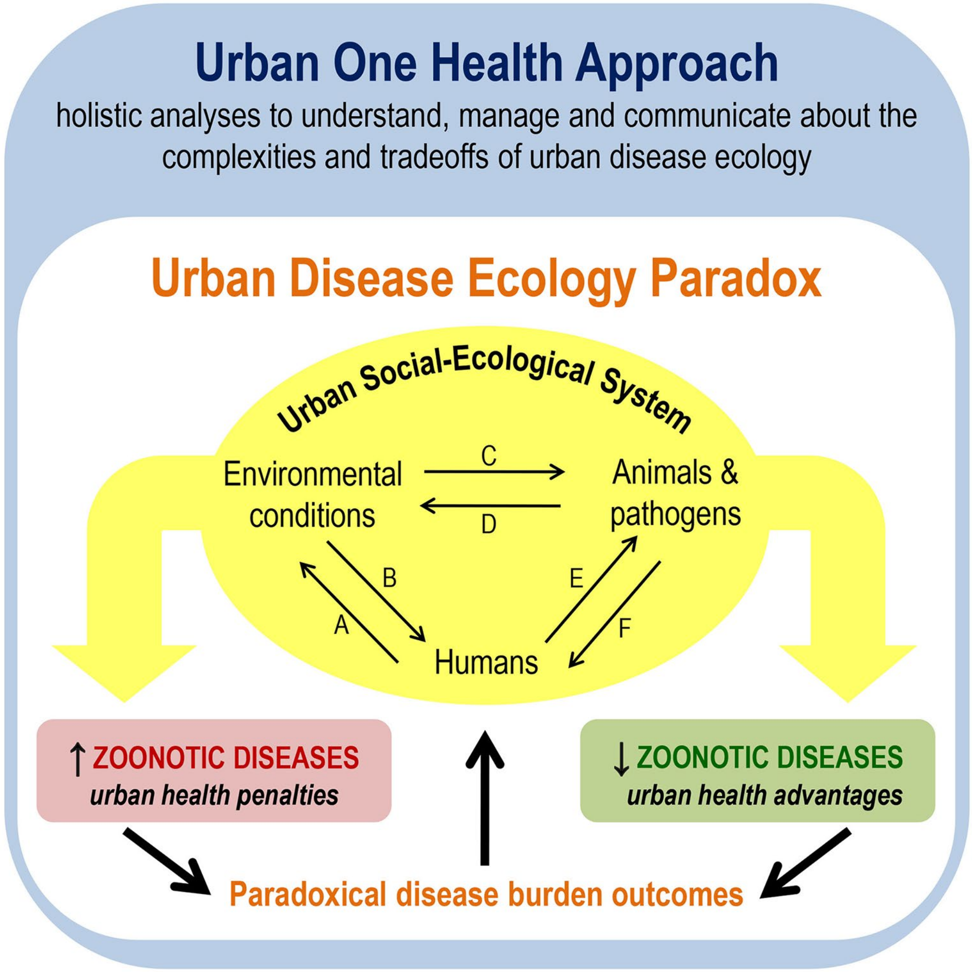

Fig. 1 The paradox of urban disease ecology. Urbanization results in an urban disease ecology paradox by creating characteristics of urban social-ecological systems that both increase and decrease zoonotic disease burden through interactions among environmental, wildlife, pathogen, and human factors. The Urban One Health approach holistically considers this paradox and is therefore necessary to understand and manage infectious diseases in urban places. Key relationships within social-ecological systems to examine include, but are not limited to, the following: (A) human activities associated with urbanization change environmental conditions that directly and indirectly impact (B) environmental effects on human health including through (C) environmental effects on vector and pathogen populations & communities. (D) Ecological variables of animal populations affect environmental conditions such as distribution of and human proximity to pathogen reservoirs. (E) Humans have many direct interactions with animal vectors and pathogens, including management, which affects (F) disease transmission risk

Ellwanger et al. 2020; 2021). This approach can be adapted into an Urban One Health framework (de Leeuw 2020) that specifically considers the multivariate aspects of urban disease ecology introduced above, including unique ecological conditions and diverse socioeconomic factors like equity, governance, and those affecting landscape management behaviors (e.g., Lowe et al. 2019, Evans et al. 2022).

Urban ecologists have a central role to play in advancing basic and applied research for a comprehensive Urban One Health view. For instance, further studies are needed about how abiotic conditions, biodiversity, and landscape patterns affect vector populations and pathogen spread in urban systems, including dilution effect (Keesing and Ostfeld 2021; Johnson et al. 2015b; Combs et al. 2022). Such research is also needed about species not often examined by ecologists such as domesticated livestock and stray dogs (Box 1). Basic ecological investigations can be integrated into epidemiological surveillance, including in urban-wildland interfaces, which is one of the most effective mechanisms for identifying spillover risk and developing response plans such as priorities for vaccination (Halliday et al. 2007; Alirol et al. 2011; Ellwanger and Chies 2018; Ellwanger et al. 2019; Lee et al. 2020).

Urban disease ecology research should be conducted in ways that will allow it to contribute to development of actionable ecological knowledge that informs planning, policymaking, and management (Zhou et al. 2019). For instance, more studies are needed about how well-planned management and restoration of native biodiversity, green spaces, and ecosystem services can contribute to the control

Box 1. Challenges of managing dogs as a public health concern

The role of dogs, both pets and strays, in the transmission of diseases is an especially complex urban health penalty (Deplazes et al. 2011; Saldanha-Elias et al. 2019). Due to the circulation of dogs across diverse environments (green spaces, densely paved urban cores, and peri-urban areas), they contribute to the spillover and spillback of pathogens among rural and urban animals, and humans (Ellwanger and Chies 2019). For example, in Europe dogs and other canids (e.g., European red fox) living in urban-forest interfaces are vectors of canine parvovirus, rabies, *Echinococcus multilocularis*, *Leishmania infantum*, *Giardia duodenalis*, *Babesia canis*, and *Toxoplasma gondii* (Bradley and Altizer 2007; Otranto et al. 2015). In Chile, interactions between domestic dogs and wild foxes created opportunities for pathogen host shifts between these animals, potentially affecting animal health (Hernández et al. 2021). Humans living in proximity to these animals can also be affected if the pathogen involved in the spillover event has zoonotic potential (Ellwanger and Chies 2021). Management of stray dogs is challenging due to the unpopularity of euthanasia, difficulty of sterilization, continuous births, and pet abandonment (Amaku et al. 2010). Adopting the Urban One Health approach can help because it emphasizes disease prevention through multiple means including expanded vaccination of people and dogs; more coordination among government agencies and stakeholders; enhanced surveillance; and expanded public outreach and education programs (Cunningham et al. 2017; Acharya et al. 2021). Further, public policies focused on the control of stray domesticated animals and the provision of veterinary services for them are also fundamental to mitigate urban zoonotic diseases (Otranto et al. 2017).

Box 2. Managing urban mosquitoes

In addition to green spaces, urban blue spaces provide habitats for disease vectors and pathogens, including *Ae. aegypti* mosquitoes, a species with diverse synanthropic niches (Lõhmus and Balbus 2015; Valle 2016). Given insecticide related-problems of toxicity to humans and emergence of resistance, integrated pest management (IPM) is an important Urban One Health strategy because of its emphasis on alternatives to chemical control of disease vectors; however, urban IPM faces many challenges because of limited actionable urban ecological knowledge and diverse, sometimes conflicting stakeholder knowledge and priorities (Lowe et al. 2019). For example, appropriate management of mosquito breeding sites requires reducing the amount and number of plant species that contribute to the proliferation of mosquito larvae in ponds, some of which may be desired for aesthetic or functional reasons (e.g., bromeliads, bamboo) (Medeiros-Sousa et al. 2015; Zhao et al. 2020). Ecologists must collaborate with government authorities and other stakeholders to study such details of urban mosquito ecology, and develop plans for removing and managing breeding sites found in both public areas and private property, including in garbage, bird baths, and ornamental ponds (Augusto et al. 2016; Valle 2016; Valle et al. 2016). Further, to reduce health risks to human and non-target animal populations, investment in developing less toxic pesticides, especially plant-based ovicides and larvicides, will be especially beneficial for residential and urban areas, alongside more geographically targeted, rather than broad-scale, applications (Benelli et al. 2016). Community-wide adoption of healthier, more sustainable mosquito management will require holistic public education programs that identify common misunderstandings about vector ecology—for instance, that mosquito abundance will increase if lawns are not mowed often enough (Yang et al. 2019)—and develop targeted messages based on public lay knowledge, concerns, and everyday experiences (Biehler et al. 2019; Evans et al. 2022).

of zoonotic species (Lõhmus and Balbus 2015; Box 2). For example, the risk of contracting Lyme disease in urban green spaces can be reduced by removing invasive plant species (e.g., *Berberis thunbergii* - Japanese barberry) that benefit ticks and their hosts (Reaser et al. 2021).

For such work, we advocate an Ecology with Cities approach in which scientists form partnerships with diverse stakeholders to develop research questions, collect data, and implement evidence-based solutions (Byrne 2022). Collaboration is particularly important to the Urban One Health approach that integrates many complex sociocultural variables that impact disease. For instance, because inadequate sanitation systems and urban wildlife (wet) markets generate significant risks for zoonotic disease spread, understanding their dynamics is as crucial to the study and management of urban disease ecology as basic vector population data (Woo et al. 2006; Prüss-Ustün et al. 2014; Ellwanger et al. 2021). For such variables, both Urban One Health and Ecology with Cities approaches must be cooperatively and democratically linked to people's daily lives (i.e., through translational ecology) to encourage pro-health actions such as supporting government projects, political candidates, and community health and environmental organizations that are aligned with beneficial environmental health outcomes, and participating in disease prevention mitigation actions such as urban cleaning and landscape improvements (e.g., trash pick up and tree planting) (Ellwanger et al. 2021; Gruetzmacher et al. 2021; Yuan et al. 2021). As emphasized by Yuan et al. (2021), "There is no public health without the support of the community" (p. 14). As such, the only way that urban ecologists will be able to fully translate urban ecological knowledge into practical and effective public health solutions is by seeking partnerships with urban residents, social scientists, policy makers, public health organizations, and many others. Gruetzmacher et al.'s (2021) conclusion about more intentionally linking human health to environmental conditions applies well to pursuing such partnerships: "The time to act is now" (p. 1).

To support community awareness and engagement, the Ecology with Cities view emphasizes stronger education and public outreach programs as crucial for advancing ecologically-based solutions to societal problems (Byrne

2022). Thus, linking this view with Urban One Health points to a role for urban ecologists in educating diverse audiences about urban disease ecology and creating novel teaching and outreach materials and methods. Brewer et al. (2008) provide a compelling argument for the value and content of such education, and Pasari's (2016) teaching activity about Lyme disease exemplifies an engaging lesson to help students develop knowledge and skills relevant to the complexity of disease dynamics. Further, citizen and community science programs (Cooper et al. 2021) can contribute to both urban health research and education in many ways. Diverse urban and disease-focused initiatives have been effective in increasing people's involvement in the monitoring of biodiversity and animal behavior (Roger and Motion 2022), wildlife health risks (Chame et al. 2019), and infectious diseases (Lawson et al. 2015; Curtis-Robles et al. 2015; Bartumeus et al. 2018; Hamer et al. 2018; Gardiner and Roy 2022). Investing in such learner- and community-centered education and research programs is crucial to helping people understand the complexity of urban disease ecology, including its paradoxical nature, and enabling them to better consider, appreciate and use relevant Urban One Health solutions for managing vectors and pathogens (Gruetzmacher et al. 2021).

Conclusions

Urbanization aggregates diverse social and environmental characteristics that facilitate the emergence and spread of zoonotic diseases. At the same time, aspects of urban living offer advantages to human health. The contradictory outcomes create what we have called the urban disease ecology paradox (Fig. 1). Understanding and responding to this paradox can be facilitated by an Urban One Health approach, which should be considered foundational for urban planning and public health research and programs. The paradoxical advantages and disadvantages of urban living are generally not distributed evenly across urban systems and even within distinct regions of the same city, especially in developing countries (Bowser and Cid 2020). Less wealthy people, especially the homeless and those living in slums, can mostly experience urban health disadvantages while people living in wealthier areas can predominantly experience the advantages (Stephens 1996). Through research, urban ecologists and other scholars can advance environmental justice outcomes by examining how ecological aspects of urban planning can help reduce urban health inequalities and promote more equitable access to the health advantages provided by urban environments (Corburn 2015; Bowser and Cid 2020).

In particular, urban ecologists have an important role in advancing the study, management, communication and education about urban zoonotic disease ecology, all of which are needed to achieve sustainable public health outcomes for all people (LaDeau et al. 2015; Hassell et al. 2017; Eskew and Olival 2018; Lowe et al. 2019; Combs et al. 2022), especially those in understudied tropical and developing regions (Lindahl and Magnusson 2020). We propose that Urban One Health and Ecology with Cities provide helpful terms and frameworks for such holistic and collaborative work, especially as needed for robust educational and citizen science programs. In this short essay, we can only introduce and roughly sketch the outlines of these perspectives. Future work is needed to enlarge their scope and deepen their synthesis, including through integrating issues not considered here, addressing challenges and limitations (Box 3), and distilling insights from case studies to guide future work. We encourage urban scholars and practitioners from all disciplines, careers, and organizational affiliations to investigate the urban disease ecology paradox through actionable science and apply ecological knowledge to more effectively manage the tradeoffs of its health advantages and penalties. It is only through multi-disciplinary partnerships and

Box 3. Limitations and Challenges to Synthesis and Application

Synthesizing Urban One Health and Ecology with Cities approaches can be challenging for many reasons. The One Health approach is originally derived from the integration of veterinary and human medicine (Destoumieux-Garzón et al. 2018), and still suffers from epistemological hierarchies and segregation of disciplines, especially regarding inadequate consideration of ecological dimensions (Manlove et al. 2016). Ecology with Cites is a recently articulated perspective that similarly requires further development to more thoroughly couple ecological with diverse sociocultural concepts and methods (Byrne 2022). Further, for both approaches, a major challenge is to translate integration of disciplines into practical actions. For example, recruiting professionals from different disciplines can be logistically challenging when performing studies addressing zoonotic diseases or carrying out environmental education initiatives with communities. Financial limitations, lack of awareness regarding One Health, and insufficient institutional support for multidisciplinary work are some factors that aggravate these issues (Ribeiro et al. 2019b). Operationalizing and translating the Urban One Health approach into policies focused on public health and environmental conservation are also important challenges (Lee and Brumme 2013). When trying to engage urban residents, citizen and community science programs may suffer from participation inequality that reproduces existing social, economic, and education inequalities (Blake et al. 2020). Further discussion of these issues and evaluation of the successes and failures of practical experiences involving Urban One Health and Ecology with Cities can contribute to overcoming these limitations. Finally, greater receptivity from journals to interdisciplinary and practical studies alongside more grants for interdisciplinary, collaborative research may also encourage projects that seek to synthesize and apply these two perspectives (Manlove et al. 2016).

practical solutions that the Urban One Health and Ecology with Cities approaches will enable urban societies to tackle challenges of the urban health paradox and create more sustainable, health-promoting social-ecological systems.

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Declarations

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