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Forum

Navigating the urban landscape: Integrating animal movement ecology with the One Health framework to better understand urban ecosystems

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Abstract

The expansion of urban areas and anthropogenic activities have intensified human–wildlife interactions, increasing zoonotic disease emergence and transmission. Understanding factors influencing urban wildlife movement and their interactions with humans is critical for addressing disease transmission. We examine factors driving zoonotic risks in urban ecosystems, emphasizing the human–wildlife interactions, and suggest their integration into a One Health framework. Urban environments facilitate contact with wildlife reservoirs of zoonotic pathogens such as rabies, Lyme disease, and SARS-CoV-2. Factors such as green spaces, altered wildlife behavior, and human mobility amplify disease spillover risks. We emphasize applying movement ecology concepts, particularly for understanding how animals and humans navigate and use urban spaces to identify hotspots interaction and inform management strategies. Despite advancements, challenges such as data standardization and limited interdisciplinary collaboration persist. We advocate for an integrative approach combining animal movement ecology, human mobility, and public health to foster coexistence and safeguard human health.

Keywords: animal movement, human mobility, human–wildlife conflict, urban wildlife, zoonotic disease

Urbanization is a global phenomenon, with over half of the world's population living in urban areas and an urban population projected to reach nearly 70% by 2050 (UN 2018). Although urbanization has brought significant advancements in infrastructure, healthcare, and technology, it also presents new challenges, particularly in zoonotic disease emergence from human–wildlife interactions (Jones et al. 2008, Neiderud 2015, Hassel et al. 2017). Rapid and often unplanned urban growth alters landscapes, creating new ecological niches and intensifying interactions between humans and animals (Esbah et al. 2005, Soulsbury and White 2015, Parsons et al. 2019). Simultaneously, urban settings often provide abundant resources including food and other waste, which attract synanthropic species—animals adapted to live near humans such as rodents, bats, birds, and ungulates (Park and Cristinacce 2006, Newsome and Van Eeden 2017, Shukla and Wilmers 2024). These species are known reservoirs of zoonotic pathogens, including viruses such as rabies, hantavirus, and coronaviruses, and their frequent interaction with humans creates transmission pathways for zoonotic emerging infectious diseases (EIDs; White and Razgour 2020, Bonilla-Aldana et al. 2021).

Ecological disruptions, such as habitat fragmentation, supplemental resource provisioning, and altered species distributions, drive 70% of EIDs originating in wildlife (Brema et al. 2022, Goldstein et al. 2022). For example, food animal husbandry and deforestation in urban fringes has been linked to the spillover of pathogens such as the Nipah virus, which is transmitted from bats to humans (Jones et al. 2017). Similarly, encroachment of urban settlements into forested areas has been associated with increased mosquito exposure and yellow fever outbreaks in South America (Ortiz et al. 2021). As humans encroach on natural habitats, the frequency and intensity of contact between wildlife and humans increases, creating conditions for the transmission of novel pathogens. These diseases not only have devastating consequences for global health but also strain healthcare systems and impede socioeconomic progress (Cascio et al. 2011, Di Bari et al. 2023). Furthermore, the presence of multiple hosts and vectors in urban ecosystems can lead to pathogen spillover. For example, species such as white-tailed deer (*Odocoileus virginianus*) play a significant role in interspecies disease transmission and the spread of antimicrobial-resistant bacteria in urban landscapes (Wilkins et al. 2008, Ward and Smith 2012, Lavelle et al. 2016, Lindsay et al. 2018, Muller et al. 2022). Their population expansion across America, coupled with their proximity to urban and suburban areas, has raised concerns about spillover of diseases such as Lyme disease, chronic wasting disease, and SARS-CoV-2 (VanAcker et al. 2019, Chandler et al. 2021, Hale et al. 2022).

Urbanization often leads to increased human to human contact (crowding), which can facilitate the spread of zoonotic disease in urban ecosystems (Esposito et al. 2023). Respiratory virus transmission, such as of influenza and COVID-19, are more directly linked to human interactions and movement, making mobility a primary determinant of disease spread (Eum and Yoo 2022). Human movement into undeveloped areas can alter animal behaviors, leading to increased contact between animals and humans, and can facilitate spillover of wildlife pathogens into human hosts (Ditchkof et al. 2006, Slabbekoorn and den Boer-Visser

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2006, Levey et al. 2009, Stoddard et al. 2009). Urbanization also introduces novel host species that can promote the emergence of zoonotic pathogens (Hassell et al. 2017). For example, free-ranging marmosets and feral cats have been linked to the transmission of diseases such as toxoplasmosis and other zoonotic infections (Oliveira et al. 2022, Sousa 2023).

Despite the growing recognition of the link between urbanization and zoonotic diseases, significant gaps remain in our understanding of human–wildlife interactions in urban environments. Although rural zoonotic spillover events have been studied extensively (Daszak et al. 2000, Keesing et al. 2010, Rhyan and Spraker 2010), the unique, complex dynamics of urban ecosystems are not well understood. The transmission of zoonotic diseases through human movement and wildlife interactions in urban areas is a multifaceted issue that requires a comprehensive understanding of ecological dynamics, human behavior, and effective management strategies. Therefore, the use of movement ecology tools such as high-resolution tracking (Craft et al. 2011, Lee et al. 2020, Pruvot et al. 2020, Rambhatla et al. 2022, Zhang et al. 2024) and network analyses (Emch et al. 2012, White et al. 2018, Desvars-Larrive et al. 2024) is crucial for modeling potential disease spread and understanding the behavioral underpinnings of transmission. Movement data can reveal patterns of shared space use and interactions, which are critical for identifying areas where disease transmission is likely intensified. In addition, the One Health approach coupled with multisourced data can provide a better understanding of zoonotic disease transmission in urban areas to manage and reduce risk. One Health recognizes the interconnectedness of human, animal, and environmental health (Singh et al. 2024), emphasizing the need for integrated and interdisciplinary strategies. By addressing the factors that contribute to zoonotic disease emergence and transmission, stakeholders can work toward reducing the risks associated with urban wildlife interactions and protecting public health.

In the present article, we highlight the integration of movement ecology tools with the One Health framework to better manage and mitigate coupled human–wildlife systems in urban ecosystems. To support this, we propose a framework for understanding human–wildlife interactions in urban ecosystems that integrates fine-scale movement data, socioenvironmental conditions, and human activity dynamics. By contextualizing interactions through this framework, we contribute to the One Health paradigm by providing a systematic approach to addressing the interconnected health of humans, animals, and ecosystems in urbanized landscapes.

Human–wildlife interactions in urban ecosystem

Human–wildlife interactions in urban ecosystems have become increasingly significant as urbanization expands globally (Elmqvist et al. 2016, Wierucka et al. 2023). Urban expansion transforms natural habitats into fragmented landscapes, creating zones where human and wildlife activities overlap. The availability of green spaces plays a critical role in facilitating the interactions between humans and wildlife. These spaces, which include parks, gardens, and natural habitats, serve not only as recreational areas for urban residents but also as vital habitats for various species (Swanwick et al. 2003), creating potential hotspots for human–wildlife encounters. The dynamics of human movement within these green spaces significantly influence wildlife behavior and space use, leading to increased potential interactions.

Research indicates that urban wildlife can adapt their behaviors in response to human activity patterns, often as a strategy to minimize direct interactions. For example, lower bat activity has been documented on weekends, when human presence is heightened (Li et al. 2020). Urbanization can also lead to changes in daily activity patterns of carnivores, making them more nocturnal to avoids humans (Gallo et al. 2022). Similar adjustments are seen in prey species through changes in predator avoidance behaviors, which can have cascading effects on local ecosystems (Gallo et al. 2019). Species such as raccoons (*Procyon lotor*), coyotes (*Canis latrans*), and rhesus macaques (*Macaca mulatta*) have showed behavioral flexibility in urban environments, modifying their activity and foraging patterns in response to human movements and the availability of anthropogenic food sources (Bateman and Fleming 2012, Bindhani et al. 2025). This adaptability is essential for wildlife survival in increasingly human-dominated landscapes (Hume et al. 2019).

However, behavioral adaptations do not always reduce human–wildlife interactions and can lead to greater spatiotemporal overlap with humans, thereby increasing the potential for interaction. The availability of anthropogenic food sources and intentional or unintentional feeding can also drive wildlife to frequent human spaces (Schulte-Hostedde et al. 2018). Human-provided food can create dependencies, altering natural foraging strategies and significantly increasing the rate of human–wildlife interactions (Sha and Hanya 2013). For example, chacma baboons (*Papio ursinus*) in South Africa, scavenge human food in suburban areas, resulting in closer and more frequent proximity to people (Fehlmann et al. 2017). Therefore, although behavioral flexibility can help wildlife navigate urban environments, it can simultaneously increase opportunities for conflict or close encounters with humans.

The shared urban environment fosters interactions that can be categorized as direct and indirect types, each with unique implications for public health**.** Direct interactions occur when physical proximity brings humans and wildlife into contact (figure 1). Such interactions are often observed in urban parks, gardens, and within backyards or inside homes, where species such as deer, raccoons, rodents, birds, and urban primates such as macaques and baboons, exploit resources within human-modified habitats (Goddard et al. 2010, Fehlmann et al. 2017, Bindhani et al. 2025). Indirect interactions occur through an intermediary such as livestock or domestic pets or through contaminated water, soil, or air (figure 1; Bosco-Lauth et al. 2021, Clarke et al. 2022). Both direct and indirect human–wildlife interactions increase the risk of potential zoonotic disease transmission, particularly in densely populated urban environments, where pathogens can spread rapidly (Santiago-Alarcon and MacGregor-Fors 2020).

From a broader perspective, human–wildlife interactions in urban ecosystems are shaped by behavioral changes in both humans and animals (figure 1). As we've described, wildlife often alter their foraging strategies (Ciuti et al. 2012, Fehlmann et al. 2021), movement patterns (Doherty et al. 2021, Habib et al. 2021), and reproductive behaviors (Zuberogoitia et al. 2008, French et al. 2011) in response to urban pressures and increased human activity. Similarly, humans also modify their behaviors to navigate shared spaces with wildlife. For example, urban residents may adjust their daily routines to avoid areas known for frequent wildlife activity (Lischka et al. 2020), implement wildlife-proofing measures such as securing garbage bins or installing fencing to deter animals (Baruch-Mordo et al. 2011), and alter recreational practices by keeping dogs on leashes or avoiding certain parks during periods of high wildlife use (Schell et al. 2021, Larson et al. 2016). In addition, some communities adopt proactive coexistence strategies, including community-based education initiatives and participatory monitoring programs to reduce conflict (Pooley et al. 2017, Young et al. 2021). These mutual behavioral adjustments under-

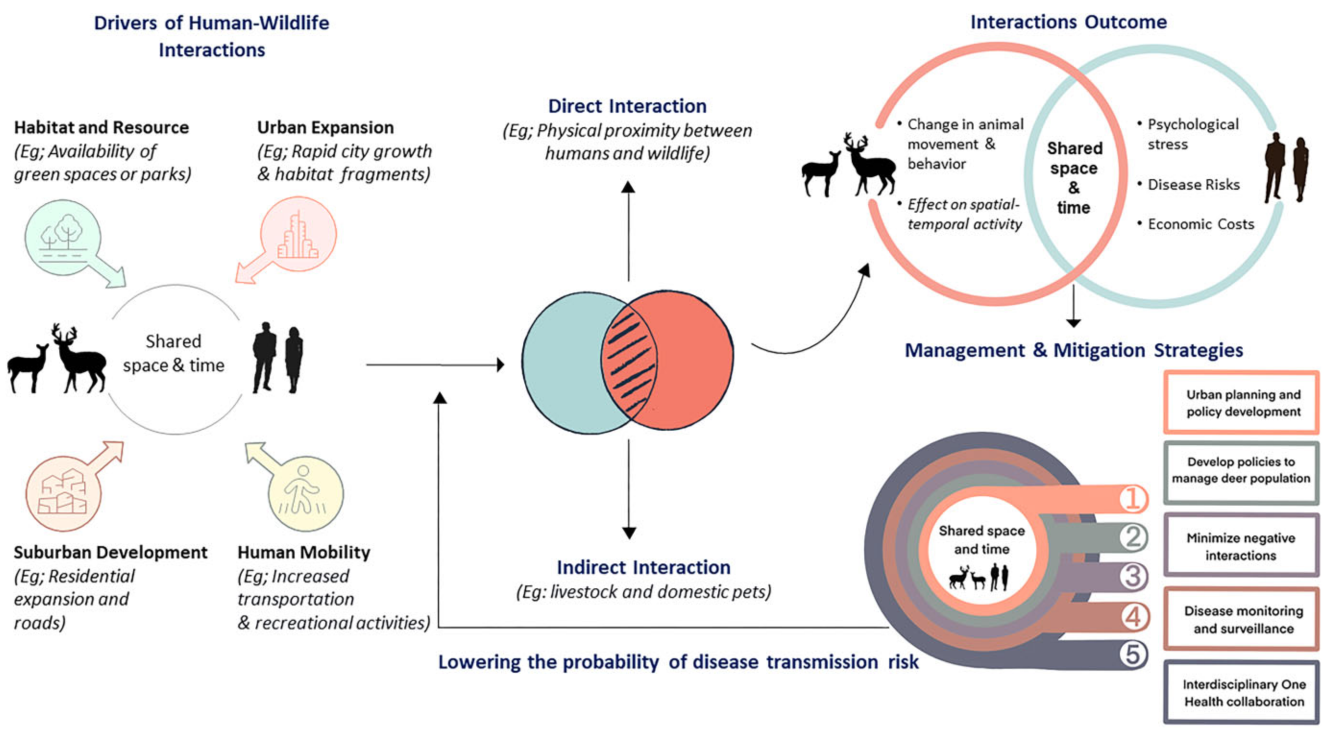

Figure 1. A conceptual representation of coupled human–wildlife systems. Little is known about what drives human–wildlife interactions in urban ecosystems. Integrating human and animal behaviors more explicitly into One Health research will improve management and mitigation strategies that can reduce negative interactions between humans and wildlife.

score the coupled dynamics of human and natural systems in urban environments.

Building on this understanding, examining the spatial and temporal dimensions of human–wildlife interactions becomes critical for developing effective mitigation and management strategies. Recognizing when and where spatial and temporal overlaps occur between human and wildlife can inform measures such as targeted habitat management, the design of wildlife corridors, and strategic urban landscaping to minimize conflict, thereby minimizing the risk of zoonotic disease transmission. Moreover, public education and awareness campaigns can also play a significant role in promoting responsible human behaviors, such as avoiding the feeding of wild animals, securing waste, and appreciating the ecological and cultural ecosystem services provided by urban wildlife. Together, these approaches reflect the intricate, bidirectional relationships between shared space use, animal movement, and human behavioral adaptation in increasingly urbanized landscapes.

Urban human–wildlife interactions as a driver of zoonotic disease transmission

The risk of zoonotic disease transmission is highest for humans who come into frequent contact with wildlife, either directly or indirectly, a phenomenon that is increasingly prevalent in urban ecosystems because of high human population densities. Urban ecosystems create numerous opportunities for human–wildlife interactions that can facilitate potential pathogen transmission. Species that successfully adapt to urban environments, known as *urban exploiters*, often thrive in human-modified landscapes, thereby intensifying their interactions with people (Murray and Daszak 2023). For example, urban rodents (*Rattus* spp.) thrive in unsanitary conditions, acting as reservoirs for diseases such as leptospirosis and hantavirus and facilitating transmission through direct or indirect contact with humans (Himsworth et al. 2014, Hassell et al. 2017). Similarly, bats roosting in buildings and trees in urban settings have been implicated in the spread of rabies (Schatz et al. 2013) and coronaviruses (Plowright et al. 2015a), with evidence suggesting that urban-induced stress may elevate viral shedding (Kessler et al. 2018). In addition, urban wildlife movement between fragmented habitat patches and through urban development increases spatiotemporal overlap with humans, enhancing pathogen transmission risk (Jung and Threlfall 2018, Parsons et al. 2020).

Beyond these encounters, human movement itself plays a critical role in shaping zoonotic transmission dynamics. Increased mobility across outdoor spaces via transportation networks and recreational activities (McDonald et al. 2008, Kasana 2020) results in more frequent and sustained overlap with urban wildlife (Bateman and Fleming 2012, Magle et al. 2012). As direct and indirect encounters increase, understanding the ecological (e.g., space use) and behavioral (e.g., movement patterns) drivers of human–wildlife interactions becomes essential for mitigating EID risks in urban settings. Meeting this challenge requires an integrated approach that links patterns of human and wildlife movement to identify and predict potential zones of contact.

Although major zoonotic events such as the emergence of HIV/AIDS (Sharp and Hahn 2011), H5N1 avian influenza (Peacock et al. 2024), and SARS-CoV-2 (Mahdy et al. 2020, Gryseels et al. 2021) were not strictly urban in origin, the same factors that are characteristic of urbanization played a crucial role in amplifying the spread of those pathogens namely high human population densities, wildlife markets, and rapid global connectivity. Urban wet markets, such as those linked to SARS outbreaks, have been identified as key interfaces for cross-species pathogen transmission (Webster 2004, Woo et al. 2009). Furthermore, periurban areas, where rural and urban landscapes merge, are particularly vulnerable to zoonotic spillover. These transitional landscapes often feature fragmented habitats and mixed land use that support diverse assemblages of wildlife, domestic animals, and humans, with domestic animals frequently acting as bridging hosts (McKinney 2002, Bradley and Altizer 2007, Mackenstedt et al. 2015). For example, research from Brazil demonstrates that periurban expansion increases the risk of yellow fever virus spillover from nonhuman primates to humans via mosquito vectors (de Thoisy et al. 2020). Similarly, suburbanization in North America has been associated with rising Lyme disease incidence because of changes in deer and rodent movement patterns and population densities, which increase the risk of tick exposure (Kilpatrick et al. 2017).

Urban green spaces, including parks, community gardens, and urban forests, further increase the risk of disease transmission between humans and wildlife. Although these spaces provide essential habitat for wildlife and important recreational opportunities for humans, they also increase the likelihood of direct and indirect contact with zoonotic reservoirs (Goddard et al. 2010, Murray and Daszak 2013). For example, suburban white-tailed deer (*Odocoileus virginianus*) often inhabit urban green spaces, and human activities such as jogging, dog walking, and recreation use of these areas create opportunities for pathogen exposure through ticks carried by deer, the primary vectors of Lyme disease (Kilpatrick et al. 2014, Swei et al. 2020).

Furthermore, anthropogenic activities such as supplemental wildlife feeding, ineffective waste management, urban farming, and pet ownership further create direct and indirect contact points for disease transmission (Hassell et al. 2017, Santiago-Alarcon and MacGregor-Fors 2020). For example, poorly managed household waste serves as an attractant for synanthropic species, such as rats and raccoons, which carry pathogens, such as leptospirosis and hantavirus (WHO 2022, MDPI 2023).

Domesticated animals, such as cats and dogs, further complicate these dynamics by serving as intermediaries for zoonotic diseases. For example, domesticated dogs often play a significant role in the transmission of rabies in urban areas, particularly highlighting how limited veterinary care, underfunded vaccination programs, and large free-roaming dog populations often tied to socioeconomic constraints contribute to disease persistence (WHO 2012, Hampson et al. 2015). Collectively, these overlapping ecological, anthropogenic, and socioeconomic factors underscore the complexity of transmission pathways within urban ecosystems, where wildlife, domestic animals, and human behavior interact to drive emerging public health risks.

Human and wildlife movement in disease epidemiology

The combination of increased spatiotemporal overlap, high human population densities, and changing animal movement patterns has escalated the risk of zoonotic disease transmission in urban environments. For example, urbanization promotes high human mobility through dense transportation networks, commuting, and recreational activities, enabling human-to-human spread of pathogens rapidly across regions (Hassell et al. 2017). Furthermore, urban populations collectively generate more frequent movements across diverse land use types because of their size and density (Gonzalez et al. 2008, Wesolowski et al. 2012). As a result, increased human use of urban green spaces, such as hiking trails, parks, and community gardens, fosters frequent opportunities for direct and indirect interaction with wildlife (Kays et al. 2017, Huddart and Stott 2019). Simultaneously, a shift in animal movement patterns within fragmented urban landscapes creates dynamics human–wildlife interfaces that further influences zoonotic disease risk.

Given these complex and overlapping drivers of contact, addressing the challenges of zoonotic disease transmission in urban ecosystems requires an integrated approach that explicitly considers the coupled human–wildlife system. Integrating movement analyses into disease research offers transformative potential for understanding the complex interplay between human and animal behaviors via direct and indirect interactions between hosts and pathogens. Movement ecology, which examines spatial and temporal patterns of movement, is increasingly being linked with disease ecology to refine predictive models and enhance disease management strategies (Jeltsch et al. 2013, Dougherty et al. 2018, Wilber et al. 2022). Technological advancements (table 1), such as GPS telemetry, proximity sensors, and accelerometry have enabled researchers to track individual animals with high precision, thereby providing insight into spatial overlap, resource use, and contact rates (Kays et al. 2015). These methods have been applied to predict potential transmission risks in systems ranging from anthrax in zebras, where seasonal movement shifts modulate exposure, to rabies dynamics in carnivores, where contact frequency drives transmission (Plowright et al. 2015b). Movement analyses can also help to distinguish between direct transmission, which is dependent on close contact among hosts, and indirect transmission, which involves pathogen exposure through shared environmental reservoirs (Altizer et al. 2011). For example, anthrax risk maps have been generated by integrating movement data with environmental variables such as soil quality and water availability, revealing how spatial overlap influences exposure (Fisher et al. 2012). Studies have also used movement parameters to detect behavioral shifts, such as reduced mobility in wolves affected by sarcoptic mange, which not only indicate infection but also influence transmission dynamics by altering host–pathogen contact rates (Cross et al. 2016).

Recognizing the value of this integrated perspective, we adopt a conceptual framework rooted in the coupled human and natural systems paradigm (e.g., Morzillo et al. 2014) to enhance One Health approaches by explicitly linking human and wildlife movement, behavior, and contact rates to zoonotic disease risk. To illustrate this approach, we propose a conceptual model applying the framework to urban deer populations, highlighting how spatial overlap in green spaces, human recreational activities, and wildlife foraging behaviors create dynamic contact zones that facilitate potential pathogen spillover (figure 1). By identifying and modeling these high-risk interfaces, urban disease surveillance and intervention strategies can be better targeted to mitigate emerging public health threats.

Extending this integration further, recent advancements in human mobility data (table 1) provide powerful new tools for zoonotic disease research. Big data sources, including cellular phone locations, GPS tracking, and social media feeds, have revolutionized the field of human mobility, enabling researchers to analyze human movements at unprecedented spatial and temporal resolutions (Demsar et al. 2015, Miller et al. 2019). For instance, mobile phone data have been used to predict dengue outbreaks in Brazil and malaria persistence in sub-Saharan Africa, showcasing the potential of such data for real-time disease monitoring and prevention (Bomfim et al. 2020, Mbunge et al. 2021). Critically, understanding how humans move through and interact with environments occupied by wildlife, particularly in areas

Table 1. Summary of movement tracking technologies, data types, applications in disease ecology, and definitions.

Technology	Data type	Applications in disease ecology	Definition
GPS telemetry	Spatial location, movement trajectories	Tracks animal movement, identifies home ranges, predicts contact points for zoonotic spillover	A method of tracking animals using GPS units to record spatial coordinates over time, often used to study large-scale movement patterns.
Accelerometry	Movement intensity, activity levels	Analyzes behavioral patterns, detects mobility changes in response to disease	A technique that records movement activity through accelerometers, often attached to animals to measure acceleration and orientation.
Proximity sensors	Contact frequency, location proximity	Determines when animals come into contact with humans or other wildlife, aiding in disease transmission studies	Sensors that detect proximity between animals or between animals and other species, providing data on interaction rates and contact zones.
Biologging	Continuous movement data, physiological data	Provides in-depth insight into animal behavior, stress response, and disease exposure risk	A technique for attaching small devices to animals to record not only location but also environmental factors such as temperature, light, and physiological states.
Mobile phone Data	Human movement, spatial trajectories	Helps track human mobility patterns, predict potential zoonotic disease spread through human activity	Uses data from mobile phone apps to analyze human movement, often for epidemiological purposes in tracking disease spread in urban areas.
Social media data	Human location, social interaction patterns	Identifies hotspots for human–wildlife interactions, informs targeted disease prevention efforts	Analyzes human interactions and locations shared on social media platforms, useful in mapping areas of potential high-risk human–wildlife encounters.

of high vector presence can inform public health interventions such as targeted education campaigns or vaccination strategies (Kraemer et al. 2019a). Therefore, integrating animal and human movement data provides a system-based approach for zoonotic disease mitigation, identifying overlapping risk areas, and informing urban planning decisions.

Despite these promising developments, several challenges remain in integrating movement ecology into zoonotic disease models. Key challenges include the granularity of available data, computational complexity of analyzing large multispecies data sets, and the need for interdisciplinary collaboration across ecology, epidemiology, public health, and urban planning (Kays et al. 2015). Addressing these challenges will require standardized data collection protocols, open-access repositories, and recent technological innovation. Emerging tools, such as biologging and AI-powered analytics are helping to overcome these barriers by enabling more sophisticated analyses of complex movement and disease data sets (Pruvot et al. 2020, Dougherty et al. 2022, Nathan et al. 2022). Together, these advancements pave the way for a more predictive and preventive approach to managing potential zoonotic disease risks in an increasingly urbanized world.

Case study: White-tailed deer at the urban–wild interface

White-tailed deer are among the most adaptable large mammals in North America and can thrive in diverse environments, ranging from rural forests to densely populated urban areas (Hewitt 2011). This adaptability is supported by their flexible habitat preferences, resource use, and behavioral flexibility (Roden-Reynolds et al. 2022, Ellison et al. 2024). In urban environments, they primarily use parks, residential gardens, and other green spaces that provide cover and foraging opportunities (Kilpatrick and LaBonte 2007, Walter et al. 2009, Potapov et al. 2014, Radeloff et al. 2018). These green spaces, often interspersed with residential and commercial properties, allow them to navigate human-dominated landscapes relatively easily (Stephens et al. 2024).

Their resource use is driven by the availability of ornamental plants, supplemental feeding by humans, and abundant vegetation, which, together, ensure a year-round food supply (Grund et al. 2002, Ward and William 2020) and encourage their presence close to human dwellings (Urbanek et al. 2011). Behaviorally, deer in urban areas exhibit smaller home ranges and higher site fidelity than their rural counterparts, reflecting the spatial constraints of urban settings and reduced need for extensive movement because of resource availability (Etter et al. 2002, Orange et al. 2021). Seasonal variations in movement patterns also align with the changes in resource distribution and human activity. Deer often move into residential areas during winter, exploiting easily accessible food sources and finding shelter in less disturbed patches of urban vegetation (Roden-Reynolds et al. 2022).

Human–deer interactions in urban ecosystems are complex, and deer's movement into residential areas increases the likelihood of those interactions, posing significant public health risks. They play a critical role in the ecology of zoonotic diseases, particularly as hosts for ticks that transmit pathogens, such as *Borrelia burgdorferi* and *Anaplasma phagocytophilum* (Kilpatrick et al. 2014, Stafford and Williams 2017). Urban areas in the northeastern United States, including suburban Connecticut and New York, have reported higher tick densities and Lyme disease incidences associated with deer presence in residential neighborhoods (Cromley 2019). They have also been identified as reservoirs for *Neospora caninum*, a protozoan that causes abortions in cattle, and *Mycobacterium bovis*, which is linked to bovine tuberculosis at wildlife–livestock interfaces (Roden-Reynolds et al. 2022, Stephens et al. 2024). In addition, their proximity to agricultural areas can facilitate the transmission of *Escherichia coli* O157:H7, a bacterium with serious implications for foodborne illnesses, particularly when deer forage near crops (Fischer et al. 2001). Their adaptability to urban and suburban landscapes amplifies these risks, highlighting the need for integrated management strategies that address habitat use, movement patterns, and zoonotic disease dynamics to mitigate human health risks.

Until recently, deer have been limited in direct transmission of pathogens that can be transmitted to humans, with high public health risks. However, the emergence of SARS-CoV-2 in wildlife has shifted this paradigm. White-tailed deer have been found infected with SARS-CoV-2 across multiple US states, with evidence suggesting possible deer-to-human transmission (Chandler et al. 2021, Palmer et al. 2021, Hale et al. 2022, Kuchipudi et al. 2022, Feng et al. 2023). This highlights the role of the deer as a potential wildlife reservoir, which could complicate efforts to control the spread of the virus and reintroduce risks to humans or other animals. Therefore, epidemiology at the deer–human interface has become an increasingly significant area of research, particularly owing to the increase in zoonotic diseases that spill over from wildlife to humans. Given these emerging risks, effective urban deer management requires an integrated approach that combines habitat manipulation (Nielsen et al. 2003), targeted seasonal interventions (McKinney 2006, Gorham and Porter 2011), and population control (McAninch and Parker 1991). Moreover, managing human–deer interactions requires a comprehensive understanding of human movement and deer behavior to better identify when and where potential interactions might occur and the drivers that promote them (figure 1). Urban deer studies have shown that mapping human recreation activities (e.g., trail use in forest preserves) against deer movement data can predict zones of increased encounter risk (Etter et al. 2011, Davis et al. 2020). Such integrative approaches not only inform better surveillance and intervention strategies but also promote coexistence while minimizing conflict. By addressing the factors that drive these interactions, management efforts can focus on reducing negative encounters with humans while promoting coexistence. Such an approach not only mitigates conflicts but also supports broader goals of ecological balance and urban biodiversity.

Challenges and future directions

As urbanization accelerates globally, the challenges associated with managing zoonotic disease risks at the human–wildlife interface are becoming increasingly complex. Therefore, understanding human–wildlife interactions demands innovative approaches that integrate technological advancements, behavioral ecology, human and animal movement, and landscape-level interventions. Addressing these challenges requires a comprehensive understanding of the ecological and social dimensions of urban ecosystems, coupled with interdisciplinary collaboration and global coordination. Below, we explore key areas for future research and intervention, highlighting opportunities for inter and multidisciplinary One Health framework to mitigate zoonotic disease risk in urban landscapes.

Data integration and technological advances

The integration of high-resolution telemetry data with epidemiological models poses challenges, particularly in handling the computational complexity of large data sets and scaling them for use in urban landscapes. Advances in machine learning and big data analytics offer promising solutions, enabling the synthesis of telemetry data using environmental and epidemiological models to improve prediction accuracy (Nathan et al. 2008, Kays et al. 2015, Bomfim et al. 2020). The use of spatially explicit movement models can bridge the gaps between fine-scale telemetry data and broader-scale epidemiological processes (Manlove et al. 2022, Herraiz et al. 2024). These innovations allow for the real-time monitoring of wildlife movement and pathogen transmission, which is particularly useful in urban systems characterized by fragmented landscapes and overlapping human–wildlife activity (Kraemer et al. 2019b). Integrating telemetry data with environmental variables, such as temperature, vegetation cover, and human population density, can provide new insights into how urban ecosystems influence zoonotic disease risks (Hassell et al. 2017, Esposito et al. 2023). In urban settings, where human–wildlife interfaces are dynamic and multifaceted, these tools are particularly valuable. For example, proximity sensors can reveal how urban green spaces function as hotspots for human–wildlife contact, whereas accelerometers can detect stress responses and behavior changes in animals exposed to anthropogenic disturbances (Li et al. 2020, Oliveira et al. 2022). Combining these data with environmental monitoring systems, such as weather stations or satellite imagery, can provide a more holistic view of the ecological drivers of disease risk (Hassell et al. 2017).

Incorporating behavioral ecology into management

Incorporating behavioral ecology and animal movement into urban disease research is vital for understanding the drivers of zoonotic risk. Combining GPS telemetry with accelerometers enhances the ability to classify behaviors, such as resting, foraging, or traveling, which are critical for understanding contact rates and transmission hotspots (Fisher et al. 2012, Cross et al. 2016). For example, accelerometer-based studies on deer have revealed diel movement patterns that align with human activity, increasing the likelihood of human–deer interactions during high-use periods in urban parks (Kilpatrick et al. 2014, Plowright et al. 2015a, Stafford and Williams 2017). Expanding these techniques to understudied urban species could uncover additional behavioral mechanisms driving disease transmission.

Multiscale modeling

Effective disease research in urban systems requires models that operate across multiple spatial and temporal scales. Multiscale approaches ensure that fine-scale behavioral data can inform broader ecological and epidemiological models, providing a more comprehensive understanding of disease dynamics (Nathan et al. 2008, Altizer et al. 2011). For instance, coarse-graining techniques allow researchers to integrate detailed movement data with large-scale landscape features and to identify disease hotspots that might otherwise be overlooked (Fisher et al. 2012, Murray and Daszak 2023). Urban zoonotic diseases often involve complex interactions among wildlife, domestic animals, and humans. Multiscale modeling can capture these interactions by linking individual movement patterns, such as foraging or migration, to broader processes, such as human mobility and behavioral patterns (Goddard et al. 2010, Kraemer et al. 2019b). Such models are particularly useful for informing targeted interventions, such as creating buffer zones or modifying urban green spaces to disrupt disease transmission pathways (Kilpatrick et al. 2014, Hassell et al. 2017).

Human mobility and animal movement dynamics

Integrating human mobility data, such as GPS tracking and cellular phone records, with animal movement data sets offers a powerful new tool for identifying hotspots of human–wildlife interaction and zoonotic disease transmission (Dougherty et al. 2018, Griffin et al. 2022). Such approaches can inform urban planning initiatives that minimize overlapping risk zones and public health campaigns that address high-contact areas. Combining these data sets with epidemiological models allows for a more accurate understanding of how movement behaviors influence disease dynamics across urban ecosystems (Plowright et al. 2015b, Kraemer et al. 2019b). Future research should prioritize the development of integrative frameworks that account for the bidirectional influence of human and wildlife movements on zoonotic disease transmission. This includes exploring how human activities, such as commuting patterns and recreational use of green spaces, alter wildlife behaviors and create opportunities for spillover events. Addressing these dynamics will require interdisciplinary collaboration among ecologists, human geographers, public health professionals, and urban planners to develop sustainable solutions that mitigate zoonotic risks while promoting coexistence in urban landscapes.

One Health framework for managing wildlife–human interactions

The current One Health approach provides a framework for managing zoonotic risks by addressing the interconnectedness of human, animal, and environmental health. In urban areas, this approach has emphasized interventions such as improving sanitation and waste management to reduce wildlife attractants, creating ecological corridors to minimize habitat fragmentation, and implementing integrated disease surveillance systems (Daszak et al. 2000, Hassell et al. 2017). Creating ecological corridors can help wildlife traverse fragmented urban landscapes and reduce the likelihood of animals entering high-risk areas of human activity (Murray and Daszak 2023). However, these corridors may also inadvertently facilitate pathogen transmission among wildlife populations by increasing connectivity and contact rates. This highlights the need to balance conservation goals with disease mitigation strategies. Integrated One Health disease surveillance systems that integrate wildlife, domestic animals, and human health data are critical for early detection and prevention of outbreaks, particularly in densely populated urban regions (Keesing et al. 2010, WHO 2022). Although these strategies address fundamental challenges, current One Health efforts have not included some key elements that are essential for predicting and managing zoonotic risks effectively. For example, integrating data on human and wildlife movement could enhance models and predict zoonotic EIDs. Given the high potential for zoonotic EIDs in urban spaces, a more holistic and detailed ecosystem-based One Health approach is needed. Such measures would ensure scalable and adaptable interventions aligned with sustainability goals, ultimately fostering coexistence between humans and wildlife while reducing zoonotic risks in urban settings.

Conclusions

The convergence of urbanization, wildlife ecology, and public health presents a critical opportunity to advance zoonotic disease prevention science. Integrating the coupled human–wildlife system into the One Health framework offers a comprehensive pathway for mitigating risks. Tackling the underlying drivers of human–wildlife interactions in urban spaces where the majority of humans live is essential to protect both biodiversity and human health in an increasingly urbanized world. Ecosystem services have gained recognition as a guiding framework for urban planning, highlighting the interconnected relationships between human health, biodiversity, and urban ecosystems (Haase et al. 2014, Zabelskyte and Matijosaitiene 2020). As urban ecosystems become more fragmented, wildlife increasingly adapts to anthropogenic landscapes, leading to heightened human contact. These interactions create generative grounds for pathogen spillover driven by habitat encroachment, resource provisioning, and urban mobility patterns. This article underscores the complex interplay between ecological, and behavioral factors driving disease transmission in urban landscapes. It is also evident that the integration of movement ecology tools, high-resolution telemetry, and behavioral studies provides valuable insights into the spatial and temporal dynamics of coupled human–wildlife systems. By leveraging animal and human movement data with disease ecology, researchers can identify hotspots of pathogen transmission and inform targeted interventions. Despite advancements in understanding these dynamics, significant gaps remain in the standardization of methodologies, integration of interdisciplinary research, and addressing the socioeconomic disparities that amplify vulnerabilities particularly as they apply to urban settings or that occur in both urban and rural settings. To mitigate the risks associated with zoonotic spillovers, it is essential to prioritize collaborative, multiscale approaches that encompass technological innovation, policy reform, and public awareness. In the present article, we highlight the framework required as a proactive management strategy, such as understanding human–wildlife interactions, enhanced disease surveillance, and public health interventions, to foster coexistence between humans and wildlife specifically in urban ecosystems. Incorporating this framework into the existing One Health framework will create a critical strategy for addressing zoonotic disease risks by better capturing the interconnectedness of humans, wildlife, and the environment.

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