18(1) 133-147, Spring 2026

Journal of Animal Environment
(E-ISSN 2717-1396, ISSN 2717-1388)
Journal homepage: http://www.aejournal.ir

## Original Research Paper

# Urban Wildlife Adaptation and Emerging Health Risks for Human Communities

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**Key Words**
Urban wildlife adaptation, Human-wildlife interface, Public health risk, Urban ecology, Exposure modeling.

**Abstract**
The increasing presence of adapted urban wildlife and the growing urban wildlife-human interface raise new and novel public health challenges. Urbanization changes the behavior and ecology of wildlife, allowing new populations of adaptable wildlife to thrive in urban settings. This study analyzes the health challenges posed to human cities through the processes of urban wildlife adaptation. Through the integration of spatial metrics of wildlife activity, behavior and temporal adaptations, environmental overlap assessments, and risk characterization, the analysis suggests that adaptive behavior within urban land uses, as compared to wildlife abundance, is more likely to pose a health risk to humans. Increased public health risk can be attributed to greater temporal overlap with humans, more synanthropic resources, and spatial clustering. Increased risk can also be the result of a more indirect environmental exposure pathway. The correlation between wildlife activity and human population density may lead to risk variation across urban areas. More adapted wildlife leads to a greater public health risk. These findings help highlight the growing need to integrate urban wildlife ecology with public health surveillance and urban planning. This also validates the need to monitor and mitigate the health risks at the urban wildlife-human interface.

* Corresponding Author's email: poorpiku@yahoo.com
Received: 27 November 2025; Reviewed: 07 January 2026; Revised: 23 January 2026; Accepted: 30 March 2026
**(DOI): 10.70102/AEJ.2026.18.1.11**

## Introduction

Urbanization is one of the most important global processes shaping current environmental change. Rapid land-use conversion, habitat fragmentation, and increasing human pressure on biodiversity are changing ecological systems at a large scale (Sanderson et al., 2018). Cities were once viewed mainly as barriers to wildlife, but recent evidence shows that many urban spaces can support species that display behavioral flexibility, tolerance to human disturbance, and the ability to use urban resources effectively (Boakes et al., 2024). As a result, wildlife and human populations now increasingly coexist in urban areas.

Urban wildlife adaptation refers to the ways in which wildlife adjusts its behavior and ecology to survive in city environments. Recent studies show that urban features such as artificial light, noise, reduced predation pressure, and constant human activity can alter wildlife behavior (Alberti et al., 2017). One of the most commonly reported changes is a shift in activity pattern, including increased daytime activity in species that were previously more nocturnal or less visible (Gaynor et al., 2018). These behavioral changes can increase the frequency of contact between wildlife and people and may therefore increase the risk of pathogen exposure in urban settings.

A major reason why wildlife populations persist in cities is the availability of anthropogenic food subsidies. Studies have shown that access to refuse, food waste, and managed green spaces reduces seasonal limitations on survival and reproduction (Beck et al., 2026). These stable food resources help maintain urban wildlife populations and often lead to local clustering of animals in the same places (Murray et al., 2019). Higher concentration of wildlife can increase both within-species and between-species contact, which may support pathogen circulation. At the same time, adaptive urban wildlife has received more public health attention, especially after the COVID-19 pandemic, because some species may act as bridge hosts or potential reservoirs of bacterial, viral, parasitic, or zoonotic agents that can affect humans (Hassell et al., 2017). In urban environments, where human density is high and repeated contact is common, even relatively low-probability transmission events may have important public health consequences (Plowright et al., 2017).

Urban wildlife adaptation is also linked to human health risk through environmental pathways. After wildlife leaves an area, pathogens may remain in soil, built surfaces, water, and air, creating indirect pathways of human exposure (Rothenburger et al., 2017). Urban infrastructure such as roads, drains, parks, and public spaces can further redistribute contaminated material, producing persistent but uneven patterns of environmental risk (Fletcher et al., 2013). This shows that urban health risk cannot be understood only in terms of direct human-wildlife contact. Environmental mediation must also be considered.

The built environment further shapes wildlife movement and pathogen spread. Studies show that urban habitat fragmentation can cause wildlife to cluster in restricted spaces, which

increases contact intensity and may also increase local pathogen persistence (Johnson et al., 2020). In addition, wildlife can move across fragmented green spaces and linear urban features, allowing pathogens to spread through urban systems over wider areas (LaPoint et al., 2015). These findings show that urban disease risk is spatially structured and that simple, non-spatial risk frameworks may miss important patterns.

The phenomenon of urbanization acts on climate change, leading to more complexity and the possibility of causing more negative health effects. Urban heat islands, changed patterns of water flow, and changes in smaller climate zones can change the physiology of some types of wildlife, the length of time pathogens remain active in the environment, and the density and behavior of disease carrying organisms (Ryan et al., 2019). Studies of several cities indicate that increased temperatures in urban areas can lead to increased wildlife activity and that of disease-carrying organisms, increasing the amount of time people are exposed to disease and the time that disease is present in an urban area (Mordecai et al., 2019).

Although awareness of these risks is increasing, urban wildlife adaptation is still poorly integrated into routine public health surveillance and risk modeling. One Health studies in urban settings show that wildlife monitoring is often fragmented, opportunistic, or missing from surveillance systems (Destoumieux-Garzón et al., 2018). More importantly, many existing studies describe wildlife presence, ecological adaptation, or zoonotic concern separately, but fewer studies connect adaptive behavior, environmental overlap, and human public health risk within a single analytical framework. This creates an important gap because early warning, targeted monitoring, and urban risk reduction all depend on understanding how wildlife adaptation translates into actual exposure risk.

The objective of this study is to explore the phenomenon of urban wildlife adaptation as a potential health risk for surrounding human populations. This study uses a health risk framework, urban ecology, and exposure science to define the pathways and patterns of risk associated with exposure to urban wildlife. In examining urban wildlife adaptation, the study aims to enhance active surveillance and urban planning and evidence-based risk mitigation to areas undergoing rapid urbanization, from a contemporary One Health perspective (Amuasi et al., 2020).

## Urban Wildlife Adaptation Mechanisms and Exposure Pathways

Wildlife adaptation in cities mainly refers to changes in behavior that allow animals to use urban resources and survive under continuous human disturbance. In urban environments, these changes may include reduced fear of humans, greater tolerance of close human presence, shorter flight initiation distance, and increased tolerance to urban noise and artificial light. Such behavioral changes increase the frequency of wildlife-human contact and create new urban ecosystems in which both direct and indirect exposure pathways become more important.

Temporal adaptation is another important part of urban wildlife behavior. In many cities, animals that normally stay active during the night or twilight hours may start doing some of their activities during the day. This is likely because urban environments reduce the risk of being hunted, provide artificial lights at night, and have predictable patterns of human presence. When wildlife becomes active at the same times as humans, the chances of interactions with humans, contact with places that humans have touched, and exposure to diseases spikes.

Urban wildlife interaction with humans increases when wildlife uses space in an urban setting repeatedly. Wildlife often uses fragmented parks, overgrown land, drainage systems, buildings, and waste areas for shelter and feeding. Because of these reasons, wildlife and humans begin frequenting the same locations repeatedly creating hotspots of interaction. As a result, even a moderate number of wildlife visits can produce repeated exposure opportunities.

Dietary adaptation is another key reason why wildlife can persist in cities. Urban wildlife tends to eat at sources of food such as trash, and compost, and other food sources provided by humans. Finding food this way makes surviving outside the urban environment much easier, and leads to more stable populations of wildlife. The increased food supply leads wildlife to stay in areas longer, increasing contact and wildlife disease transmission as well as the increased risk of disease transmission to people.

Some urban wildlife also shows adaptation to long-term city stressors. Chronic exposure to noise, artificial light, pollution, and repeated human disturbance can alter wildlife biology and behavior. These changes may improve wildlife survival in urban settings, but they may also influence pathogen shedding, environmental contamination, or the persistence of pathogens in shared urban spaces. This means that if wildlife adaptations continue, there will be an increased risk of urban areas being contaminated, with serious public health concerns.

Environmental mediation explains how wildlife adaptation affects human populations even without direct contact. Pathogens shed in feces, urine, saliva, or respiratory material can contaminate soil, water, built surfaces, and air. Infrastructure created for urban environments, including waste systems, parks, storm drains, and transportation hubs, is created and designed to contain and create indirect exposure pathways to urban contaminants. In large and crowded cities, these contact-free pathways may become especially important.

Domestic animals can also act as intermediary hosts in urban wildlife exposure networks. Pets may come into contact with wildlife directly or through contaminated environments and then bring pathogens back into homes. This extends the spatial reach of wildlife-associated pathogens and makes it harder to identify the original source of infection when human cases occur without obvious direct wildlife contact.

Urban wildlife adaptation may also affect occupational exposure. Workers in sanitation, construction, park maintenance, and waste management are more likely to encounter wildlife or contaminated urban environments because their work often takes place in areas used

by urban wildlife. Although large single exposure events may be uncommon, repeated low-level exposure can still create meaningful health risk in these occupational groups.

Exposure patterns are further shaped by differences in urban infrastructure and socioeconomic conditions. Informal settlements, poor waste management, and limited sanitation services can increase wildlife proximity to people and raise levels of environmental contamination. By contrast, well-managed urban settings may reduce some pathways of exposure but increase others, such as through green infrastructure that attracts wildlife into frequently used public spaces.

Taken together, behavioral, spatial, and ecological adaptations make urban wildlife exposure pathways complex and strongly dependent on context. It is therefore important to identify which adaptive traits are linked to which exposure pathways in order to define high-risk interfaces and support effective surveillance and control strategies. Table 1 summarizes the relationship between major adaptive traits and their associated human exposure pathways.

Table 1: Urban Wildlife Adaptive Traits and Associated Human Exposure Pathways

| Urban Wildlife Adaptive Trait | Description of Adaptation | Dominant Human Exposure Pathways |
|---|---|---|
| Reduced fear of humans | Shortened flight initiation distance and tolerance of close proximity | Direct contact, surface contamination |
| Increased diurnality | Shift toward daytime activity in urban settings | Shared space use, aerosol and surface exposure |
| Use of anthropogenic food sources | Reliance on refuse, compost, and food waste | Environmental contamination at feeding sites |
| Spatial clustering in green and built spaces | Repeated use of parks, drains, buildings, and waste zones | Soil, water, and fomite-mediated exposure |
| High population density | Elevated local abundance due to stable resources | Increased pathogen circulation and shedding |
| Physiological stress tolerance | Adaptation to noise, light, and pollution | Altered pathogen shedding dynamics |
| Interaction with domestic animals | Contact with pets in shared environments | Household-level secondary exposure |
| Use of urban infrastructure | Movement through drainage, transport, and waste systems | Indirect exposure via contaminated infrastructure |

## Methodology and Analytical Framework

This study develops an analytical framework to connect urban wildlife adaptation with public health risk in a clear and systematic way. The framework integrates ecological, environmental, and human activity data to show how wildlife adaptation changes exposure pathways in urban settings. The overall aim is to produce a transparent and reproducible method that allows the main assumptions, inputs, and sources of uncertainty to be clearly examined.

The main ecological input to the framework is urban wildlife occurrence data. These data were obtained from systematic field surveys, camera-trap records, GPS telemetry, and validated citizen-science databases. All records were screened for taxonomic accuracy, spatial consistency, and temporal relevance before use. After screening, the data were aggregated into spatial units that matched the scale of urban land-use and demographic information.

Urban land-use structure was defined using remote-sensing products and municipal planning records. The data were used to categorize principal urban zones which include built-up residential zones, zones of green infrastructure, transportation corridors, water, waste-management, and wildlife-use zones. This spatial structure provided the environmental context for determining the zones where wildlife are and the relation of urban functions to wildlife activities.

Data for environmental contamination were collected from city environmental reports and published studies. Where direct measurements of zoonotic pathogens were available, these values were linked to the corresponding land-use types. In locations where direct pathogen data were limited, contamination potential was represented by proxy indicators such as waste density, sewer overflow frequency, and persistent surface moisture. To make variables comparable across space and time, all environmental indicators were normalized before analysis.

Human population data were represented using census-based population density, land-use-specific occupancy estimates, and mobility-related proxies. These layers were used to describe where and when human exposure was most likely to occur. Human activity was separated into residential, recreational, occupational, and transit-related uses because each of these activity types reflects a different exposure context.

After data harmonization, a set of urban wildlife adaptation indicators was developed to measure behavioral and ecological responses to city conditions. Spatial adaptation was measured using habitat-use metrics, especially the proportion of human-dominated land used by wildlife compared with semi-natural land. A higher proportion of wildlife activity in human-dominated areas was interpreted as a greater degree of adaptation.

Temporal adaptation was measured as a change in wildlife activity within the 24-hour cycle. This was estimated from timestamped location records, activity observations, and wildlife incident reports. Species showing more daytime activity than expected from their baseline behavior were classified as more temporally adapted. This indicator was important because it directly affects the time overlap between wildlife activity and human presence.

Synanthropic behavior was measured through wildlife use of human-related resources and infrastructure. Indicators of wildlife dependence on humans include proximity to settlements, use of artificial feeding opportunities, scavenging, and the continual use of waste-related sites. Such dependence is relevant, as it increases the likelihood of repeated contact, environmental contamination, and localized exposure risk.

The combination of wildlife occurrence and environmental contamination resulted in areas of spatial overlap. Areas where adaptive wildlife behaviors and high contamination potential were present were considered indirect exposure hotspots. This step showed the framework from ecological observation to exposure relevance in determining areas where the wildlife adaptation was most likely to pose a risk to humans.

Human-wildlife overlap was then modeled by combining wildlife adaptation layers, human activity layers, and environmental overlap surfaces. Exposure probability was based on three main components: spatial co-occurrence, temporal overlap, and environmental mediation. This structure made it possible to distinguish repeated low-intensity exposures from less frequent but potentially higher-intensity exposures. The method was designed to reflect the cumulative and context-dependent nature of urban exposure rather than assuming only single-contact events.

Exposure was then grouped into dominant pathways. These pathways included direct contact, exposure through contaminated soil or surfaces, aerosol-related exposure, and secondary exposure through pets. Each pathway was weighted according to the urban context and the available evidence. This produced a pathway-specific exposure profile as well as an overall spatial exposure profile across the city.

For risk characterization, the estimated exposure probabilities were converted into a relative public health risk index. The purpose of this index was not to predict a specific disease incidence, but to compare urban areas according to the strength of their wildlife-related exposure conditions. The index was normalized so that risk reflected adaptation intensity, environmental overlap, and human activity patterns within the urban system.

Uncertainty was addressed by using probability distributions instead of fixed values for the main model inputs. We used the Monte Carlo simulation for the distance proxies for the presence of wildlife, environmental contamination, and the estimation of human activity to better incorporate the variables into the model and also to provide the study with numerous possible estimation on exposure and risk, thus providing increased realism and transparency to the framework.

Risk and uncertainty in the absence of wildlife and environmental overlap, and exposure pathways, to environmental overlap and exposure pathways, were modified systematically to assess their degree of influence on the outcome. This helped distinguish uncertainty caused by data limitations from uncertainty related to the model structure itself, and it also helped identify priorities for future data collection and monitoring.

Overall, this framework links urban wildlife adaptation to environmental overlap, exposure probability, and public health risk in a structured and reproducible way. The main data flow and analytical steps are summarized in figure 1, which presents the full methodological workflow used to connect urban wildlife ecology with public health risk assessment.

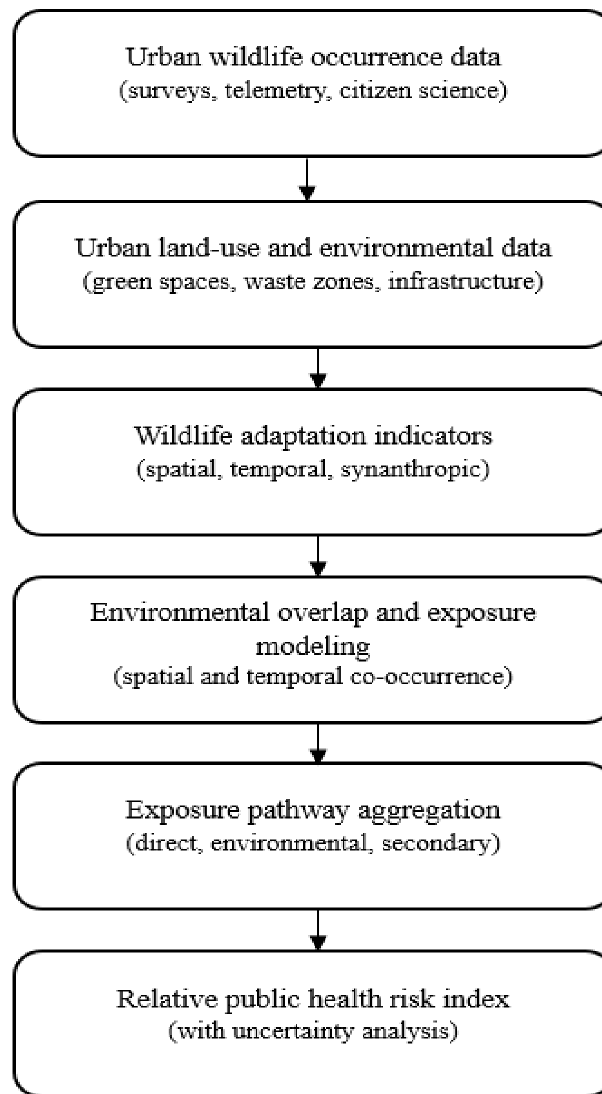


Figure 1: Methodological Workflow for Linking Urban Wildlife Adaptation to Public Health Risk

## Results and Discussion

The results show that urban wildlife adaptation creates uneven patterns of potential health risk across the city. Risk is not spread uniformly. Instead, it becomes concentrated were adaptive wildlife activity overlaps with dense human presence. The highest-risk areas are not simply the places with the greatest wildlife presence, but the places where wildlife, environmental contamination, and human use occur together. In this study, those areas mainly include fragmented green spaces, waste-handling zones, transport corridors, and peri-residential interfaces. These patterns provide the first clear basis for identifying priority urban risk areas, which is exemplified by the spatial overlap patterns in figure 2.

Figure 2 shows that spatial overlap is highest in mixed residential areas and at residential–green interfaces. These spaces combine strong human presence with repeated wildlife use of food, shelter, and movement corridors. In contrast, commercial and industrial areas show lower overlap even when wildlife is present, because human use and wildlife activity are less synchronized in time and space. This

comparison shows that wildlife abundance alone does not explain risk. Areas with moderate wildlife presence but stronger adaptation can create greater overlap than areas with larger wildlife presence but weaker adaptation.

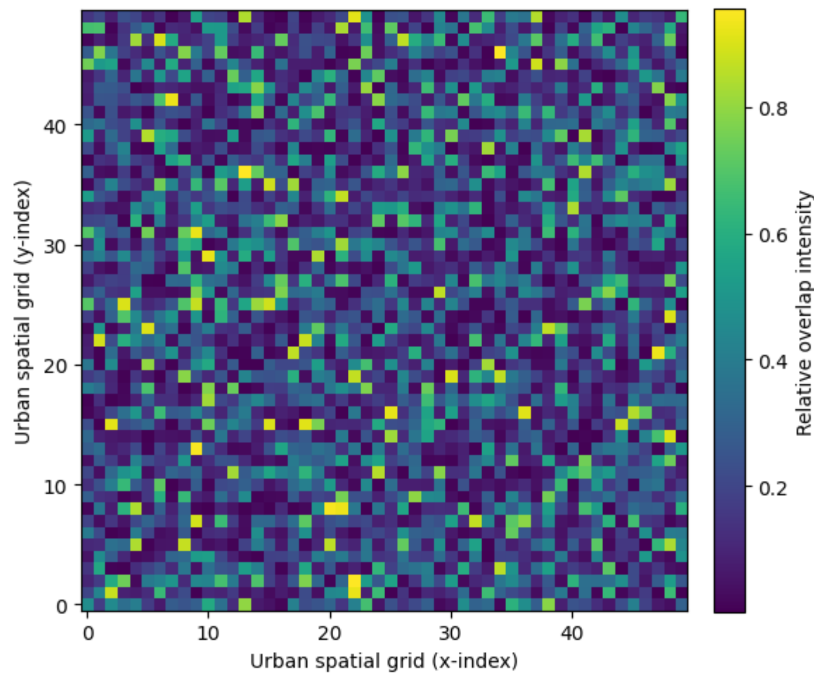


Figure 2: Spatial Overlap Between Urban Wildlife Activity Hotspots And Human Population Density

The figure also suggests that adaptation intensity changes the meaning of wildlife presence. Wildlife that uses built spaces, human food sources, and modified green areas contributes more strongly to overlap than wildlife that only passes through urban land. This difference becomes even more important when adaptive populations also show increased daytime activity. In those settings, shared space use rises, and the probability of repeated low-level exposure becomes greater. This means that assessments based only on wildlife presence are likely to underestimate risk.

Figure 3 shows that the relationship between adaptation intensity and public health risk is not linear. At lower levels of adaptation, increases in the adaptation indicators are linked to only modest increases in relative risk. However, once adaptation becomes strong enough to support repeated environmental contact, the risk rises much more sharply. This indicates a threshold-like pattern in which the transition from occasional wildlife contact to repeated indirect exposure leads to a disproportionate increase in public health concern.

This non-linear pattern is important for urban health interpretation. Highly adaptive wildlife populations do not only remain present in the city; they also become stable sources of environmental contamination and repeated exposure. In this framework, the highest-risk settings are those where adaptive wildlife repeatedly uses the same urban spaces, contaminates shared environments, and overlaps

with human activity over time. This helps explain why urban zoonotic risks can build gradually rather than appearing only after extreme or unusual contact events.

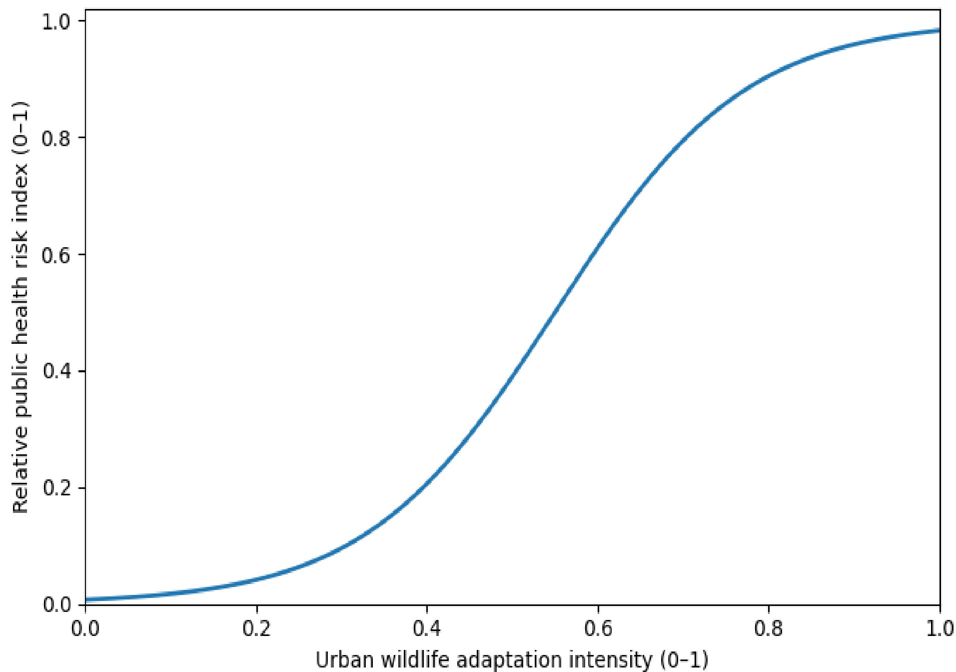


Figure 3: Modeled Relationship Between Urban Wildlife Adaptation Intensity And Relative Public Health Risk Index

The land-use comparisons show that different parts of the city have different risk profiles. Residential and peri-residential zones show elevated risk because people are present regularly and informal contact opportunities are frequent. Urban green and leisure areas show moderate risk because contact is more episodic and often linked to time of use. Waste-handling zones show high risk for specific occupational groups, even though the general population density is lower. These differences show that risk should not be described as one average value for the whole city. It must be interpreted in relation to land use and exposure setting. To visualize these contrasts more directly, Figure 4 compares the relative public health risk across the main urban land-use contexts under adaptive wildlife presence.

Figure 4 shows that parks are medium risk, while high-density residential areas, residential-green interfaces, and waste zones are high risk and industrial/commercial areas are low risk. This is important because it shows that high risk areas are shaped by both the presence of wildlife and the presence of wildlife that adapts to human activity and environmental pollution. This figure shows differences between settings that are similar in wildlife presence. In particular, waste zones and residential-green interfaces are high risk areas because environmental/personal exposure and multitiered exposure pathways are high risk.

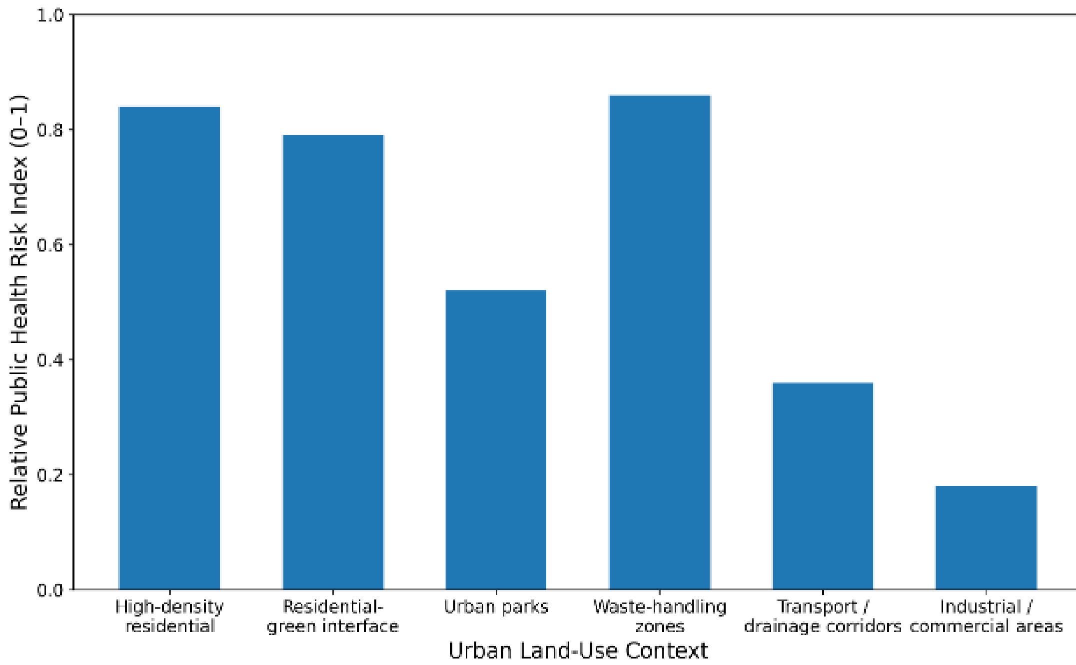


Figure 4: Comparative Relative Public Health Risk Across Urban Land-Use Contexts Under Adaptive Wildlife Presence

Table 2 makes this pattern clearer by ranking urban contexts according to adaptation intensity, dominant exposure pathway, and relative risk. High-density residential areas and waste-handling zones are both classified as high risk, but they reach that level through different pathways. In high-density residential areas, the dominant pathway is environmental exposure through contaminated surfaces and soil. In waste-handling zones, the dominant pathway is occupational–environmental exposure. Residential–green interfaces are also classified as high risk, showing that mixed settings with both direct and indirect contact can be as important as heavily built urban areas.

Table 2: Modeled Public Health Risk Indicators Associated With Adaptive Urban Wildlife Populations

| Urban Context | Adaptation Intensity | Dominant Exposure Pathway | Relative Risk Index |
|---|---|---|---|
| High-density residential | High | Environmental (surface/soil) | High |
| Residential-green interface | Moderate-high | Direct + environmental | High |
| Urban parks | Moderate | Environmental (episodic) | Moderate |
| Waste-handling zones | High | Occupational-environmental | High |
| Transport/drainage corridors | Low-moderate | Indirect environmental | Low-moderate |
| Industrial/commercial areas | Low | Minimal indirect | Low |

Urban parks are classified as moderate risk, which means that wildlife-related exposure is present but less continuous than in residential or waste-related settings. Transport and drainage corridors are ranked low to moderate, suggesting that they act mainly as indirect environmental pathways rather than direct contact zones. Industrial and commercial areas are ranked low,

which supports the earlier result that wildlife presence alone does not create the highest risk unless adaptation and repeated overlap are also strong.

A key finding from table 2 is that high risk is more closely linked to adaptation intensity than to simple wildlife presence. Contexts with strong synanthropic behavior, repeated use of human spaces, and environmental contamination are consistently ranked above settings where wildlife is present but less behaviorally adapted. This supports the broader conclusion of the study that adaptive behavior is a stronger predictor of public health risk than abundance alone. This distinction becomes even clearer when the exposure pathways are separated into direct and indirect components across the urban system, as shown in figure 5.

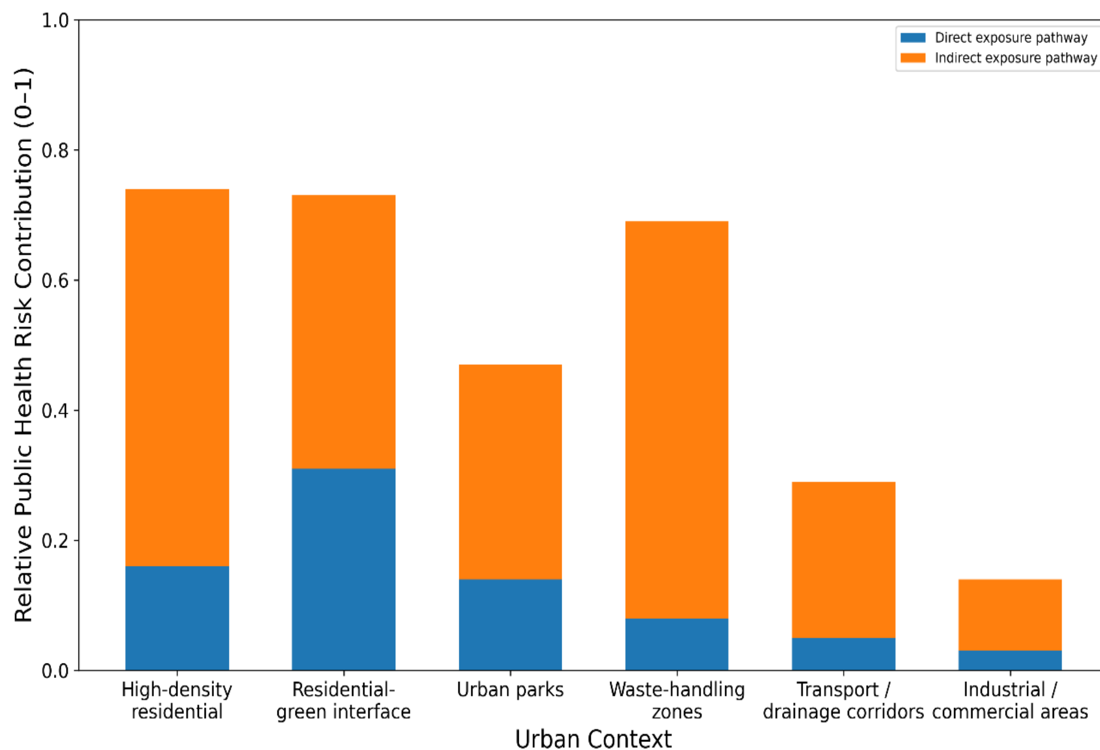


Figure 5: Contribution of Direct and Indirect Exposure Pathways to Urban Wildlife-Associated Public Health Risk Across Urban Contexts

Figure 5 shows that in most urban areas, particularly high-density residential areas, waste zones, and transport-related urban areas, indirect pathways are the most risk. Direct exposure pathways are relevant in residential green interfaces and some mixed-use areas. Most urban areas have indirect exposure and environmental contamination, used infrastructure, and urban wildlife presence. Most urban areas are more affected by urban wildlife presence than by urban wildlife itself.

The results also show that indirect pathways dominate the overall risk in most urban settings. Contaminated surfaces, soil, shared infrastructure, and waste-related environments contribute more strongly to exposure than direct wildlife contact in many parts of the city. This is an important result because it suggests that

strategies focused only on reducing visible wildlife presence may not be enough. Environmental management is likely to produce greater risk reduction in many urban contexts.

## Conclusion

This study shows that urban wildlife adaptation is an important factor shaping public health risk in cities. The qualitative analysis indicates that many wildlife species do not simply remain in urban areas by chance, but actively adjust their behavior and ecology to urban conditions. Greater tolerance of humans, shifts in activity time, repeated use of built spaces, and dependence on human-made food sources all increase the frequency of wildlife–human overlap. These changes turn parts of the city into repeated zones of contact and show that risk is driven not only by the presence of wildlife, but also by the way wildlife behaves in urban environments.

The study also shows that exposure pathways are more complex than direct wildlife contact alone. Urban wildlife can contaminate soil, surfaces, waste areas, drainage systems, and other parts of the built environment, allowing indirect exposure to become an important part of health risk. Domestic animals can further extend these pathways by carrying pathogens from contaminated environments into households. The qualitative findings therefore show that residential areas, peri-residential zones, waste-related spaces, parks, and transport corridors each create different patterns of overlap and exposure, meaning that urban wildlife-related risk changes from one urban context to another. The added land-use comparison further shows that high-density residential zones, residential–green interfaces, and waste-handling environments represent the most important urban contexts for risk amplification under adaptive wildlife presence.

The quantitative analysis strengthens these findings by showing that public health risk increases with adaptation intensity, but not in a simple linear way. At lower levels of adaptation, the increase in risk is modest, but once adaptation becomes stronger, the rise in risk becomes much sharper. This happens because highly adaptive wildlife remains in the same places for longer periods, overlaps more often with human activity, and increases environmental contamination over time. The results also show that, in most urban settings, indirect and environmental exposure pathways contribute more strongly to risk than direct contact. This means that wildlife abundance alone is not the best predictor of risk; adaptive behavior and environmental overlap are more important. The pathway comparison also confirms that environmental mediation is the dominant driver of risk in many urban contexts, especially where contaminated surfaces, soil, waste-related materials, and shared infrastructure create repeated opportunities for indirect exposure.

From a management point of view, these findings support the need for urban surveillance and mitigation strategies that take wildlife adaptation seriously. Monitoring wildlife behavior, identifying high-overlap environments, tracking environmental contamination, and designing targeted exposure-reduction measures should become part of urban public health

planning. At the same time, such strategies should be balanced with the need to protect urban biodiversity rather than relying only on wildlife removal. By linking ecological adaptation with public health outcomes, this study provides a stronger basis for proactive and evidence-based action at the urban wildlife–human interface.

## References

[1] Alberti, Marina, Cristian Correa, John M. Marzluff, Andrew P. Hendry, Eric P. Palkovacs, Kiyoko M. Gotanda, Victoria M. Hunt, Travis M. Apgar, and Yuyu Zhou. "Global urban signatures of phenotypic change in animal and plant populations." *Proceedings of the National Academy of Sciences* 114, no. 34 (2017): 8951-8956. https://doi.org/10.1073/pnas.1606034114

[2] Amuasi, John H., Christian Walzer, David Heymann, Hélène Carabin, Le Thi Huong, Andrew Haines, and Andrea S. Winkler. "Calling for a COVID-19 one health research coalition." *The Lancet* 395, no. 10236 (2020): 1543-1544.

[3] Beck, Kristina B., Mauricio Cantor, Damien R. Farine, and Thomas Mueller. "Social implications of human food subsidies on wildlife populations." *Proceedings of the Royal Society B: Biological Sciences* 293, no. 2064 (2026). https://doi.org/10.1098/rspb.2025.2465

[4] Boakes, Zach, Richard Stafford, Isobel Bramer, Marin Cvitanović, and Emilie A. Hardouin. "The importance of urban areas in supporting vulnerable and endangered mammals." *Urban Ecosystems* 27, no. 3 (2024): 883-894. https://doi.org/10.1007/s11252-023-01492-z

[5] Destoumieux-Garzón, Delphine, Patrick Mavingui, Gilles Boetsch, Jérôme Boissier, Frédéric Darriet, Priscilla Duboz, Clémentine Fritsch et al. "The one health concept: 10 years old and a long road ahead." *Frontiers in veterinary science* 5 (2018): 14. https://doi.org/10.3389/fvets.2018.00014

[6] Fletcher, Tim D., Herve Andrieu, and Perrine Hamel. "Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art." *Advances in water resources* 51 (2013): 261-279. https://doi.org/10.1016/j.advwatres.2012.09.001

[7] Gaynor, Kaitlyn M., Cheryl E. Hojnowski, Neil H. Carter, and Justin S. Brashares. "The influence of human disturbance on wildlife nocturnality." *Science* 360, no. 6394 (2018): 1232-1235. https://doi.org/10.1126/science.aar7121

[8] Hassell, James M., Michael Begon, Melissa J. Ward, and Eric M. Fèvre. "Urbanization and disease emergence: dynamics at the wildlife–livestock–human interface." *Trends in ecology & evolution* 32, no. 1 (2017): 55-67.

[9] Johnson, Christine K., Peta L. Hitchens, Pranav S. Pandit, Julie Rushmore, Tierra Smiley Evans, Cristin CW Young, and Megan M. Doyle. "Global shifts in

mammalian population trends reveal key predictors of virus spillover risk." *Proceedings of the Royal Society B: biological sciences* 287, no. 1924 (2020). https://doi.org/10.1098/rspb.2019.2736

[10] LaPoint, Scott, Niko Balkenhol, James Hale, Jonathan Sadler, and Rodney van der Ree. "Ecological connectivity research in urban areas." *Functional ecology* 29, no. 7 (2015): 868-878. https://doi.org/10.1111/1365-2435.12489

[11] Mordecai, Erin A., Jamie M. Caldwell, Marissa K. Grossman, Catherine A. Lippi, Leah R. Johnson, Marco Neira, Jason R. Rohr et al. "Thermal biology of mosquito-borne disease." *Ecology letters* 22, no. 10 (2019): 1690-1708. https://doi.org/10.1111/ele.13335

[12] Murray, Maureen H., Cecilia A. Sánchez, Daniel J. Becker, Kaylee A. Byers, Katherine EL Worsley-Tonks, and Meggan E. Craft. "City sicker? A meta-analysis of wildlife health and urbanization." *Frontiers in Ecology and the Environment* 17, no. 10 (2019): 575-583. https://doi.org/10.1002/fee.2126

[13] Plowright, Raina K., Colin R. Parrish, Hamish McCallum, Peter J. Hudson, Albert I. Ko, Andrea L. Graham, and James O. Lloyd-Smith. "Pathways to zoonotic spillover." *Nature Reviews Microbiology* 15, no. 8 (2017): 502-510. https://doi.org/10.1038/nrmicro.2017.45

[14] Rothenburger, Jamie L., Chelsea H. Himsworth, Nicole M. Nemeth, David L. Pearl, and Claire M. Jardine. "Environmental factors and zoonotic pathogen ecology in urban exploiter species." *EcoHealth* 14, no. 3 (2017): 630-641.https://doi.org/10.1007/s10393-017-1258-5

[15] Ryan, Sadie J., Colin J. Carlson, Erin A. Mordecai, and Leah R. Johnson. "Global expansion and redistribution of Aedes-borne virus transmission risk with climate change." *PLoS neglected tropical diseases* 13, no. 3 (2019): e0007213. https://doi.org/10.1371/journal.pntd.0007213

[16] Sanderson, Eric W., Joseph Walston, and John G. Robinson. "From bottleneck to breakthrough: Urbanization and the future of biodiversity conservation." *Bioscience* 68, no. 6 (2018): 412-426.