Proc. of the European Safety and Reliability Conference (ESREL 2026)
Edited by José C. Matos, Paulo B. Lourenço, Michael Beer, Daniel Oliveira,
Edoardo Patelli, Hélder S. Sousa, Rui A. Silva and Monica Santamaria

doi: 10.3850/ESREL2026061419_esrel26-p26381-cd

Zoonotic health risk assessment and nature-based solutions: a pluridisciplinary decision-support approach applied to dengue disease case study

Maria Agustina Aranda

Univ. Grenoble Alpes, CNRS, INRAE, IRD, Grenoble INP, IGE, 38000 Grenoble, France. UMR EPIA, INRAE, VetAgro Sup, University of Lyon, 69280 Marcy l'Etoile, France. E-mail: maria.aranda@vetagro-sup.fr

Christophe Bérenguer

Univ. Grenoble Alpes, CNRS, Grenoble INP, GIPSA-lab, 38000 Grenoble, France

Agnès Leblond

UMR EPIA, INRAE, VetAgro Sup, University of Lyon, 69280 Marcy l'Etoile, France

Jean-Marc Tacnet

Univ. Grenoble Alpes, CNRS, INRAE, IRD, Grenoble INP, IGE, 38000 Grenoble, France

Nature-based solutions (NbS) for climate change adaptation such as urban forests, sponge wet areas are classically recognized for both their physical capacities and their economic, environmental, social, and cultural co-benefits. However, in some cases, urban NbS may induce risks such as zoonosis emergence. Those potential negative impacts remain largely understudied. This study develops a framework to characterize induced infectious risks. An original multidisciplinary integrated approach associating epidemiology and safety-risk-decision techniques is proposed to assess infectious risk. The methodology is based on a literature review and expert interviews, followed by the formalization of dengue transmission processes and infectious risk definition. Infectious risk is then analyzed using bow-tie and event tree diagrams in collaboration with safety experts, and finally assessed through a multicriteria decision-making model. Preliminary infectious risk rankings are consistent when comparing one Lyon's experimental and one virtual site. Overall, assessment of infectious risks possibly associated with NbS may contribute in a more comprehensive and unbiased perspective to make better decisions about urban NbS implementation.

Keywords: Nature-based solutions, risk analysis, zoonosis, decision-support, One Health approach.

1. Introduction

1.1. *Nature based Solutions*

The International Union for Conservation of Nature (IUCN) defines Nature-based Solutions (NbS) as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, while simultaneously providing benefits for human well-being and biodiversity" (Cohen-Shacham et al. 2016).

Although NbS are widely recognized for their economic, environmental, social, and cultural co-benefits (Li et al. 2025), their potential negative impacts remain largely understudied (Ommer et al. 2022). Initiatives aimed at increasing urban biodiversity may promote the introduction and persistence of organisms that act as vectors or reservoir hosts of infectious pathogens, potentially leading to the emergence and spread of infectious diseases.

In practice, infectious risk related to zoonotic transmission is rarely considered during the implementation of NbS. Zoonoses are diseases that can be transmitted between animals and humans and may pose significant risk to both human and animal health, with potentially substantial economic consequences. They typically emerge and spread at the human–animal–environment interface (World Health Organization et al. 2019). Addressing these issues requires an integrated approach that accounts for the impacts of NbS on human, animal, and environmental health, as embodied in the "One Health" paradigm.

1.2. *Aedes albopictus and dengue disease in Lyon, France*

Aedes albopictus, also known as the Asian tiger mosquito, originates from Southeast Asia and the Indian Ocean and has spread worldwide since the late 1970s due to international trade in used tires and ornamental plants. Females bite during the daytime, especially at sunrise or sunset, and show a preference for humans, although they are not strictly host specific. Their average flight distance is approximately 75 m, indicating limited dispersal compared with other mosquito genera. During the day, adults rest mainly in low vegetation (Delaunay et al. 2012).

Dengue is a tropical viral notifiable disease transmitted by *Aedes* mosquitoes. Viruses are regularly imported from endemic areas, including French overseas territories. In 50–90% of cases, infection is asymptomatic; when symptoms occur, incubation lasts 4–7 days, and the classical form presents abruptly with high fever, headache, retro-orbital pain, nausea, and other symptoms (Santé publique France 2024). No specific antiviral treatment exists; management is symptomatic, and only one vaccine is currently available for high-transmission areas (World Health Organization 2025).

1.3. *Infectious risks and multicriteria risk scoring framework*

The concept of risk is complex and varies across disciplines. The term "risk" is often used to refer to an undesirable event that may occur. Traditionally, risk is defined as the intersection of a hazard, with an exposure and vulnerability dimension involving populations, assets, and/or infrastructure.

The definition of infectious risk remains unclear and ambiguous. Similarly, characterizing the notion of hazard in the context of infectious risk is challenging, as it depends not only on the presence of an element but also on the presence of a specific property or condition. For example, in the case of dengue, the Asian tiger mosquito itself does not constitute a hazard. It becomes a risk vector only when infected. The strict hazard in this case is the pathogen—the dengue virus—but as an arbovirus, it cannot exist or propagate without a host or vector. The hazard is therefore inseparable from this biological relationship, making its identification more complex than for other types of risk.

The general objective of our study is to develop a multicriteria risk scoring framework to characterize overall infectious risks associated with NbS in urban environments, leveraging knowledge of factors that promote the introduction or spread of pathogens.

This paper is structured as follows, the first part presents an in-depth review of the research topic and study area. The second part develops the methodological framework, while the third presents the framework alongside the results. The fourth part provides a discussion, and the fifth offers a concise conclusion, highlighting remaining open questions and outlining perspectives for future research.

2. Development of an integrated methodological framework and results

An original multidisciplinary integrated approach associating epidemiology, risk assessment and multicriteria decision-support methodologies is proposed to assess infectious risk. It combines epidemiology experts' knowledge formalization, bow-tie and event tree diagrams, and risk scoring framework (Fig. 1). Application is done in Lyon, the fourth greenest and the third largest city in France.

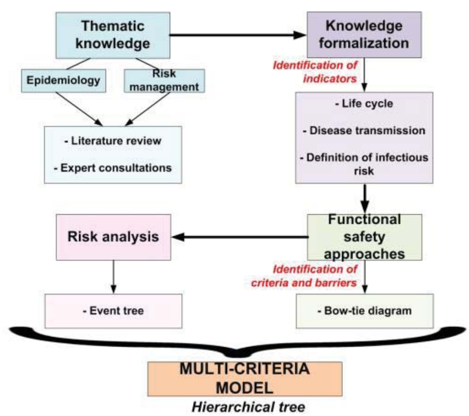

Fig. 1: Methodological synthesis.

2.1. *Epidemiological framework*

Diagrams of the life cycles of vector and reservoir animals, as well as disease spread, are developed to identify key factors in infection emergence and to synthesize health risks. Based on these diagrams, the criteria influencing each stage of the life cycle and the transmission mechanisms are pre-identified and formalized, including the temporal phases of each stage and of transmission to humans. Barriers, corresponding to measures limiting risk are also defined.

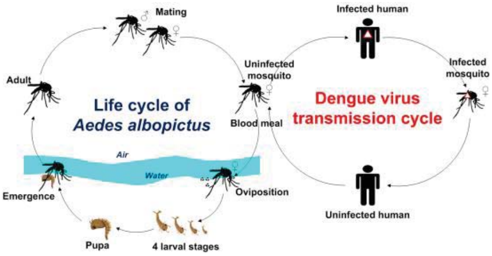

Fig. 2: Life cycle of *Aedes albopictus* and dengue virus transmission cycle.

The life cycle of Aedes albopictus in dengue transmission is shown on Fig. 2. Gravid females take blood meals to obtain amino acids for oviposition, during which they may acquire the virus from an infected person or transmit it to an uninfected individual. Key factors in the mosquito life cycle included the presence of water and vegetation, their characteristics (e.g., water temperature and distance between vegetation and larval sites). Human mobility, especially from endemic regions where dengue virus circulates, was the most important factor for virus transmission.

2.2 *Infectious risk definition*

The classical risk assessment approach is based on the concepts of hazard, exposure, and vulnerability (Fig. 3).

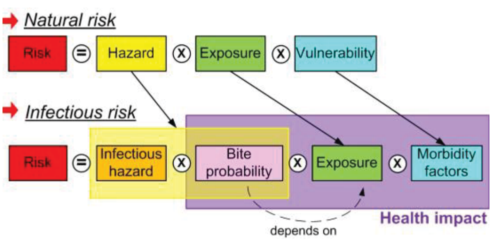

Fig. 3: Risk components across the natural and health domains.

Infectious **hazard** is not limited to the presence of a mosquito, but requires that the mosquito is infected with a virus and that all conditions allowing this co-occurrence are met at the same time and in the same place. The bite probability is conditioned by individual characteristics and activities of people, which influence their exposure to infected mosquitoes.

For infectious risk, the event occurrence's probability also depends on exposure. For example, in the case of arboviral diseases, the probability of being bitten depends on an individual's exposure to mosquitoes while, in the context of natural hazards, a natural phenomenon is independent of human exposure (e.g. flood occurrence probability does not vary according to human presence).

The concept of **vulnerability**, which refers to the extent to which an exposed individual, object at risk is susceptible to being harmed, damaged by a danger to a risk is replaced by the concept of morbidity factors, which refer to the conditions that contribute to the onset or worsening of disease within a population.

Exposure varies according to the age group, the number of people present, and the frequency of visits to the location, since the presence of infected mosquitoes in a sparsely frequented area represents a lower risk.

This step allows a pre-identification of criteria corresponding to factors required for or favoring each stage of the process. Regarding the mosquito life cycle, the main criteria relate to the presence of water and vegetation and their characteristics. Concerning viral transmission, the key determining factor was the movement of people from endemic areas. The presence of the virus depends exclusively on the importation of infected mosquitoes or viremic individuals, as no autochthonous circulation has been observed in metropolitan France. This approach also highlighted that, in the case of diseases transmitted by the Asian tiger mosquito, the spatial and temporal coexistence of the mosquito, the virus, and human exposure is essential.

2.3. *Using some RAMS-inspired tools (bow-tie analysis and event trees) to support risk assessment*

RAMS process and methods (reliability, availability, maintainability, safety) are used to model evolution of complex systems (Rausand 2011). Bow-tie diagrams are used to illustrate the relationship between an identified hazardous event, its causes and consequences, considering barriers (Fig. 4). Event trees are an inductive method to represent pathways from an initiating event to consequences depending on event and barrier failure probabilities (Fig. 5).

Each event or barrier is represented by a decision branch: "yes" above and "no" below. Selecting one of the two alternatives at each node allows the development of all possible scenario combinations to the end. At this stage, the tree is qualitative, but probabilities can later be assigned to each branch to compute scenario likelihoods.

2.3.1. *Bow-tie diagram*

In the case of dengue, hazardous event (central node) a human being bitten by an infected *Aedes albopictus* mosquito (Fig. 4). Hazard factors and measures reducing the probability of hazardous event, called preventive (pro-active) barriers are on the left of the central node. Hazards include the circulation of the virus in the area (imported by viremic individuals), the presence of the mosquito under conditions favorable to its survival (breeding sites, short vegetation), and human presence at the site.

All possible outcomes and measures designed to mitigate the consequences, called reactive barriers, are on the right of the central node. The diagram is built with experts from various disciplines.

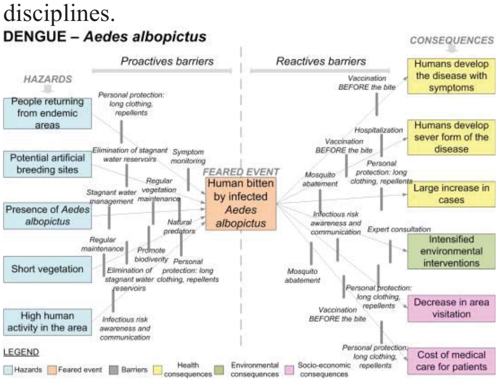

Fig. 4: Bow-tie diagram for arboviral diseases transmitted by *Aedes albopictus*.

Potential consequences include health consequences (asymptomatic cases, mild or severe symptoms, hospitalization), environmental consequences (harmful effects of mosquito abatement treatments), and socio-economic consequences (reduced use of public spaces and costs related to diagnosis and treatment). Reactive barriers such as symptomatic treatment, isolation and protective measures for infected individuals, epidemiological investigations, targeted mosquito abatement, and public communication can reduce consequences.

2.3.2. *Event tree*

The event tree (Fig. 5) is applied to tiger mosquito in metropolitan France, where vaccination is not recommended. In the case of dengue, the initiating event is the start of the enhanced surveillance season, which coincides with the onset of favorable conditions for mosquito activity.

The barriers prevent the occurrence of subsequent events (e.g. the absence of vector control measures, elimination of stagnant water reservoirs, mosquito abatement). Barriers such as individual protective measures or collective actions can prevent mosquito infection.

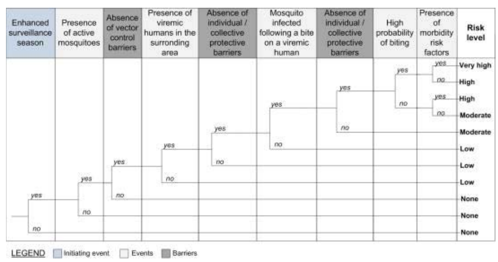

Fig. 5: Event tree for arboviral diseases transmitted by *Aedes albopictus*.

The events include the presence of active mosquitoes and viremic humans, which are necessary conditions for virus introduction.

Even in the presence of viremic individuals and active mosquitoes, transmission is not systematic. Bite probability is influenced by individual attractiveness and activities. Presence of morbidity factors further increases the risk, potentially shifting it from moderate to high, or from high to very high when bite probability is elevated and comorbidities are present.

2.4. *Developing and using a multi-criteria decision-making model*

2.4.1 *Multi-criteria decision-making methods*

Infectious risk analysis also raises complex decision-making challenges, which are often addressed using multicriteria decision analysis (MCDM) approaches. In general, within a decision-support framework, one or more options are evaluated against multiple objectives, each defined by a set of criteria. The performance of an option with respect to these objectives and criteria—which may have different weights—is represented by scores (Dean 2022).

A multicriteria decision-support methodology aims either choosing, sorting, and ranking solutions or alternatives based on criteria for which decision-makers express preferences. Several methods exist using total or partial aggregation principles. AHP (Analytic Hierarchy Process) (Saaty 1980) is used to both structure the problem and assess solution (NbS test sites). It is a basis before using another more robust rank reversal free method called SPOTIS based on normalized distance of solution to criteria evaluation minimum and maximum bounds (Dezert et al. 2020). This approach enables transparent explanation and justification of different choices, ultimately supporting the selection of the most appropriate solution.

2.4.2 *Model development*

The final step involved constructing a model to evaluate situations, solutions, and options using a multi-criteria approach.

For the total aggregation hierarchical approach, the criteria and monitoring indicators used by experts were identified and specified based on literature review, expert discussions, and previously developed diagrams, including the bow-tie diagram and event tree (Fig. 4 and 5).

Using this information and the proposed definition of infectious risk, a hierarchical tree was developed to assign an infectious risk level based on a performance score. The criteria were then ranked according to their relative contribution to infectious risk. Initially, criteria were pre-ranked using qualitative arrows to facilitate the subsequent construction of preference matrices.

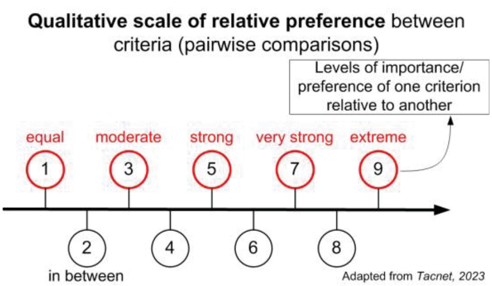

Fig. 6: Qualitative scale of relative preference between criteria.

Next, each criterion at the same level of the tree was compared pairwise to evaluate its relative importance by a qualitative preference scale (Fig. 6).

The preference matrix allows assessment of each criterion's relative importance compared to the others. Each value represents the preference of the row criterion relative to the column criterion. After normalizing the matrix, criterion weights are obtained by calculating the eigenvalue of the preferences matrix using a simplified calculation process described in Ishizaka and Lusti (2006). Each weight thus reflects the relative importance of the corresponding criterion in the overall decision (Fig. 7).

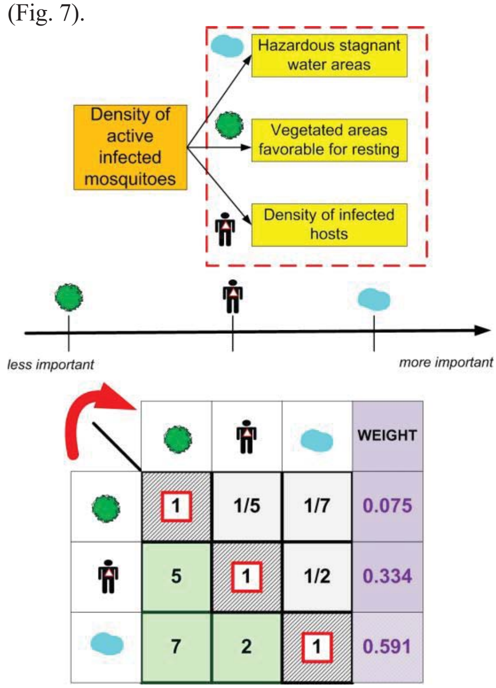

Fig. 7: Qualitative scale and preference matrix for the density of active infected *Aedes albopictus.*

Given the multiplicity of situations to be considered—such as the exposure of different population groups with varying levels of vulnerability in contexts where the mosquito vector may or may not be present—a seasonal risk model was proposed (Fig. 8), distinguishing three levels (x): low risk from May to June, high risk from September to October and peak risk from July to August. Overall risk is structured around two main components: density of active infected mosquitoes, and health impact on exposed populations.

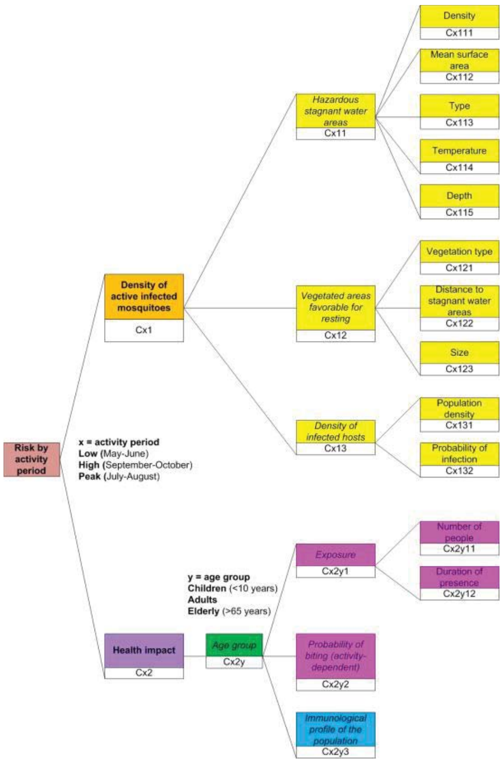

Fig. 8: Multi-criteria decision-making model for arboviral diseases transmitted by *Aedes albopictus*.

The density of active infected mosquitoes depends on three main factors: the presence of hazardous stagnant water areas, the presence of vegetated areas favorable for mosquito resting, and the density of infected hosts.

The hazardousness of stagnant water areas depends on several criteria, including density, mean surface area, type, temperature, and depth.

Identifying indicators for the density of stagnant water is challenging due to the importance of spatial configuration for diseases transmitted by the Asian tiger mosquito. To address this, we adopted a "zone of influence" approach, in which a minimum number of points ensures that the mean nearest-neighbor distance matches the mosquito's zone of influence.

A scale was developed to represent the mean surface area of stagnant water bodies at the site. Stagnant water types were classified from less to more favorable for mosquito development: (1) ponds, puddles, ditches, temporary pools; (2) large artificial water bodies; (3) tree holes, concave leaves, bamboo; (4) containers such as buckets, pots, cisterns or vases. Optimal temperature (25–30 °C) and water depth (1–3 cm) ranges from the literature were used to construct corresponding scales.

Moving on to the vegetated areas favorable for mosquito resting are characterized by vegetation type, distance to stagnant water areas, and size.

For the vegetation type, all combinations of trees, grasses, and shrubs in urban green spaces were considered. For vegetation, all combinations of trees, grasses, and shrubs in urban green spaces were considered. Optimal distances to stagnant water (50 m) and vegetated area sizes (60–120 m^2) were obtained from the literature (Bartholomée et al. 2025) and used to construct proportion-based scales, reflecting the weak dispersal capacity of the Asian tiger mosquito (~150 m).

The density of infected hosts depends on population density and infection probability. A scale was built using population data from INSEE (National Institute of Statistics and Economic Studies, France), and qualitative exposure scenarios will be defined based on site-specific surveys.

The second major component of the model is health impact, which depends primarily on the type of exposure. Three exposure categories (y) are defined: children (< 10 years), adults, elderly (> 65 years). Health impact depends on exposure level, probability of mosquito biting, and probability of disease detection.

Exposure depends on the number of people and their duration of presence. The number of people is measured via the occupancy rate (maximum capacity / visitors present), while duration is estimated from hourly profiles, seasonal attendance, and utilization scenarios.

The probability of being bitten is activity-dependent and difficult to quantify (Coutinho-Abreu et al. 2022). Individual attractiveness factors (e.g., CO_2 emissions, lactic acid, skin odors) were excluded due to measurement challenges. Instead, biting probability is approximated based on activity type, which can be obtained through surveys or direct observation. Park use is determined by layout, natural features, size, and context (Zanella et al. 2025). User activity types (leisure, sports, cultural, and transit) are inferred from park structure. A SPOTIS-based multi-criteria model assigns an activity profile to each site based on the shortest distance to these predefined activity types.

Finally, since arboviral diseases transmitted by the Asian tiger mosquito are non-endemic, lack vaccines, and are notifiable in France, morbidity was expressed using alternative approaches. Immune status data, obtained through surveys, were categorized into immunized healthy individuals, non-immunized healthy individuals, and non-immunized individuals with at least one risk factor (e.g., diabetes, hypertension, chronic kidney disease).

The implementation was carried out using two sites: an existing site, Blandan Park, a 17 hectares urban park, the development of which was preceded by an environmental impact assessment, and a virtual site designed to represent a potentially high-risk situation to demonstrate the model's behavior under contrasting conditions. For each evaluation class, the weight corresponding to the situation observed was considered. The weights were then summed to obtain the overall score.

In this case, the score obtained for Blandan Park was 0.319, comprising 0.110 for infectious hazard and 0.209 for health impact, whereas the score for the hypothetical site was 0.573, comprising 0.275 for infectious hazard and 0.298 for health impact. It is important to note that this score is a dimensionless value with no physical meaning, whose sole purpose is to enable comparisons.

3. Discussion

3.1. *Infectious risk*

Risk in the health context is specific in that damage occurs in two phases: exposure (in this case to a mosquito) does not directly produce damage but instead defines a composite and conditional hazardous situation. Another specificity of health risk related to diseases transmitted by the Asian tiger mosquito lies in its associated temporal window, particularly linked to the virus incubation period and human viremia.

3.2. *Relevance of combining formalisms*

The proposed methodology for characterizing and quantifying infectious risk associated with NbS, particularly for diseases transmitted by the Asian tiger mosquito, is based on a multidisciplinary approach. It adopts a "One Health" perspective, integrating human, animal, and environmental health to sustainably balance and optimize well-being across these domains, while explicitly considering ecosystems and biodiversity.

The multi-criteria decision-making model was developed through the integration of several formalisms: representations of animal life cycles (vectors and reservoirs) and disease transmission pathways, the bow-tie diagram, and the event tree. These formalisms not only allow for accurate modeling of event sequences leading to a hazardous infectious situation but also help identify relevant criteria and explicitly define the indicators required to assess different situations.

The application of this methodology also facilitates the identification of critical intervention points and the definition of effective preventive measures. Moreover, it ensures an integrated approach that combines biological, environmental, and human knowledge, enabling a comprehensive understanding of health risk.

3.3. *Proposal and use of a multi-criteria decision-making model to assess risk*

Another challenge encountered was the construction of indicators capable of accounting for the complexity of the system while remaining simplified and easily measurable. We proposed an approach inspired by methods from reliability engineering, promoting a multidisciplinary perspective that simultaneously integrates biological / epidemiological, environmental, human, and risk-related dimensions.

In particular, the bow-tie diagram and the event tree make it possible to analyze the risk context, to model sequences of events leading to a hazardous health situation, identify critical points for intervention, and define appropriate preventive measures. The proposed formalization also facilitates dialogue with epidemiology experts, who can validate, refine, or adjust the model construction at each stage, including the selection and prioritization of criteria and indicators.

Multi-criteria analysis has previously been applied in the context of infectious risk assessment in France. Lebert et al. (2022) aimed to estimate the hazard component of overall risk by using a knowledge-based method to produce a habitat suitability map for *Ixodes ricinus* ticks, vectors of Lyme disease.

This highlights the potential of such tools, which, when combined with other formal frameworks, facilitate informed decision-making based on reliable data.

4. Conclusion

The infectious risk associated with the transmission of zoonoses remains insufficiently considered in the design and implementation of NbS in urban areas. In response to this gap, this study developed a decision-support methodology to characterize overall infectious risk.

This work proposes an original, multidisciplinary, and integrated approach combining epidemiology with safety, risk, and decision sciences. The methodology has also been applied to other zoonoses, such as tick-borne Lyme disease, and could be extended to additional decision-making contexts related to NbS implementation.

From a future perspective, the proposed AHP-based framework could serve as a foundation for a SPOTIS approach, which offers a more robust, rank-reversal-free decision-making method.

Acknowledgement

This work has been funded by the project HealthyRisk (INRAE X-Risques program), the Grenoble Risk Institute (Univ. Grenoble-Alpes) and the French National Research Agency (ANR) under the Investments for the Future program 'Excellence' of France 2030 (SHAPE-Med@Lyon; ANR-22-EXES-0012).

The authors thank Vincent Raquin (UMR0754, Viral Infections and Comparative Pathology, INRAE, EPHE, University of Lyon 1) and Claire Valient-Moro (UMR5557, Microbial Ecology, INRAE, CNRS, University of Lyon 1) for providing their expertise and assistance in formalizing the transmission cycles of diseases transmitted by *Aedes* mosquitoes.

The authors also thank the City of Lyon's partners for their participation in the project and for providing data on the study sites: Diana Sepulveda and Fabrice Delaveau from the Health Department; Elsa Bombrun and Tatiana Bouvin from the Biodiversity and Nature in the City Department;

References

Bartholomée, C. et al. 2025. "Investigating the Role of Urban Vegetation alongside Other Environmental Variables in Shaping *Aedes albopictus* Presence and Abundance in Montpellier, France." Ecology.

Calistri, P. et al. 2013. "The Components of 'One World – One Health' Approach." Transboundary and Emerging Diseases 60: 4–13.

Cohen-Shacham, E. et al., eds. 2016. Nature-based Solutions to Address Global Societal Challenges. Gland, Switzerland: IUCN.

Coutinho-Abreu, I. V. et al. 2022. "Human Attractive Cues and Mosquito Host-Seeking Behavior." Trends in Parasitology 38 (3): 246-264.

Dean, M. 2022. A Practical Guide to Multi-Criteria Analysis.

Delaunay, P. et al. 2012. "*Aedes albopictus* en France Métropolitaine." Annales de Dermatologie et de Vénéréologie 139 (5): 396-401.

Dezert, J. et al. 2020. "The SPOTIS Rank Reversal Free Method for Multicriteria Decision-Making Support." In 2020 IEEE 23rd International Conference on Information Fusion (FUSION), 1–8. IEEE.

Ishizaka, A., and M. Lusti. 2006. "How to Derive Priorities in AHP: A Comparative Study." Central European Journal of Operations Research 14 (4): 387-400.

Lebert, I. et al. 2022. "Habitat Suitability Map of Ixodes ricinus Tick in France Using Multi-Criteria Analysis." Geospatial Health 17 (1).

Li, M. et al. 2025. "Solution to What? Global Assessment of Nature-Based Solutions, Urban Challenges, and Outcomes." Landscape and Urban Planning 256: 105294.

Lõhmus, M., and Balbus, J. 2015. "Making Green Infrastructure Healthier Infrastructure." Infection Ecology & Epidemiology 5, no. 1: 30082.

Ommer, J. et al. 2022. "Quantifying Co-Benefits and Disbenefits of Nature-Based Solutions Targeting Disaster Risk Reduction." International Journal of Disaster Risk Reduction 75: 102966.

Rausand, M. 2011. Risk Assessment, 1st ed. Wiley.

Santé publique France. 2024. Dossier Thématique: La Dengue – La Maladie.

Saaty, T. L. 1980. The Analytical Hierarchy Process. New York: McGraw-Hill.

World Health Organization. 2025. Dengue Vaccines: Questions and Answers.

World Health Organization, Food and Agriculture Organization of the United Nations, and World Organization for Animal Health. 2019. Taking a Multisectoral, One Health Approach: A Tripartite Guide to Addressing Zoonotic Diseases in Countries.

Zanella, A. F. et al. 2025. The Digital Life of Parisian Parks: Multifunctionality and Urban Context Uncovered by Mobile Application Traffic. arXiv:2508.15516.