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PERSPECTIVE

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Sustainable urban planning needs stronger interdisciplinarity and better co-designing: How ecologists and climatologists can fully leverage climate monitoring data

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Abstract
Research has provided considerable evidence that temperature significantly influences species biology. Its influence is so great that climate corridors have been proposed to assist species in tracking their climatic niche at macroecological scales, reinforcing the importance of accounting for this variable at all scales to address the climatic threat to biodiversity. This threat is exacerbated in cities where artificialization enhances the effect of climate change, to the extent that urban temperatures are a public health concern, with heatwaves causing excess human mortality and having a stark impact on biodiversity. Recent developments in climate monitoring networks enable characterizing the spatiotemporal structure of urban climates in ever greater detail, with many cities already equipped with such networks. The impact of temperature on biodiversity, on the same scale as these networks allows, has never been explored. Characterizing urban climate infrastructures and cool corridors, and thus thermal connectivity for species, would enrich and strengthen existing ecological infrastructures, on the basis of scientific evidence. In this perspective, we discuss how stronger collaborations between ecologists and climatologists could help leverage the full potential of urban climate monitoring networks. We highlight research opportunities they could offer in terms of studying the impact of urban climate on biodiversity and the efforts that need to be pursued to enable co-designing and make interdisciplinary collaborations operational. Such interdisciplinary research on urban climate and its impact is all the more important that its outcomes can help better inform urban planning and mitigate the impacts of climate change on people and biodiversity.

This article is categorized under:
Climate and Development > Urbanization, Development, and Climate Change
Assessing Impacts of Climate Change > Observed Impacts of Climate Change
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KEYWORDS
climate connectivity, decision-making support, habitability, one health, urban heat island

1 | INTRODUCTION: URBANIZATION MODIFIES THE LOCAL CLIMATE, AND URBAN EXPANSION RAISES QUESTIONS ABOUT THE FUTURE HABITABILITY OF CITIES

More than half of the world's population lives in urban areas (UNDESA, 2018). The combined effects of population growth and increased attractiveness of cities are responsible for diverse and major structural anthropogenic pressures on urbanized landscapes (e.g., Forman, 2014; Hölker et al., 2010; Jerem & Mathews, 2021; McKinney, 2006). In particular, the increase in artificial surfaces, built-up or impervious (e.g., roads and pavements), fragments the habitats of many species (LaPoint et al., 2015), and substantially alters the local climate perceived by people and organisms living in cities (Li et al., 2023; Wilby & Perry, 2006). This influence of urbanization on local climate was first documented in the 19th century by Howard (1833/2007), who described differences in temperature records between the city of London and the surrounding countryside. This phenomenon, known as the Urban Heat Island (UHI), is the result of differences in the energy balance between urban and rural areas. While the UHI phenomenon results from the complex interactions between human activities (e.g., air conditioning, combustion engines, etc.), it is mainly associated with artificial surfaces that accumulate the energy of solar radiation during the day and release it as heat at night, whereas in rural areas, this energy is utilized mainly by vegetation for evapotranspiration. The intensity and extent of this phenomenon are further modulated by the spatial configuration of built-up areas—that is, by the nature of urban geometries and their patterns, also known as urban morphology—that locally modify heat exchange (Kim & Brown, 2021; Oke et al., 2017). The effects of urbanization on the local climate are sometimes so strong that they precede the effects of global climate change, as described by Zhang et al. (2010) for the city of Shanghai.

This raises questions about the habitability and safety of cities (Nieuwenhuijsen, 2021), and all the more so in the current context of global warming and its acceleration (Pörtner et al., 2022). Not only are cities warmer on average than their surrounding areas, but the effects of global warming are also more pronounced (Arnfield, 2003). Accordingly, because of its impact on heatwaves and their consequences – with episodes of excess mortality observed on a planetary scale (Ho et al., 2017; Luber & McGeehin, 2008; Oleson et al., 2015)—UHI is now attracting a growing body of work in geography and climatology (Kim & Brown, 2021), which has even led to the creation of the journal "Urban Climate" in 2012, devoted to the subject. The detrimental effects of urban climate as a whole on human health are now well documented (Argaud et al., 2007) but paradoxically, demographic pressure on urban areas continues to increase worldwide. Models predict that by 2050, 68% of the world's human population will live in cities (UNDESA, 2018), leading to an increase in urban areas over 2015 of 78%–171% (Huang et al., 2019). The projected growth of urban areas raises concerns not only about the future well-being of city dwellers but also about the future of all organisms inhabiting urban ecosystems. Protection of biodiversity in urban areas will require thoughtful consideration of suitable ecological infrastructures and depend on well-informed policy and urban planning decisions (Huang et al., 2019). At the local level, certain territories and policies are addressing the issue of managing heat—and coolness—in cities, notably in urban planning (Climate-ADAPT, 2023; IPBES, 2019). These initiatives are supported by climatologists and geographers whose aim is to get as close as possible to what city dwellers feel (SNO Observil, 2023) to help prioritize management actions in relation to the challenges associated with urban heat and UHI. Similar engagement by ecologists is needed to understand the climatic conditions to which species are exposed in cities, to anticipate the overall impact of heat on biodiversity and ultimately target and strengthen local actions to build resilience and ensure sustainable urban development.

Strong synergies and collaborations between ecologists and climatologists are essential to initiate this engagement. Research at this interface would be all the more beneficial in that it enables leveraging the full potential of urban monitoring networks and maximize its relevance for urban planning. In this perspective, we first highlight that while temperature is shaping the biology of most species, its fine spatiotemporal structure, available from climate monitoring networks, has never been used to understand species assemblages and persistence in cities. Second, considering that research into ecological corridors has found an operational translation and is a tool for urban planning projects, understanding the impact of its climatic component, including temperature, on the distribution and conservation of urban biodiversity can only strengthen these projects. Last, we discuss the representativeness of the data and propose ways of adapting and co-designing these urban climatic networks to make interdisciplinary collaborations fully operational.

2 | RESEARCH IN ECOLOGY IS EXPLORING THE IMPACTS OF URBANIZATION ON BIODIVERSITY, BUT ITS CLIMATIC COMPONENT IS STILL LARGELY UNDEREXPLORED

The number of ecological studies conducted in urban ecosystems has seen considerable growth since the 2000s, making urban ecology a major disciplinary field in ecology (Niemelä et al., 2011). Such momentum can be explained by the fact that understanding and predicting the future of biodiversity is a real ecological and societal challenge given the rapidly changing footprint of cities. But also, urban ecosystems allow changes that otherwise take place at macroecological scales to be studied locally (Diamond & Martin, 2021; Merckx et al., 2024; Merckx, Souffreau, et al., 2018; Rivkin et al., 2019). In particular, the magnitude of urban warming (1–5°C on average) being close to current global warming scenarios and projections (Gao & O'Neill, 2020; Youngsteadt et al., 2015), understanding species responses to urban temperatures could be a good indicator of their ability to adapt more globally to climate change (Diamond & Martin, 2021).

There is ample evidence in the literature of the diverse impacts of cities on biodiversity (Dennis et al., 2017; Hansen et al., 2005; Merckx, Kaiser, & Van Dyck, 2018; Mimet et al., 2009; Thimmegowda et al., 2020), but it is often limited to describing general patterns and how aspects of anthropogenic landscape, particularly habitat fragmentation and, to a lesser extent, climate, shape biodiversity and the biology of urban populations. The impact of the spatial and temporal dimensions of urban climate on biodiversity remains in many aspects largely unexplored (Collins et al., 2024) and the misalignment between the scale biodiversity is sampled, and the temperature data often restricts our capacity to derive robust inferences about the impact of temperature on biodiversity (e.g., Ombugadu et al., 2024). For example, while the importance of UHI is increasingly recognized in ecology, works that do refer to UHI are based on a limited number of temperature records (Battles & Kolbe, 2019; Kaiser et al., 2016; Merckx et al., 2021; Merckx, Souffreau, et al., 2018), or refer to (broad) surrogate variables, such as population density and distance to city centers, which only indirectly indicate altered climatic conditions (Szulkin et al., 2020). In recent decades, however, technological advances associated with dense climate monitoring tools have enabled the collection of high-resolution data on driving forces that shape biodiversity, such as temperature (McDonnell & Hahs, 2013). The spatial structure of heat in cities and its temporal variations is now described at ever finer scales, and the associated raw temperature data can be used to contrast their fluctuations between urban areas and their rural peripheries, as well as between neighborhoods and across temporal scales (i.e., daily, monthly, seasonal, or annual; Dubreuil et al., 2022). These spatiotemporal variations in temperature result from climatological processes that operate at different scales, which explains that their characterization is likely to better capture the complexity of the urban climate that species in cities actually face. Thus, these high-resolution data open new opportunities to study species' distribution in cities and their responses to small-scale variations in urban climate. Making better use of the extensive data collected by climate scientists as part of their ongoing UHI monitoring is, therefore, not only a way of capitalizing on existing data but also an opportunity to unlock new research opportunities for ecologists and environmental scientists, which are all the more relevant given that temperature structures and shapes the biology and population dynamics of most species (Parmesan, 2006).

3 | FROM UHI MONITORING DATA TO INTEGRATIVE NOTIONS OF CLIMATIC LANDSCAPE AND THERMAL CONNECTIVITY FOR BIODIVERSITY

The methods and research questions in landscape ecology, which aim to understand the distribution of individuals and ecological processes in space, feed into our reflections on the impact of urban climatic landscapes on the dynamics of biodiversity. At present, landscape ecology applied to the urban environment focuses mainly on describing how landscape mosaics, and in particular soil mineralization and habitat fragmentation, explain species distributions (Balbi et al., 2021; Hilty et al., 2019; Merckx, Kaiser, & Van Dyck, 2018). If we transpose those works and describe cities through their climate component, with a specific interest in temperature, comprehensive UHI monitoring data could be used to describe this urban climatic landscape, composed of a mosaic of habitats which would be thermally more or less favorable for the establishment and survival of species and thereby explain their distributions in urban landscapes.

Since the effects of temperature on species are well documented, with response curves and thermal optima, we can develop mechanistic hypotheses and test them to assess how temperature shapes the distribution of species in urban areas. In this regard, thermal tolerance and dispersal ability of species are key biological traits to understand their capacity to adapt to new environmental conditions (e.g., higher temperatures) and, if available, to disperse into habitats that are thermally more favorable (Bellard et al., 2012). For example, by comparing species' thermal tolerance (the lower and upper limits) with the temperature of the habitat, we can assess the extent to which species are living at the edge of their thermal limits, and predict their fate in the face of expected warming (Bennett et al., 2018, 2021). The ability of species to persist in heterogeneous and highly fragmented urban landscapes is additionally understood by accounting for their ability to disperse, which will determine their capacity to reach thermally suitable habitats, and thereby have a direct impact on their fate and risk of extinction (Thomas et al., 2004). Even temporary exposure to temperatures above critical thresholds can be lethal for species that cannot escape and threatens those that can only compensate for such a temperature in the medium term by using local microhabitats through behavioral thermoregulation, such as burrowing (Fey et al., 2019).

Research into the relationships between the spatiotemporal structure of temperature and the distribution of species and their biological traits could help to identify functional thermal corridors to increase connectivity in urban environments. The concept of corridors is certainly not new and the operational implementation of movement corridors is widely supported by public policies and conservation actions from local to international levels (IPBES, 2019), but here, we propose to extend this concept to climate corridors. The concept of corridors was initially defined solely on the basis of land use that, combined with reservoirs, define a network of ecological continuities favorable to the movement and reproduction of species, that are the green and blue infrastructures. Since then, and because of their effects on the behavior and reproduction of many species (Hölker et al., 2010; Hoy & Robert, 1996; Vaz et al., 2022; Zapata et al., 2019), other constraints to the movement and persistence of species such as anthropogenic light sources (the ALAN effect and its associated dark corridors) and noise, are also considered when defining functional ecological corridors. At this stage, however, and while there is a wealth of work on the impact of temperature on species, few have proposed climate corridors as such (see Hilty et al., 2019), and to our knowledge none at a city scale. The few studies that exist on this topic have been conducted to predict the fate of biodiversity in the face of environmental change, mostly measured at macroecological scales. For example, McGuire et al. (2016) sought to assess the extent to which species would be able to follow their climate niche on the scale of 100-year climate predictions. A similar approach was taken by Su et al. (2021) to assess climate connectivity in the Yangtze Delta, a densely populated economic region in China. In both cases, climate connectivity depends on the availability, contiguity, and suitability of land use required for species to move and reach thermally favorable habitats. However, reduced habitat contiguity does not necessarily impair individual movement, especially if species have few interactions with the land use when they move (as is the case for species that fly to migrate). This is exacerbated in urban environments because the geographical extent considered is, for many species, at a smaller scale than the extent of their dispersal capacities. Therefore, the movement of species in urban environments may be more restricted by UHI and temperature extremes than by the geographical distance between habitats. The climatic resistance to movement through an urban matrix, measured as the cumulative values of temperature over a distance between two suitable habitats, may become a real barrier to species' movement or, at the very least, significantly limit species capacity to move between thermally suitable habitats. The climatic resistance to movement, or conversely climatic permeability, is all the more structuring in cities where temperatures vary on extremely short time and space scales. We thus need to characterize this climatic landscape to define cool infrastructures and the movement corridors they can provide, in the same way as it is done for the green and blue, and dark infrastructures that exist for land use and light, or maps of sound pollution. Recent works emphasize even more clearly the need to study thermal fluctuations and extreme high-temperature events, knowing their impacts on population dynamics (Ma et al., 2021) and species evolution (Buckley & Huey, 2016; Clusella-Trullas et al., 2011; Kingsolver & Buckley, 2017; Paaijmans et al., 2013). Accounting for the non-linear relationship between species performance and temperature would significantly improve the accuracy of our predictions on species population dynamics (Denny, 2018) and help to identify and prioritize biodiversity-friendly corridors in urban landscapes based on quantitative and functional elements in terms of population dynamics.

4 | LIMITS IMPOSED BY THE RESOLUTION OF CLIMATIC AND BIOLOGICAL DATA

To develop an understanding of the biological mechanisms that determine species composition and distribution in cities from temperature data collected through UHI monitoring networks, we need to overcome the mismatch in data requirements (e.g., type and resolution) between ecology and climatology. The difference in data resolution highlights the need to adapt the UHI monitoring network to provide and retain fine-scale data needed by ecologists if we are to ensure that such interdisciplinary research can be conducted and thrive.

What first led climatologists' to study UHI phenomenon was their interest in understanding its formation and dynamics, in other words, the physical processes that drive the phenomenon. Therefore, work on urban climates generally involved UHI data measured at a resolution that describe the phenomenon at the local or meso scales (as defined by Kim & Brown, 2021), and for stratum in or above the urban canopy and buildings (Oke, 1976). However, these scales are (horizontally) larger than the habitats in which city dwellers live and for a (vertical) stratum that is far above where most urban biodiversity disperses. Indeed, urban dwellers and a large proportion of urban species are likely to be sensitive to UHI occurring at the micro-scale that results from air temperature measured at the street level (Hwang et al., 2015). On the other hand, the few studies that have attempted to describe the UHI phenomenon at the micro-local scale are confronted with an inconsistency between the resolution of the climate data used to calculate the UHI and the scale at which its effect is interpreted (Kim & Brown, 2021). Indeed, most of these studies rely on infra-red data obtained from satellites available at a resolution of 60 m and a frequency that does not allow daily tracking. Temperature derived from satellite imagery also presents the caveat that information is limited to temperature variations at the surface, and does not include a direct measurement of air temperature variations. Although the processes that explain the genesis and dynamics of UHI phenomena at the surface and in the air are related, they are shaped by different processes and result in regional differences (Oke et al., 2017). Other studies rely on data collected through networks of climate stations which, while partly compensated with spatial statistics methods to interpolate values between measurement points (Amorim et al., 2021; Foissard et al., 2019), are limited by the location and number of stations.

However, in their effort to identify and isolate the causes of UHI, climatologists have considerably developed and densified the urban climate monitoring networks and thereby partly addressed these caveats. Historically, large conurbations and metropolises were often the first to set up climate networks. Since UHI phenomena are generally proportional to city size, they are often more pronounced and have far greater consequences in large and dense urban areas (Manoli et al., 2019). Nevertheless, the phenomenon occurs in cities of all sizes, further vary across climate zones, and is modulated by the texture and the morphology of the city (Manoli et al., 2019). This explains why, alongside technological development and reduced costs, climate monitoring networks are being deployed around the world to characterize and monitor UHI, as is the case in Rennes (467,580 inhabitants in 2020, Brittany, France, Dubreuil et al., 2022). In particular, technical developments in semi-professional stations since the 1990s have made it possible to densify the network of fixed weather stations at an affordable cost, while reducing the workload associated with mobile measurements along transects. The spatial resolution for modeling the UHI has also continued to increase over the last decade with the use of low-cost connected or participatory sensors strategically located to better capture the heterogeneity and complexity of urban space where people live, capture micro-scale phenomena such as wind or radiation or explore the impact of urban planning (generally described by the LCZ). Yet, even though there are continuous efforts to refine the monitoring network and place sensors in a homogeneous and controlled manner, cities represent complex climatic mosaics whose diurnal micro-scale variation in temperature remains difficult to understand. These climate data are also restricted to the vertical stratum where the weather stations and sensors are placed, that is, at a height of 2 or 3 m, which represents a compromise between the reference measurement in climatology and the risk of damage. Moreover, only few networks currently allow to study the impact of UHI over time (Bai et al., 2018; Dubreuil et al., 2022). More generally, what is true for temperatures (the preferred parameter for studies on the UHI) is also true for the other parameters that these stations and sensors can monitor, such as humidity or wind, and that describe the state of the urban atmosphere.

With respect to the characterization of the spatial structure of temperature, we strongly believe that extending current climate monitoring in other vertical strata (soil, ground surface, air) would be particularly useful for urban ecology.

Temperature profiles are highly variable between strata (He et al., 2022; Wong et al., 2021), especially at ground level where many species live, while UHI monitoring is mainly derived from air temperatures measured at about 2 m above ground level. Hence, knowledge of the temperature profiles across strata (using drone or sodar technologies) would allow us to more accurately describe and link ecological processes and population dynamics of species to the thermal environment they experience. This work is essential if we want to support evidence-based decisions and guide urban planning to improve the habitability of cities. To this end, the location and the density of weather stations and sensors within climate monitoring networks are crucial. A monitoring network design that providing reliable data of night-time and daytime temperature would make it possible not only to characterize and track UHI, which occurs mainly at night, but also to identify areas prone to extreme daytime temperatures and that can represent a threat to many species. Other climate parameters such as hygrometry and precipitation—yet sometimes already available from climate monitoring networks—could also be monitored and characterize, not only because they interact with temperature and the overall local conditions conducive to the formation of UHI (Kastendeuch et al., 2019), which further differ between climate regions (Manoli et al., 2019), but also because they can influence the effects of heat on organisms. For some species, water stress can be more harmful than climatic stress (Burdine & McCluney, 2019).

While the shortcomings in climate records and the lack of comprehensive climate monitoring networks across cities hamper our ability to explore general patterns between the spatial structure of temperatures and species distribution in cities, a proxy approach can, on the short term, partly compensate for the limitations in the current data and be used to start exploring these associations. Zhao (2018) shows that surface UHI correlates strongly with city Local Climate Zones (LCZs) classification, which are based on morphological and land-use units. With certain limitations (Richard et al., 2018), LCZs can be used as climate proxies to assess climatic connectivity at the city-wide scale. Much work also remains to be done in ecology and evolution to understand the dynamics of biodiversity in urban environments and decipher the underlying mechanisms. To give just one example where improvement is needed: while species' thermal tolerance is often used to explain the pattern of species' occurrence in urban areas, the reference data available in the Globtherm database (Bennett et al., 2018) are derived from measurements made on individuals from populations collected in distant geographical areas. However, because adaptive change can occur on very short timescales (Brans et al., 2017; Diamond et al., 2017, 2018; Merckx et al., 2024), intra-specific and inter-populations measures collected across small spatial (and climatic) gradients are needed to assess species' plasticity, their ability to adapt to changes, and at which speed. We also need to better understand the physiological mechanisms that determine species' thermal tolerance, an area that remains largely unknown (González-Tokman et al., 2020), despite its importance for predicting species' response to climate.

5 | CONCLUSION

There is no doubt that temperature is an important determinant of species' distribution and survival, and that understanding its spatiotemporal dynamics in cities—and even further explore how they vary across climate zones, between urban morphologies, including the temporal trajectories of urban sprawl—is crucial if we are to rethink and plan ahead the design of cities to enable essential ecological processes for species to move, persist and evolve in urban environments. In this context, we believe it is crucial that ecologists work more closely with geographers and climatologists so that the temperature, and more widely all the other climatic variables collected as part of the monitoring of UHI, can eventually be used to understand the dynamics of biodiversity in cities.

Habitat, generally delineated by land cover type, is often the only object upon which conservation measures are undertaken. Although habitats can be physically identified, mapped, and manipulated through land-use planning their suitability for species is also determined by other factors such as climatic conditions. Thinking about climatic infrastructures and thermal corridors, and integrating them into ecological infrastructures that already exist to characterize anthropized environments (associated with artificial surface, light, and noise pollution, etc.) would greatly improve our understanding of the permeability of urban areas for biodiversity and contribute to the development of more sustainable urban planning. The increasing number of days with strong UHI observed over the last decades and the so-called tropical nights, due in part to the pressure on land biased against natural habitats, makes these ecological and thermal corridors all the more vital for species persistence. Their implementation is also reinforced by the obvious benefits they represent for human health. Evidence-based understanding of the role of urban climate on biodiversity and how it varies around the globe is urgently needed to guide, support, and reinforce initiatives already undertaken by decision-makers, for whom climate management is becoming a central political issue in the face of the threat posed by global warming to the habitability of cities. The development of a climate monitoring network that can inform on climatic conditions in areas where species live and transit, combined with a deeper understanding of species' climatic requirements, along urbanization gradients, would help ecologists and climatologists work toward that objective. Finally, we would like to emphasize the importance of investigating the relationships between the temperature landscape measured at multiple scales and across strata (i.e., three-dimensional structure) and the dynamics of species living and transiting in these complex environments. Such research could be used to identify urban morphologies and develop infrastructures that "work" for biodiversity and people in different urban contexts.

AUTHOR CONTRIBUTIONS

Hélène Audusseau: Conceptualization (lead); investigation (lead); visualization (lead); writing – original draft (lead); writing - reviw and editing (equal). **Reto Schmucki:** Visualization (supporting); writing – original draft (supporting); writing – review and editing (equal). **Solène Croci:** Conceptualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Vincent Dubreuil:** Conceptualization (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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