ACADEMIA
ENVIRONMENTAL SCIENCES &
SUSTAINABILITY

Opinion
Published: 2025-10-29
https://doi.org/10.20935/AcadEnvSci7981

Why urban greening requires more than just species biodiversity

Ángel Enrique Salvo-Tierra[1,*], Ángel Ruiz-Valero[1]

Academic Editor: Romina D. Dimarco

Abstract

Over the past decades, a noticeable shift has taken place in the relationship between humans and nature. There is a growing interest in re-naturalizing urban environments by increasing vegetation cover as a means to foster more resilient cities and enhance environmental comfort for urban dwellers. Numerous policy recommendations emphasize vague targets such as increasing urban biodiversity or expanding tree canopy cover. While these indicators are indeed relevant and contribute to ecosystem service provision, they remain insufficient as standalone goals, failing to account for the complexity of factors involved in the design and planning of green urban infrastructure. This article places particular emphasis on the role of trees as the core unit of green infrastructure. Other vegetative strata, such as herbaceous layers or vertical greening systems, are acknowledged but regarded as secondary or complementary to tree-based systems. We highlight the conceptual ambiguity surrounding terms like "biodiversity" or "canopy increase" and argue that these metrics, although widely used, must be subordinated to a more integrative and function-driven planning paradigm. Urban forestry strategies should not aim merely to boost biodiversity indices but rather to develop evidence-based planting proposals that consider plant functional traits, optimize ecosystem service delivery, minimize disservices, and ensure species selection aligns with future climate conditions. This also involves maximizing genetic diversity, conducting detailed assessments of below-ground conditions (soils), as well as canopy height and diameter class structures, to enhance resilience against pests and diseases. Furthermore, spatial distribution must be planned to ensure justice and equity across socioeconomic groups. Ultimately, fulfilling all these criteria is likely to result in more biodiverse urban forests, but this diversity will be the consequence of well-defined, objective, and scientifically grounded decisions, rather than an arbitrary increase in a metric whose optimal threshold remains undefined. The goal is not simply more biodiversity, but smarter, functionally informed biodiversity.

Keywords: *plant diversity, urban forestry, ecosystem services, climate-resilient cities, green infrastructure*

Citation: Salvo-Tierra ÁE, Ruiz-Valero Á. Why urban greening requires more than just species biodiversity. *Academia Environmental Sciences and Sustainability* 2025;2. https://doi.org/10.20935/AcadEnvSci7981

1. Reintroducing nature into urban spaces: the ecocentric turn

We are witnessing the dawn of a new era, marked by technological advances and shifting paradigms in the human-nature relationship. The relationship between humans and nature has undergone a significant shift in recent decades, moving away from the traditional anthropocentric worldview towards a more ecocentric perspective [1–3]. This shift is reflected in the growing body of research on environmental worldviews and their influence on pro-environmental attitudes and behaviors. Such research is influenced by various factors, including socialization processes, such as education and cultural influences [4, 5], as well as personal values, such as biospheric and altruistic values [6, 7]. The shift towards a more ecocentric worldview has also been observed in various contexts, such as in the field of environmental education [8], sustainable development [9, 10], and environmental policy [11, 12].

Cities, as the most densely populated human settlements, are undergoing a significant paradigm shift toward the reintegration of nature into the urban fabric. This transition is increasingly driven by robust scientific evidence highlighting the multifaceted benefits of urban green spaces, including improvements in physical and mental health, air quality regulation, and overall urban livability [13–16]. Moreover, the strategic incorporation of nature into urban planning plays a crucial role in climate change adaptation, mitigating the urban heat island effect, and fostering urban biodiversity. These outcomes underscore the pivotal function of nature-based solutions in advancing sustainable, resilient, and inclusive cities [17–19].

Given the proven capacity of urban green spaces and urban green infrastructure more broadly to provide multiple ecosystem services in a measurable and well-documented manner, such as sequestering carbon and producing oxygen through photosynthesis, as well as supporting wildlife via the resulting biomass [18, 20–22]; removing atmospheric pollutants [23–25]; mitigating the urban heat island effect [26–29]; and reducing stormwater runoff [30–34], in addition to delivering diverse social, cultural, and human health benefits [35–38], multiple cities worldwide are increasingly adopting urban greening initiatives (**Table 1**). For a more comprehensive overview of cities globally implementing urban greening strategies, see Kumar et al. [39] and references therein. These strategies are aligned with Sustainable

[1]Department of Botany and Plant Physiology, Faculty of Sciences, University of Malaga, Málaga, Spain.
*email: salvo@uma.es

Development Goal 11 (SDG 11), which emphasizes making human settlements safe, resilient, and sustainable [40], as well as with complementary strategies such as the 3-30-300 rule. However, global assessments continue to reveal insufficient tree canopy cover in most of the cities analyzed [41–44].

This opinion article examines whether cities should aspire to become both refuges and engines of biodiversity in the Anthropocene and whether such a goal is justified. Drawing on ecological theory, urban resilience, and landscape planning, the article challenges the conventional view of cities as entropy-driven systems and instead highlights their latent potential for ecological regeneration. It calls for a paradigm shift in urban planning, advocating for a multidimensional and integrative framework grounded in functional diversity, long-term resilience, and socio-environmental equity. Rather than pursuing biodiversity as an abstract metric, it proposes a scientifically guided design of urban ecosystems that are adaptive, just, and capable of sustaining ecosystem services in the face of accelerating global change. Although the proposed integrated assessment framework, based on scientific literature review, supports conducting urban forestry interventions in a context-specific manner to enhance tree viability, survival, and ecosystem service provision and would be applicable to any city under any climate given its function of constraining the pool of usable species for each specific location within the urban matrix, it may have greater influence or applicability in Mediterranean-temperate climates, where the authors of this opinion article primarily conduct their research. Nevertheless, we consider that the proposed framework, similar to a multi-criteria analysis, is applicable to any city, though detailed studies are needed to evaluate its applicability in cities with different climates and characteristics.

Table 1 • Examples of cities implementing urban greening strategies worldwide. This table presents a non-exhaustive selection of cities demonstrating diverse approaches to urban greening implementation across different geographical contexts, scales, and timeframes. The examples illustrate how multiple cities worldwide are actively considering and implementing urban greening measures as integral components of their sustainable urban development strategies.

City	Country	Timeline	Key objectives	References
Paris	France	2020–2030	Transform 50% of the city into an urban forest; plant 170,000 new trees by 2026	[45, 46]
Barcelona	Spain	2021–2030	Nature-based solutions, ecological connectivity, Tree Master Plan 2017–37	[47, 48]
Milan	Italy	2018–2030	Plant 3 million trees in metropolitan areas for climate neutrality integration	[49, 50]
Singapore	Singapore	Ongoing	Comprehensive urban greening with green corridors and vertical vegetation	[51–53]
Melbourne	Australia	2021–2040	Increase tree canopy cover from 22% to 40%; resilient and diverse forest	[39, 54, 55]
New York	USA	2007–2017	Plant one million trees, focusing on underserved neighborhoods (MillionTreesNYC)	[39, 56]
Copenhagen	Denmark	Ongoing	Green roof policies and street-level greening for flood risk mitigation	[39, 57]
Adelaide	Australia	2018–2035	Increase tree canopy cover from 33% to 40% with water-sensitive design	[39, 58]
Cardiff	UK	2020–2030	10-year afforestation program for carbon neutrality; 82,000+ trees planted	[39, 59]
São Paulo	Brazil	Ongoing	City-wide rain gardens and linear parks for urban drainage management	[39]
Nanjing	China	2018–ongoing	Architectural vertical forests with 800+ trees and 2500 shrubs on towers	[39, 60]

As with the transition from the Gothic to the Renaissance, fueled by the printing press, maritime advances, and global connectivity, our current transition is driven by artificial intelligence, aeronautics, and exploration beyond Earth. Crutzen and Stoermer [61] named this epoch the Anthropocene, characterized by technological acceleration, explosive population growth, and massive resource consumption. Lovelock [62] pushes this further in his concept of the Novacene, where intelligence no longer relies solely on DNA- or RNA-based organisms but on digital systems and "cyborgs." In both scenarios, the urban habitat becomes central to the human condition, resembling the evolution of eusocial species (Harrison et al., 2018) [63].

Homo sapiens has transitioned from a rural to an urban species. The urban ecosystem, despite its tensions and linear metabolism, remains a magnet for human settlement. Urban sprawl, often dictated by market logic and disconnected planning, disrupts ecological equilibrium [64]. Urban areas now cover around 3% of continental surfaces [65], while farmland covers five times more [66]. Forests, home to 80% of terrestrial biodiversity, occupy a shrinking proportion. These disparities underscore humanity's growing ecological footprint.

Conceptual provocations such as Liam Young's "Planet City" or the space colonization fantasies of tech billionaires illustrate our ongoing struggle to reconcile rapid urban growth with the imperative of environmental preservation. In this context, the two dominant paradigms of urban development, urban sprawl and compact city models, embody contrasting yet equally imperfect solutions. Each offers distinct advantages and limitations, underscoring the persistent tension between expansion and sustainability, and ultimately revealing their status as compromise strategies rather than definitive answers. (1) Urban sprawl, defined by low-density and decentralized growth, offers benefits such as larger living spaces, access to nature, and reduced local congestion [67, 68]. However, it also leads to greater car dependency, higher emissions, habitat fragmentation, and social segregation [69, 70]. (2) Conversely, compact cities encourage high-density, mixed-use development that enhances energy efficiency, supports sustainable mobility, and helps conserve natural and agricultural land [70–72]. Yet, this model can intensify the urban heat island effect, degrade air quality, and reduce green space availability, impacting public health and biodiversity [17, 26, 73–75].

Despite the paradigm differences between urban development models, the concept of urban resilience is gaining increasing prominence in both academic research and practical implementation, regardless of the specific system or urban development typology. Urban resilience refers to the capacity of cities to absorb, adapt to, and recover from a range of shocks and stresses, including those linked to climate change, natural disasters, and socioeconomic disruptions, while maintaining the continuity of their essential structures and functions [76]. Originally conceptualized within the framework of ecological systems theory [77], resilience has since evolved into a foundational principle of urban design and planning. Recent studies highlight that fostering resilience in urban contexts requires integrated and multidimensional approaches that encompass environmental, social, infrastructural, and institutional components. Such approaches enhance a city's adaptive capacity and contribute to long-term sustainability. As urban areas are increasingly exposed to more frequent and severe challenges, the development of resilient urban systems has become a central objective in planning and policy agendas, ensuring their ability to withstand and swiftly recover from adverse events [78].

2. Green infrastructure in cities: how do we assess it?

Urban green infrastructure plays a crucial role in strengthening the resilience of cities by delivering a wide array of ecosystem services that support adaptation and recovery in the face of environmental stresses and shocks. Beyond its adaptive functions, green infrastructure also presents significant opportunities for ecological naturalization, contributing to the regeneration of degraded urban ecosystems while simultaneously improving environmental quality and human well-being. This dual capacity to bolster resilience and restore ecological integrity underscores the vital importance of embedding green infrastructure at the core of contemporary urban development strategies [79–83].

From the medieval hortus conclusus to contemporary post-industrial urban parks, cities have progressively incorporated increasingly diverse plant assemblages. However, a widespread misconception, particularly in public discourse and non-scientific areas, is that merely increasing plant biodiversity in urban settings is inherently sufficient. For instance, Andres et al. [84] aimed to clarify the notion of "biodiverse reforestation," highlighting its relevance for both climate change mitigation and biodiversity conservation. They argue that successful reforestation must deliberately embed biodiversity goals, emphasizing species diversity not as an end in itself but as a strategy to enhance carbon sequestration, support ecosystem functionality, and ensure long-term species survival. This intentionality fosters more resilient and sustainable restoration outcomes.

Although biodiversity is frequently equated with species richness, ecological diversity more accurately captures the structural, functional, and relational complexity of ecosystems [85, 86]. As demonstrated across the literature, the sustained delivery of ecosystem services depends less on the absolute number of species and more on the presence of ecologically functional vegetation and the maintenance of interspecific interactions that uphold critical ecological processes [87–89]. A narrow focus on maximizing species count risks overlooking essential traits, such as drought resistance, phenological complementarity, or pollinator attractiveness, that underpin the ecological performance of urban green spaces. Initiatives such as Miyawaki forests or the "Alboranic biodiversity islands" exemplify how strategically designed, functionally diverse plant communities can enhance resilience and generate a broad spectrum of ecosystem services even within high-density urban environments [90, 91].

In a similarly flawed manner, indicators such as the NDVI (Normalized Difference Vegetation Index) and tree canopy cover are widely used to assess urban vegetation, yet they fall short in capturing the ecological complexity underlying the provision and accessibility of ecosystem services. While these metrics estimate the surface presence and spatial distribution of vegetation, they are insufficient to reflect key dimensions such as the functional quality of green spaces, vegetation structure or species diversity. Likewise, canopy cover, limited to a two-dimensional representation, overlooks important factors such as biomass density, vertical

stratification, etc. [92]. Relying exclusively on these indicators risks producing biased or incomplete interpretations of urban greenness.

Although both indicators, diversity and canopy cover, are fundamental components associated with the delivery of urban ecosystem services, efforts to enhance green infrastructure should not rely solely on increasing these metrics at the city scale without critically assessing the specific strategies and contextual conditions under which such increases are implemented. A purely quantitative rise, if detached from spatial, ecological, and socio-functional considerations, risks resulting in interventions that are inefficient, inequitable, or ecologically superficial. In this regard, the insight of Edwin Thompson Jaynes, originally formulated within the realm of probability theory, offers a compelling parallel for urban greening: "*It appears to be a quite general principle that, whenever there is a randomized way of doing something, then there is a nonrandomized way that delivers better performance but requires more thought*" [93]. Applied to the design of urban nature, this principle highlights the necessity of intentional, context-sensitive planning over indiscriminate or purely metric-driven approaches. Consequently, any increase in indicators such as diversity or canopy coverage must be underpinned by a comprehensive understanding of the multiple biotic and abiotic factors that influence the long-term viability of urban vegetation and its capacity to sustain ecosystem service delivery. This is particularly crucial given the growing evidence that a significant proportion of trees planted in urban environments today may not reach maturity or achieve their potential functional value, ultimately compromising the resilience and effectiveness of urban green infrastructure [94].

3. Are urban trees the central unit of green infrastructure? Mapping areas for planting and conservation

A fundamental starting point for understanding the needs and requirements associated with urban greening and the development of green infrastructure is the segmentation of green spaces according to vegetation strata, particularly the distinction between herbaceous and woody vegetated areas [95]. In this regard, features such as lawns, green roofs, green façades, and similar forms of green infrastructure should not be considered as providers of ecosystem services beyond their esthetic, visual appeal, habitat provision or the capacity of lawns to absorb water in flood-prone areas [96–99]. The literature indicates that green spaces lacking trees or dense woody vegetation often have negligible or even negative impacts on human well-being [100–103]. This underscores the importance of prioritizing tree-based and multilayered vegetation structures in urban planning if the goal is to achieve meaningful ecological and social benefits. This is not to suggest that other vegetation strata do not offer benefits; however, in spatially constrained urban environments, trees represent a particularly practical and efficient solution. Their vertical structure and large biomass enable them to deliver a disproportionately high return on investment compared to lower vegetation forms, maximizing ecosystem service provision within limited ground space. As such, trees are uniquely positioned to address both ecological and social challenges in dense urban settings.

Considering urban trees as the operational unit of work prior to the multifactorial process described below, a thorough assessment of the existing situation of the urban forest must be carried out before performing any type of planting. In this regard, knowledge of the spatial distribution of trees, identification at the species level, and certain structural characteristics such as height, crown dimensions, and DBH (diameter at breast height) constitute necessary baseline information. This information is necessary for calculating ecosystem services that can serve as a basis for delimiting hotspots and cold spots of provision that need intervention or for developing more complex management methods based on ordination methods using additional information that could be consulted in databases such as TRY [104]. Ultimately, after evaluating all relevant information, and necessarily in a spatial manner, this must be integrated through multi-criteria analysis that allows delimiting those areas of cities with higher priority for planting or for allocating existing economic resources for new urban tree planting [105–111]. Spatial prioritization should constitute the first step in any new urban tree planting project, and among the different selected areas, context-specific interventions and actions should be carried out on each one, considering the multiple factors that the authors propose should be worked on in an integrated manner. Similarly, those areas that already have significant tree cover and are not considered a priority for intervention should also take into consideration the different factors so that management is scientifically guided and effective protection of existing resources is achieved.

4. A multidimensional space: what tree factors should be assessed for planting and management?

A fundamental consideration in urban forestry is the role of functional traits, defined as morphological, physiological, or phenological characteristics measurable at the individual level that directly influence plant adaptation, survival, growth, and reproduction, and thus determine their functioning [112]. These traits are essential for understanding how different species contribute to the provision and long-term maintenance of ecosystem services [92, 113]. In this context, urban forestry should prioritize the enhancement of tree longevity and health, given that mature, vigorous individuals provide disproportionately greater benefits to urban environments [114]. Large-diameter and long-lived trees constitute critical components of urban green infrastructure due to their unique ecological contributions and structural stability [115, 116]. With fuller crowns and more extensive leaf surface areas, these trees enhance ecosystem functioning more effectively than smaller or younger individuals [117–120]. The magnitude of these contributions can vary not only across species [113, 121, 122] but also within species, depending on age and size. Therefore, the conservation and management of urban forests must focus on supporting the survival and performance of such individuals to optimize ecosystem service delivery and strengthen urban resilience in the face of accelerating climate change [123].

Large trees, despite their disproportionately critical role in the delivery of ecosystem services, are subject to the highest number of threats and are experiencing a pronounced global decline [115]. In the face of accelerating climate change, urban forestry must move

beyond treating species as taxonomically fixed and homogeneous units. Instead, it should recognize and incorporate the significant genetic variation that exists within species. Urban planning and tree selection strategies must proactively identify and promote genotypes or ecotypes that are best suited to future climatic conditions, thereby ensuring long-term planting success and optimizing ecosystem service returns on investment [124]. The urgency of this adaptive approach is underscored by recent findings from Esperon-Rodriguez et al. [125], who reported that projected urban climate conditions have already exceeded the climatic tolerance thresholds of 56–65% of tree species currently planted across 164 cities in 75 countries. This alarming mismatch highlights the necessity of shifting toward the selection of climate-resilient species and provenances that are not only capable of surviving but also of thriving in increasingly stressful and unpredictable urban environments [126].

In this context, promoting intraspecific variation and focusing on functional traits is essential. Traits such as specific leaf area, photosynthetic rate, and water-use strategies determine how trees respond to urban stressors like drought, heat, and pollution, ultimately shaping their capacity to provide key ecosystem services [127–129]. Recent research underscores that functional trait diversity and plasticity enable urban trees to adapt to the heterogeneous conditions characteristic of cities, thereby enhancing resilience and ensuring sustained ecosystem functionality. Individuals originating from harsher climates or stressful growing conditions, environments analogous to projected future climates, may possess adaptive traits that increase their likelihood of survival [130, 131]. For example, sourcing genotypes from warmer parts of a species' distribution may introduce beneficial traits that improve adaptive capacity [132]. The success of urban greening under climate change hinges on phenotypic plasticity and the standing genetic variation available for natural or artificial selection [94, 133].

Age structure diversification is also a critical consideration in urban forestry. Urban forests, particularly street tree populations, frequently exhibit limited age heterogeneity [134], which significantly increases their vulnerability to synchronous decline or failure. Such simultaneous losses can lead to abrupt and prolonged disruptions in the provision of essential ecosystem services. This vulnerability is further exacerbated by escalating pressures from climate change, pests, and diseases, underscoring the imperative to incorporate a broader range of age classes in urban tree populations to enhance their resilience and long-term sustainability.

Species diversification has generated significant debate regarding the use of native versus non-native species in urban greenery, particularly concerning the invasion potential of exotic species. According to a recent review by Kumar and Singh [135], invasive alien plant species alter native ecosystems, weakening essential ecosystem services and ultimately harming human health. Furthermore, their rapid expansion and resource competition displace native flora, exacerbate environmental pollution, and generate elevated socioeconomic costs, highlighting the urgency of transdisciplinary approaches for sustainable management. Silva et al. [136] observed that exotic tree species exhibit greater reproductive capacity than native species, and this high reproductive capacity represents a significant risk to native species by competing for pollinators, altering existing pollination networks, and potentially facilitating invasion processes that can displace native flora. They suggest that for tropical urban ecosystems, where an extensive species pool exists, native species should constitute the first option.

In Europe, Sjöman et al. [137] argue that species selection cannot categorically exclude exotic tree species, especially in regions with limited native species catalogs that prove insufficient to satisfy the ecosystem services and resilience required in harsh urban environments, a consideration that becomes even more critical in the face of climate change [125, 138, 139]. "Native-only" approaches may compromise urban ecosystem resilience, particularly in regions with extreme environmental conditions where native species lack the necessary tolerance to survive in built environments. While legitimate invasion risks may exist with some non-native species that can escape cultivation and become invasive [140], they also highlight their potential inability to support native fauna diversity comparable to their native counterparts, resulting in decreased food web complexity [141–146].

Arguments favoring non-native species include their higher growth rates and proper development of fine root biomass systems under drought conditions when originating from geographically adapted climatic areas [147], high capacity for ecosystem service provision [140, 148], and potential to contribute to climate-resilient species assemblages when selected using ecological trait-based approaches, including isohydric behavior or characteristics such as leaf critical temperature, leaf water potential at turgor loss point, or stomatal conductance [124, 149–151]. These attributes could translate into more rapid, durable, and resilient ecosystem service provision.

Such arguments, both for and against, lead to the necessity of context-specific management, consistent with this manuscript's proposal, given the existing trade-off between invasion risks and provision-resilience benefits. Site-specific risk assessments that consider bioregional context and current and projected climatic conditions are therefore necessary, adapting urban policies on non-native tree use to specific surrounding environmental characteristics of the intervention area rather than adopting blanket prohibitions across the entire urban matrix.

A comprehensive understanding of urban tree performance must begin below ground, where many of the most critical yet frequently overlooked stressors are found. Root development and soil conditions fundamentally influence tree health, structural form, and longevity; however, these factors remain insufficiently integrated into urban forestry planning and practice [123]. Urban soils are often compacted, poorly aerated, and chemically imbalanced, creating inhospitable environments that severely constrain root growth and function [152]. These below-ground limitations compromise tree stability, water and nutrient uptake, and overall resilience, constraints that cannot be fully mitigated by above-ground interventions alone. Consequently, to secure the long-term viability and functionality of urban green infrastructure, prioritizing soil quality, adequate rooting space, and optimal subsurface conditions is essential in tree selection, planting, and maintenance protocols. Recent tree-planting strategies, such as structural cells, structural soils, and enhanced tree pit systems (particularly suspended pavement systems), have demonstrated significant positive outcomes. These include increased root colonization in the soil, higher growth rates, more extensive and better-developed root systems that support larger and healthier trees and improved mechanical stability when compared with conventional tree pit plantings [153–156].

While urban trees provide numerous ecosystem services, it is crucial to recognize their potential to generate disservices. These negative impacts include economic costs associated with maintenance, property damage, safety hazards arising from reduced visibility or increased concealment, and nuisances such as leaf litter and root intrusion [157]. Among the most studied ecological disservices are the emission of biogenic volatile organic compounds, which react with nitrogen oxides to form ground-level ozone, thereby exacerbating urban air pollution [158], and the production of allergenic pollen, which poses health risks for susceptible populations [159]. These challenges highlight the critical importance of informed species selection. Implementing site-appropriate species not only optimizes the delivery of ecosystem services but also minimizes disservices, ensuring that urban forestry initiatives promote both public health and sustainable urban environments.

Finally, beyond the imperative to avoid uncritical increases in tree quantity and diversity, spatial distribution must be recognized as a fundamental priority. The literature consistently shows that socioeconomically disadvantaged groups are both exposed to the most harmful environmental conditions and have the least access to the benefits provided by urban trees.

Multiple studies have documented the strong link between environmental inequality and health outcomes [160, 161]. Low-socioeconomic status communities face higher exposure to air pollutants and other environmental hazards [162–164]. Furthermore, research on how socioeconomic position influences exposure disparities in air pollution across ethnic groups has found that these inequities persist even after adjusting for socioeconomic status [165, 166]. In both the U.S. and the Netherlands, minority ethnic groups experience higher pollutant concentrations than the majority population [164, 167, 168]. Regarding the urban heat island, individuals with lower socioeconomic status and pre-existing health conditions endure greater exposure and vulnerability to its adverse effects [169, 170]. In U.S. cities, Black residents and those living below the poverty line experience higher urban heat intensities [171]. Aznárez et al. [172] revealed significant mismatches between cooling supply and demand in Vitoria-Gasteiz, where socioeconomically disadvantaged areas face pronounced deficits, whereas more affluent neighborhoods enjoy privileged access to urban vegetation's cooling benefits.

Regarding accessibility to vegetation and its services, research has consistently identified correlations between neighborhood income and vegetation greenness [173, 174]. These studies highlight the uneven distribution of urban canopy cover, resulting in inequitable access to ecosystem services, largely influenced by socioeconomic factors [169]. This socioeconomic disparity, often referred to as the "luxury hypothesis," suggests that wealthier residents have greater financial resources to invest in the planting and maintenance of vegetated landscapes [175]. Numerous studies have documented that tree cover is frequently unevenly allocated among communities with diverse demographic and socioeconomic characteristics, with lower-income neighborhoods and ethnic minorities consistently experiencing significantly lower canopy coverage [35, 176–179]. Strategically directing planting efforts to promote equitable tree distribution addresses critical social and environmental justice concerns and advances progress toward SDG 11, which aims to create inclusive, safe, resilient, and sustainable cities.

Given that the discussion presented is highly focused on urban contexts and could lead to the incorrect conclusion that the authors suggest that the urban forest is composed solely of street trees and those existing in parks and gardens, it is also necessary to emphasize the central role that natural forests near the city, peri-urban forests, and even isolated forest patches existing within the urban matrix play in the provision of ecosystem services [180–182]. Although the manuscript and the vision presented suggest how new urban tree planting initiatives should be carried out, it should also be emphasized that integrative plans must constitute the foundation. Such documents should include strategies for new plantations, along with specific sections that follow best practices in the management of these more natural forest patches [183–189]. The urban forest is composed of the entire set of trees existing in the urban matrix or in its proximity directly accessible to the population, and following the line of what is proposed in the article, its management must be context-specific, understanding that urban trees and parks and gardens have different characteristics from forests and that our strategies must also contemplate these differences.

5. Conclusions

Can cities serve simultaneously as refuges and engines of biodiversity? The answer is yes, but only if urban planning adopts a multifaceted and strategic approach. This includes minimizing territorial fragmentation, integrating biomimicry principles into built environments, and establishing concentric green infrastructures that connect natural areas with urban interiors through corridors and nodal parks. Additionally, the use of exotic yet ecosystem service-efficient species can help cities adapt to heat island microclimates. Embracing advances in synthetic biology, under the safeguards of frameworks such as the Aichi Targets, can further facilitate the development of climate-adaptive urban species. Designing multi-layered urban forests and microforests to maximize functional diversity completes this vision, enhancing ecosystem resilience and service provision.

Should increasing plant biodiversity be the primary objective of urban greening in cities? Emphatically not. True urban sustainability demands a paradigm shift, from simply counting species to designing complex, adaptive, and equitable ecosystems. With thoughtful planning, cities can evolve into resilient, life-sustaining habitats that benefit both people and nature. Species diversification represents a step toward integrating the multiple ecological, social, and functional factors previously outlined into a unified framework. However, the critical question remains: how much diversity is truly necessary, and based on what species composition? Simply increasing diversity without considering the full range of relevant factors risks falling into the same flawed randomness Jaynes criticized, which leads to ineffective and fragmented urban forestry. We argue that a holistic approach is essential, as it determines which species to select, the functional and structural traits to prioritize, and where to plant them, ensuring the continuous provision of ecosystem services. In this context, diversity, or biodiversity, becomes a secondary outcome of a scientifically grounded selection process designed to maximize survival and sustained ecosystem function. The expected result is diverse urban forests, but the answer to "how much diversity is needed" ultimately depends on the factors that govern species survival and the ongoing delivery of ecosystem services.

Acknowledgments

We sincerely thank the "Asociación Española de Parques y Jardines Públicos (AEPJP)" for the invitation to deliver the keynote lecture at the National PARJAP Congress 2025 in Marbella, titled "The City as an Engine of Biodiversity" and for the opportunity to transform that presentation into the present manuscript. The authors acknowledge the use of Perplexity AI (GPT-5) to assist in the scientific revision of the translation from Spanish to English. The authors fully support Academia.edu Journals' adherence to COPE guidelines on AI in publication ethics and confirm that this use has been managed responsibly and ethically.

Funding

This research was sponsored by Ministry of Education, Professional Formation and Sport of Spain in the Program of University Teaching Program (Formación de Profesorado Universitario, FPU) under grant FPU22/00067.

Author contributions

Conceptualization, Á.R.-V. and Á.E.S.-T. validation, Á.E.S.-T.; investigation, Á.R.-V.; resources, Á.R.-V. and Á.E.S.-T.; writing—original draft preparation, Á.R.-V. and Á.E.S.-T.; writing—review and editing, Á.R.-V.; visualization, Á.R.-V. and Á.E.S.-T.; supervision, Á.E.S.-T.; project administration, Á.R.-V. and Á.E.S.-T.; funding acquisition, Á.R.-V. and Á.E.S.-T. Both authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that they have no competing interests.

Additional information

Received: 2025-06-17

Accepted: 2025-10-21

Published: 2025-10-29

Academia Environmental Sciences and Sustainability papers should be cited as *Academia Environmental Sciences and Sustainability 2025*, ISSN 2997-6006, https://doi.org/10.20935/AcadEnvSci7981. The journal's official abbreviation is *Acad. Env. Sci. Sust.*

Publisher's note

Academia.edu Journals stays neutral with regard to jurisdictional claims in published maps and institutional affiliations. All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright

© 2025 copyright by the author. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

References

1. Steg L, Groot JIMd, Dreijerink L, Abrahamse W, Siero FW. General antecedents of personal norms, policy acceptability, and intentions: the role of values, worldviews, and environmental concern. Soc Nat Resour. 2011;24(4):349–67. doi: 10.1080/08941920903214116
2. Liobikienė G, Poškus MS. The importance of environmental knowledge for private and public sphere pro-environmental behavior: modifying the value-belief-norm theory. Sustainability. 2019;11(12):3324. doi: 10.3390/su11123324
3. Kennedy EH, Beckley TM, McFarlane BL, Nadeau S. Rural-urban differences in environmental concern in Canada. Rural Sociol. 2009;74(3):309–29. doi: 10.1526/003601109789037268
4. Unanue W, Vignoles VL, Dittmar H, Vansteenkiste M. Life goals predict environmental behavior: cross-cultural and longitudinal evidence. J Environ Psychol. 2016;46:10–22. doi: 10.1016/j.jenvp.2016.02.001
5. Timoti P, Lyver PO, Matamua R, Jones CJ, Tahi B. A representation of a tuawhenua worldview guides environmental conservation. Ecol Soc. 2017;22(4):20. doi: 10.5751/ES-09768-220420
6. Zeng J, Jiang M, Yuan M. Environmental risk perception, risk culture, and pro-environmental behavior. Int J Environ Res. Public Health. 2020;17(5):1750. doi: 10.3390/ijerph17051750
7. Kunchamboo V, Lee CKC, Brace-Govan J. Cultivating nature identity and ecological worldviews: a pathway to alter the prevailing dominant social paradigm. J Macromarketing. 2021;41(3):484–505. doi: 10.1177/0276146721997540
8. Pepper M, Leonard R. How ecotheological beliefs vary among australian churchgoers and consequences for environmental attitudes and behaviors. Rev Relig Res. 2016;58(1):101–24. doi: 10.1007/s13644-015-0234-1
9. Ignatow G. Cultural models of nature and society. Environ Behav. 2006;38(4):441–61. doi: 10.1177/0013916505280791
10. Caniëls MC, Lambrechts W, Platje J, Motylska-Kuźma A, Fortuński B. 50 shades of green: insights into personal values and worldviews as drivers of green purchasing intention, behaviour, and experience. Sustainability. 2021;13(8):4140. doi: 10.3390/su13084140
11. Janmaimool P, Denpaiboon C. Evaluating determinants of rural villagers' engagement in conservation and waste management behaviors based on integrated conceptual framew-

ork of pro-environmental behavior. Life Sci Soc Policy. 2016;12(1):12. doi: 10.1186/s40504-016-0045-3

12. Chen M. Effects of psychological distance perception and psychological factors on pro-environmental behaviors in taiwan: application of construal level theory. Int Sociol. 2019;35(1):70–89. doi: 10.1177/0268580919881870

13. Bolund P, Hunhammar S. Ecosystem services in urban areas. Ecol Econ. 1999;29(2):293–301. doi: 10.1016/S0921-8009(99)00013-0

14. Gómez-Baggethun E, Gren Å, Barton DN, Langemeyer J, McPhearson T, O'Farrell P, et al. Urban ecosystem services. In: Urbanization, biodiversity and ecosystem services: challenges and opportunities. Dordrecht: Springer Netherlands; 2013. p. 175–251. doi: 10.1007/978-94-007-7088-1_11

15. Tan PY, Zhang J, Masoudi M, Alemu JB, Edwards PJ, Grêt-Regamey A, et al. A conceptual framework to untangle the concept of urban ecosystem services. Landsc Urban Plan. 2020;200:103837. doi: 10.1016/j.landurbplan.2020.103837

16. Pandey B, Ghosh A. Urban ecosystem services and climate change: a dynamic interplay. Front Sustain Cities. 2023;5:1281430. doi: 10.3389/frsc.2023.1281430

17. Kabisch N, Qureshi S, Haase D. Human–environment interactions in urban green spaces—a systematic review of contemporary issues and prospects for future research. Environ Impact Assess Rev. 2015;50:25–34. doi: 10.1016/j.eiar.2014.08.007

18. Tzoulas K, Korpela K, Venn S, Yli-Pelkonen V, Kaźmierczak A, Niemelä J, et al. Promoting ecosystem and human health in urban areas using green infrastructure: a literature review. Landsc Urban Plan. 2007;81(3):167–78. doi: 10.1016/j.landurbplan.2007.02.001

19. Giles-Corti B, Vernez-Moudon A, Reis RS, Turrell G, Dannenberg AL, Badland H, et al. City planning and population health: a global challenge. Lancet. 2016;388(10062):2912–24. doi: 10.1016/S0140-6736(16)30066-6

20. Nowak DJ, Crane DE, Stevens J, Hoehn R, Walton JT, Bond J. A ground-based method of assessing urban forest structure and ecosystem services. Arboric Urban For. 2008;34(6):347–58. doi: 10.48044/jauf.2008.048

21. Lovell ST, Taylor J. Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landsc Ecol. 2013;28(8):1447–63. doi: 10.1007/s10980-013-9912-y

22. Nowak DJ. Understanding i-Tree: 2021 summary of programs and methods. General Technical Report NRS-200-2021. Madison (WI): U.S. Department of Agriculture, Forest Service, Northern Research Station; 2021. 100p. doi: 10.2737/NRS-GTR-200-2021

23. Nowak DJ, Crane DE, Stevens JC. Air pollution removal by urban trees and shrubs in the United States. Urban For Urban Green. 2006;4(3–4):115–23. doi: 10.1016/j.ufug.2006.01.007

24. Livesley SJ, McPherson EG, Calfapietra C. The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. J Environ Qual. 2016;45(1):119–24. doi: 10.2134/jeq2015.11.0567

25. Nowak DJ, Hirabayashi S, Bodine AR, Greenfield EJ. Tree and forest effects on air quality and human health in the United States. Environ Pollut. 2014;193:119–29. doi: 10.1016/j.envpol.2014.05.028

26. Oke TR, Mills G, Christen A, Voogt JA. Urban climates. Cambridge: Cambridge University Press; 2017. doi: 10.1017/9781139016476

27. Rahman MA, Stratópoulos LMF, Moser-Reischl A, Zölch T, Häberle K, Rötzer T, et al. Traits of trees for cooling urban heat islands: a meta-analysis. Build Environ. 2020;170:106606. doi: 10.1016/j.buildenv.2019.106606

28. Li H, Zhao Y, Wang C, Ürge-Vorsatz D, Carmeliet J, Bardhan R. Cooling efficacy of trees across cities is determined by background climate, urban morphology, and tree trait. Commun Earth Environ. 2024;5(1):754. doi: 10.1038/s43247-024-01908-4

29. Alonzo M, Ibsen PC, Locke DH. Urban trees and cooling: a review of the recent literature (2018 to 2024). Arboric Urban For. 2025;51(5):420–44. doi: 10.48044/jauf.2025.023

30. Berland A, Shiflett SA, Shuster WD, Garmestani AS, Goddard HC, Herrmann DL, et al. The role of trees in urban stormwater management. Landsc Urban Plan. 2017;162:167–77. doi: 10.1016/j.landurbplan.2017.02.017

31. Kuehler EA, Hathaway JM, Tirpak A. Quantifying the benefits of urban forest systems as a component of the green infrastructure stormwater treatment network. Ecohydrology. 2017;10(3):e1813. doi: 10.1002/eco.1813

32. Coville RC, Kruegler J, Selbig WR, Hirabayashi S, Loheide SP, Avery WA, et al. Loss of street trees predicted to cause 6000 l/tree increase in leaf-on stormwater runoff for great lakes urban sewershed. Urban For Urban Green. 2022;74:127649. doi: 10.1016/j.ufug.2022.127649

33. Selbig WR, Loheide SP, Shuster WD, Scharenbroch BC, Coville RC, Kruegler J, et al. Quantifying the stormwater runoff volume reduction benefits of urban street tree canopy. Sci Total Environ. 2022;806:151296. doi: 10.1016/j.scitotenv.2021.151296

34. Dowtin AL, Cregg BC, Nowak DJ, Levia DF. Towards optimized runoff reduction by urban tree cover: a review of key physical tree traits, site conditions, and management strategies. Landsc Urban Plan. 2023;239:104849. doi: 10.1016/j.landurbplan.2023.104849

35. Schwarz K, Fragkias M, Boone CG, Zhou W, McHale MR, Grove JM, et al. Trees grow on money: urban tree canopy cover and environmental justice. PLoS ONE. 2015;10(4):e0122051. doi: 10.1371/journal.pone.0122051

36. Wolf KL, Lam ST, McKeen J, Richardson GRA, Bosch Mvd, Bardekjian AC. Urban trees and human health: a scoping review. Int J Environ Res Public Health. 2020;17(12):4371. doi: 10.3390/ijerph17124371

37. Wang Y, Niemelä J, Kotze DJ. The delivery of cultural ecosystem services in urban forests of different landscape features and land use contexts. People Nat. 2022;4(5):1369–86. doi: 10.1002/pan3.10394

38. Romanazzi GR, Koto R, Boni AD, Palmisano GO, Cioffi M, Roma R. Cultural ecosystem services: a review of methods and tools for economic evaluation. Environ Sustain Indic. 2023;20:100304. doi: 10.1016/j.indic.2023.100304

39. Kumar P, Sahani J, Perez K, Ahlawat A, Andrade MdF, Athanassiadou M, et al. Urban greening for climate resilient and sustainable cities: grand challenges and opportunities. Front Sustain Cities. 2025;7:1595280. doi: 10.3389/frsc.2025.1595280

40. United Nations, UN. Independent group of scientists appointed by the secretary-general, global sustainable development report 2023: times of crisis, times of change: science for accelerating transformations to sustainable development. 2023 [accessed on 2025 April 1]. Available from: https://sustainabledevelopment.un.org/content/documents/24797GSDR_report_2019.pdf

41. Nieuwenhuijsen M, Dadvand P, Márquez S, Bartoll X, Barboza EP, Cirach M, et al. The evaluation of the 3-30-300 green space rule and mental health. Environ Res. 2022;215:114387. doi: 10.1016/j.envres.2022.114387

42. Croeser T, Sharma R, Weisser WW, Bekessy SA. Acute canopy deficits in global cities exposed by the 3-30-300 benchmark for urban nature. Nat Commun. 2024;15(1):9333. doi: 10.1038/s41467-024-53402-2

43. Owen D, Fitch A, Fletcher D, Knopp J, Levin G, Farley K, et al. Opportunities and constraints of implementing the 3–30–300 rule for urban greening. Urban For Urban Green. 2024;98:128393. doi: 10.1016/j.ufug.2024.128393

44. Iqbal LM, Njaim GA, Vos DD, Permana CTH. Parks please! implementing the 3–30-300 green space rule in developing countries—the case of surakarta, indonesia. Urban For Urban Green. 2025;107:128797. doi: 10.1016/j.ufug.2025.128797

45. Happy Eco News. Paris Urban Forest Plan will transform 50% of the city. Happy Eco News. [accessed on 2024 Dec 2]. Available from: https://happyeconews.com/paris-urban-forest-plan/

46. Only Good News Daily. Paris urban forest plan to cover half the city. OGN Daily. [accessed on 2024 Dec 20]. Available from: https://www.onlygoodnewsdaily.com/post/paris-urban-forest-plan-to-cover-half-the-city

47. Interlace Hub. Green infrastructure and biodiversity plan—Barcelona. Interlace Hub. [accessed on 2023 Sep 5]. Available from: https://interlace-hub.com/green-infrastructure-and-biodiversity-plan-barcelona

48. Oppla. Barcelona's strategies to increase and enhance urban green. Oppla. [accessed on 2024 May 14]. Available from: https://oppla.eu/conexus/resource/conexus-policy-brief-1-barcelonas-strategies-increase-and-enhance-urban-green

49. Fedeli V, Arcidiacono A. Planning, planting, and maintaining new urban forests in the metropolitan area of Milano. SPOOL. 2025;12(1):113–26. doi: 10.47982/spool.2025.1.06

50. Forestami. The project. Forestami. [accessed on 2025 Apr 3]. Available from: https://forestami.org/en/chi-siamo/il-progetto/

51. CityGreen. Six international cities with outstanding green infrastructure. CityGreen. [accessed on 2019 Jan 16]. Available from: https://citygreen.com/six-international-cities-with-outstanding-green-infrastructure/

52. Tan BA, Gaw LY, Masoudi M, Richards DR. Nature-based solutions for urban sustainability: an ecosystem services assessment of plans for singapore's first "forest town". Front Environ Sci. 2021;9:610155. doi: 10.3389/fenvs.2021.610155

53. Ashinze UK, Edeigba BA, Umoh AA, Biu PW, Daraojimba AI. Urban green infrastructure and its role in sustainable cities: a comprehensive review. World J Adv Res Rev. 2024;21(2):928–36. doi: 10.30574/wjarr.2024.21.2.0519

54. City of Melbourne. Urban forest strategy 2021–2032. 2021 [accessed on 2025 Sep 29]. Available from: https://mvga-prod-files.s3.ap-southeast-4.amazonaws.com/public/2024-07/urban-forest-strategy.pdf

55. Adams C, Frantzeskaki N, Moglia M. Space for mainstreaming? Learning from the implementation of urban forest strategies in metropolitan melbourne. Aust Plan. 2023;59(2):154–69. doi: 10.1080/07293682.2023.2268222

56. Campbell LK, Monaco M, Falxa-Raymond N, Lu J, Newman A, Rae RA, et al. MillionTreesNYC: the integration of research and practice. New York (NY): New York City Department of Parks and Recreation; 2014. 43p.

57. City of Copenhagen. Green Roofs in Copenhagen. City of Copenhagen. Technical and Environmental Administration. 2010 [accessed on 2025 Sep 29]. Available from: https://kk.sites.itera.dk/apps/kk_pub2/pdf/1017_sJ43Q6DDyY.pdf

58. Government of South Australia. Urban greening strategy: a resilient and liveable adelaide for all. 2024 [accessed on 2025 Sep 29]. Available from: https://yoursay.sa.gov.au/93122/widgets/434016/documents/284479

59. Cardiff Council. Clean air cardiff. 2025 [accessed on 2025 Sep 29]. Available from: https://www.cardiff.gov.uk/ENG/resident/Parking-roads-and-travel/clean-air-cardiff/Pages/default.aspx

60. Boeri Architetti S. Nanjing vertical forest. 2025 [accessed on 2025 Sep 29]. Available from: https://www.stefanoboeriarchitetti.net/en/project/nanjing-vertical-forest/

61. Crutzen PJ, Stoermer E.F. The 'Anthropocene'. Glob Change Newsl. 2000;41:17–18.

62. Lovelock JE. Novacene: the coming age of hyperintelligence. Cambridge: MIT Press; (Trad.:Novaceno. La próxima era de la hiperinteligencia. Ed. Paidós. 183 págs. Barcelona.); 2021.

63. Harrison MC, Jongepier E, Robertson HM, Arning N, Bitard-Feildel T, Chao H, et al. Hemimetabolous genomes reveal molecular basis of termite eusociality. Nat Ecol Evol. 2018;2(3):557–66. doi: 10.1038/s41559-017-0459-1

64. Zorba R, Malarvizhi G. Urban metabolism: a dual-perspective case study and its implications in the urban political economy of developing nations for an effective SDG framework. Front Sustain Cities. 2025;7:1538006. doi: 10.3389/frsc.2025.1538006

65. United Nations. World urbanization prospects: the 2018 revision. New York: United Nations Department of Economic and Social Affairs, Population Division; 2019 [accessed on 2025 Sep 29]. Available from: https://population.un.org/wup/

66. World Bank. World development indicators: agricultural land (% of land area). 2023 [accessed on 2025 Sep 29]. Available from: https://data.worldbank.org/indicator/AG.LND.ARBL.ZS

67. Hamidi S, Ewing R. A longitudinal study of changes in urban sprawl between 2000 and 2010 in the United States. Landsc Urban Plan. 2014;128:72–82. doi: 10.1016/j.landurbplan.2014.04.021

68. Ewing R, Hamidi S. Compactness versus sprawl. J Plan Lit. 2015;30(4):413–32. doi: 10.1177/0885412215595439

69. Newman P, Kenworthy J. The end of automobile dependence. Washington (DC): Island Press/Center for Resource Economics; 2015. doi: 10.5822/978-1-61091-613-4

70. Seto KC, Güneralp B, Hutyra LR. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc Natl Acad Sci USA. 2012;109(40):16083–8. doi: 10.1073/pnas.1211658109

71. Neuman M. The compact city fallacy. J Plan Educ Res. 2005;25(1):11–26. doi: 10.1177/0739456X04270466

72. Iungman T, Khomenko S, Barboza EP, Cirach M, Gonçalves K, Petrone P, et al. The impact of urban configuration types on urban heat islands, air pollution, co_2 emissions, and mortality in europe: a data science approach. Lancet Planet Health. 2024;8(7):e489–505. doi: 10.1016/S2542-5196(24)00120-7

73. Imhoff ML, Zhang P, Wolfe RE, Bounoua L. Remote sensing of the urban heat island effect across biomes in the continental usa. Remote Sens Environ. 2010;114(3):504–13. doi: 10.1016/j.rse.2009.10.008

74. Zhao L, Lee X, Smith RB, Oleson KW. Strong contributions of local background climate to urban heat islands. Nature. 2014;511(7508):216–9. doi: 10.1038/nature13462

75. Rojas-Rueda D, Nieuwenhuijsen M, Gascón M, Perez-Leon D, Mudu P. Green spaces and mortality: a systematic review and meta-analysis of cohort studies. Lancet Planet Health. 2019;3(11):e469–77. doi: 10.1016/S2542-5196(19)30215-3

76. Meerow S, Newell J, Stults M. Defining urban resilience: a review. Landsc Urban Plan. 2016;147:38–49. doi: 10.1016/j.landurbplan.2015.11.011

77. Holling CS. Resilience and stability of ecological systems. Annu Rev Ecol Syst. 1973;4(1):1–23. doi: 10.1146/annurev.es.04.110173.000245

78. Chelleri L, Waters J, Olazabal M, Minucci G. Resilience trade-offs: addressing multiple scales and temporal aspects of urban resilience. Environ Urban. 2015;27(1):181–98. doi: 10.1177/0956247814550780

79. Demuzere M, Orru K, Heidrich O, Olazabal E, Geneletti D, Orru H, et al. Mitigating and adapting to climate change: multi-functional and multi-scale assessment of green urban infrastructure. J Environ Manag. 2014;146:107–15. doi: 10.1016/j.jenvman.2014.07.025

80. Kabisch N, Bosch Mvd, Lafortezza R. The health benefits of nature-based solutions to urbanization challenges for children and the elderly—a systematic review. Environ Res. 2017;159:362–73. doi: 10.1016/j.envres.2017.08.004

81. O'Brien L, Vreese RD, Kern M, Sievänen T, Stojanova B, Atmış E. Cultural ecosystem benefits of urban and peri-urban green infrastructure across different european countries. Urban For Urban Green. 2017;24:236–48. doi: 10.1016/j.ufug.2017.03.002

82. Oijstaeijen WV, Passel SV, Cools J. Urban green infrastructure: a review on valuation toolkits from an urban planning perspective. J Environ Manag. 2020;267:110603. doi: 10.1016/j.jenvman.2020.110603

83. Herath P, Bai X. Benefits and co-benefits of urban green infrastructure for sustainable cities: six current and emerging themes. Sustain Sci. 2024;19(3):1039–63. doi: 10.1007/s11625-024-01475-9

84. Andres SE, Standish RJ, Lieurance PE, Mills CH, Harper R, Butler DW, et al. Defining biodiverse reforestation: why it matters for climate change mitigation and biodiversity. Plants People Planet. 2022;5(1):27–38. doi: 10.1002/ppp3.10329

85. Whittaker RH. Evolution and measurement of species diversity. Taxon. 1972;21(2–3):213–51. doi: 10.2307/1218190

86. Niell Castanera FX. El marco conceptual de la biodiversidad. Jábega. 2009;101:7–18.

87. Cardinale BJ, Duffy JE, Gonzalez A, Hooper DU, Perrings C, Venail P, et al. Biodiversity loss and its impact on humanity. Nature. 2012;486(7401):59–67. doi: 10.1038/nature11148

88. Mace GM, Norris K, Fitter A. Biodiversity and ecosystem services: a multilayered relationship. Trends Ecol Evol. 2012;27(1):19–26. doi: 10.1016/j.tree.2011.08.006

89. Isbell F, Gonzalez A, Loreau M, Cowles J, Díaz S, Hector A, et al. Linking the influence and dependence of people on biodiversity across scales. Nature. 2017;546(7656):65–72. doi: 10.1038/nature22899

90. Miyawaki A. Creative ecology: restoration of native forests by native trees. Plant Biotechnol. 1999;16(1):15–25. doi: 10.5511/plantbiotechnology.16.15

91. Salvo-Tierra ÁE, González NR, Cardador T, Montoya LM. Estudio de sbns aplicables a un proyecto de zona verde: modelo de isla de biodiversidad alboránica para el parque comandante benítez (málaga). Proceedings of the IX International Greencities Congress: 9th Forum on Urban Intelligence and Sustainability; 2018 Sep; Málaga, Spain. doi: 10.13140/rg.2.2.25711.74405
92. Brown LM, Anand M. Plant functional traits as measures of ecosystem service provision. Ecosphere. 2022;13(2). doi: 10.1002/ecs2.3930
93. Jaynes ET. Probability theory: the logic of science. Cambridge: Cambridge University Press; 2003.
94. Sjöman H, Watkins H, Kelly LJ, Hirons AD, Kainulainen K, Martin KWE, et al. Resilient trees for urban environments: the importance of intraspecific variation. Plants People Planet. 2024;6(6):1180–9. doi: 10.1002/ppp3.10518
95. Jennings V, Gaither CJ. Approaching environmental health disparities and green spaces: an ecosystem services perspective. Int J Environ Res Public Health. 2015;12(2):1952–68. doi: 10.3390/ijerph120201952
96. Oberndorfer E, Lundholm J, Bass B, Coffman R, Doshi H, Dunnett N, et al. Green roofs as urban ecosystems: ecological structures, functions, and services. BioScience. 2007;57(10):823–33. doi: 10.1641/B571005
97. Sang ÅO, Thorpert P, Fransson A. Planning, designing, and managing green roofs and green walls for public health—an ecosystem services approach. Front Ecol Evol. 2022;10:804500. doi: 10.3389/fevo.2022.804500
98. Jato-Espino D, Capra-Ribeiro F, Moscardó V, Pino LEBD, Mayor-Vitoria F, Gallardo LO, et al. A systematic review on the ecosystem services provided by green infrastructure. Urban For Urban Green. 2023;86:127998. doi: 10.1016/j.ufug.2023.127998
99. Paudel S, States SL. Urban green spaces and sustainability: exploring the ecosystem services and disservices of grassy lawns versus floral meadows. Urban For Urban Green. 2023;84:127932. doi: 10.1016/j.ufug.2023.127932
100. Kuo M, Browning MHEM, Sachdeva S, Lee K, Westphal LM. Might school performance grow on trees? Examining the link between “greenness” and academic achievement in urban, high-poverty schools. Front Psychol. 2018;9:1669. doi: 10.3389/fpsyg.2018.01669
101. Kweon B, Ellis CD, Lee J, Jacobs K. The link between school environments and student academic performance. Urban For Urban Green. 2017;23:35–43. doi: 10.1016/j.ufug.2017.02.002
102. Reid CE, Clougherty JE, Shmool JLC, Kubzansky LD. Is all urban green space the same? A comparison of the health benefits of trees and grass in new york city. Int J Environ Res Public Health. 2017;14(11):1411. doi: 10.3390/ijerph14111411
103. Schwaab J, Meier R, Mussetti G, Seneviratne SI, Bürgi C, Davin ÉL. The role of urban trees in reducing land surface temperatures in european cities. Nat Commun. 2021;12(1):6763. doi: 10.1038/s41467-021-26768-w
104. Kattge J, Bönisch G, Díaz S, Lavorel S, Prentice IC, Leadley P, et al. Try plant trait database—enhanced coverage and open access. Glob Change Biol. 2019;26(1):119–88. doi: 10.1111/gcb.14904
105. Wu C, Xiao Q, McPherson EG. A method for locating potential tree-planting sites in urban areas: a case study of Los Angeles, usa. Urban For Urban Green. 2008;7(2):65–76. doi: 10.1016/j.ufug.2008.01.002
106. Bodnaruk E, Kroll CN, Yang Y, Hirabayashi S, Nowak DJ, Endreny TA. Where to plant urban trees? A spatially explicit methodology to explore ecosystem service tradeoffs. Landsc Urban Plan. 2017;157:457–67. doi: 10.1016/j.landurbplan.2016.08.016
107. Jalkanen J, Vierikko K, Moilanen A. Spatial prioritization for urban biodiversity quality using biotope maps and expert opinion. Urban For Urban Green. 2020;49:126586. doi: 10.1016/j.ufug.2020.126586
108. Werbin ZR, Heidari L, Buckley S, Brochu P, Butler L, Connolly C, et al. A tree-planting decision support tool for urban heat mitigation. PLoS ONE. 2020;15(10):e0224959. doi: 10.1371/journal.pone.0224959
109. Sousa-Silva R, Cameron E, Paquette A. Prioritizing street tree planting locations to increase benefits for all citizens: experience from Joliette, Canada. Front Ecol Evol. 2021;9:716611. doi: 10.3389/fevo.2021.716611
110. Nyelele C, Kroll CN, Nowak DJ. A comparison of tree planting prioritization frameworks: i-tree landscape versus spatial decision support tool. Urban For Urban Green. 2022;75:127703. doi: 10.1016/j.ufug.2022.127703
111. Sousa-Silva R, Duflos M, Ordóñez C, Paquette A. Keys to better planning and integrating urban tree planting initiatives. Landsc Urban Plan. 2023;231:104649. doi: 10.1016/j.landurbplan.2022.104649
112. Violle C, Navas M, Vile D, Kazakou E, Fortunel C, Hummel I, et al. Let the concept of trait be functional! Oikos. 2007;116(5):882–92. doi: 10.1111/j.0030-1299.2007.15559.x
113. Grote R, Samson R, Alonso R, Amorim JH, Cariñanos P, Churkina G, et al. Functional traits of urban trees: air pollution mitigation potential. Front Ecol Environ. 2016;14(10):543–50. doi: 10.1002/fee.1426
114. Endreny TA. Strategically growing the urban forest will improve our world. Nat Commun. 2018;9(1):1160. doi: 10.1038/s41467-018-03622-0
115. Lindenmayer DB, Laurance WF, Franklin JF. Global decline in large old trees. Science. 2012;338(6112):1305–6. doi: 10.1126/science.1231070
116. Lindenmayer DB, Laurance WF. The ecology, distribution, conservation and management of large old trees. Biol Rev. 2016;92(3):1434–58. doi: 10.1111/brv.12290
117. Gómez-Muñoz VM, Porta-Gándara MÁ, Fernández J. Effect of tree shades in urban planning in hot-arid climatic regions. Landsc Urban Plan. 2010;94(3–4):149–57. doi: 10.1016/j.landurbplan.2009.09.002

118. Díaz-Porras DF, Gaston KJ, Evans KL. 110 years of change in urban tree stocks and associated carbon storage. Ecol Evol. 2014;4(8):1413–22. doi: 10.1002/ece3.1017

119. Stephenson NL, Das AJ, Condit RC, Russo SE, Baker PJ, Beckman NG, et al. Rate of tree carbon accumulation increases continuously with tree size. Nature. 2014;507(7490):90–93. doi: 10.1038/nature12914

120. Wolf KL. Business district streetscapes, trees, and consumer response. J For. 2005;103(8):396–400. doi: 10.1093/jof/103.8.396

121. Chen L, Liu C, Zhang L, Zou R, Zhang Z. Variation in tree species ability to capture and retain airborne fine particulate matter ($PM_{2.5}$). Sci Rep. 2017;7(1):3206. doi: 10.1038/s41598-017-03360-1

122. Xiao Q, McPherson EG. Surface water storage capacity of twenty tree species in Davis, California. J Environ Qual. 2016;45(1):188–98. doi: 10.2134/jeq2015.02.0092

123. Cavender N, Donnelly G. Intersecting urban forestry and botanical gardens to address big challenges for healthier trees, people, and cities. Plants People Planet. 2019;1(4):315–22. doi: 10.1002/ppp3.38

124. Watkins H, Hirons AD, Sjöman H, Cameron R, Hitchmough J. Can trait-based schemes be used to select species in urban forestry? Front Sustain Cities. 2021;3:654618. doi: 10.3389/frsc.2021.654618

125. Esperón-Rodríguez M, Tjoelker MG, Lenoir J, Baumgartner JB, Beaumont LJ, Nipperess DA, et al. Climate change increases global risk to urban forests. Nat Clim Change. 2022;12(10):950–5. doi: 10.1038/s41558-022-01465-8

126. McPherson EG, Berry AM, Doorn NSv. Performance testing to identify climate-ready trees. Urban For Urban Green. 2018;29:28–39. doi: 10.1016/j.ufug.2017.09.003

127. Esperón-Rodríguez M, Rymer PD, Power SA, Challis A, Marchin RM, Tjoelker MG. Functional adaptations and trait plasticity of urban trees along a climatic gradient. Urban For Urban Green. 2020;54:126771. doi: 10.1016/j.ufug.2020.126771

128. Cho A, Dziedzic N, Davis AP, Hanson CA, Lee J, Nunez-Mir GC, et al. Leaf functional traits highlight phenotypic variation of two tree species in the urban environment. Front Plant Sci. 2024;15:1450723. doi: 10.3389/fpls.2024.1450723

129. Ramachandran A, Dee LE, Hayden MT, Suding KN. Leveraging plant functional traits in the design of nature-based solutions: a research agenda. J Ecol. 2024;112(11):2492–501. doi: 10.1111/1365-2745.14371

130. Sjöman H, Nielsen AB. Selecting trees for urban paved sites in scandinavia—a review of information on stress tolerance and its relation to the requirements of tree planners. Urban For Urban Green. 2010;9(4):281–93. doi: 10.1016/j.ufug.2010.04.001

131. Sjöman H, Hannus S, Bellan P, Barblishvili T, Darchidze T, Sikharulidze S. Hunting for a larger diversity of urban trees in western europe—a case study from the southern Caucasus. Arboric Urban For. 2019;45(5):221–35. doi: 10.48044/jauf.2019.018

132. Leigh DM, Hendry AP, Vázquez-Domínguez E, Friesen VL. Estimated six per cent loss of genetic variation in wild populations since the industrial revolution. Evol Appl. 2019;12(8):1505–12. doi: 10.1111/eva.12810

133. Bijlsma R, Loeschcke V. Genetic erosion impedes adaptive responses to stressful environments. Evol Appl. 2011;5(2):117–29. doi: 10.1111/j.1752-4571.2011.00214.x

134. Pauleit S, Jones N, Garcia-Martin G, García-Valdecantos JL, Rivière LM, Beaudet LV, et al. Tree establishment practice in towns and cities—results from a european survey. Urban For Urban Green. 2002;1(2):83–96. doi: 10.1078/1618-8667-00009

135. Kumar P, Singh J. Invasive alien plant species: their impact on environment, ecosystem services and human health. Ecol Indic. 2020;111:106020. doi: 10.1016/j.ecolind.2019.106020

136. Silva JLS, Oliveira MTPd, Oliveira W, Borges LA, Cruz-Neto O, Lopes AV. High richness of exotic trees in tropical urban green spaces: reproductive systems, fruiting and associated risks to native species. Urban For Urban Green. 2020;50:126659. doi: 10.1016/j.ufug.2020.126659

137. Sjöman H, Morgenroth J, Sjöman JD, Sæbø A, Kowarik I. Diversification of the urban forest—can we afford to exclude exotic tree species? Urban For Urban Green. 2016;18:237–41. doi: 10.1016/j.ufug.2016.06.011

138. Roloff A, Korn S, Gillner S. The climate-species-matrix to select tree species for urban habitats considering climate change. Urban For Urban Green. 2009;8(4):295–308. doi: 10.1016/j.ufug.2009.08.002

139. Chalker-Scott L. Nonnative, noninvasive woody species can enhance urban landscape biodiversity. Arboric Urban For. 2015;41(4):173–86. doi: 10.48044/jauf.2015.017

140. Dickie IA, Bennett BM, Burrows L, Núñez MA, Peltzer DA, Porté AJ, et al. Conflicting values: ecosystem services and invasive tree management. Biol Invasions. 2013;16(3):705–19. doi: 10.1007/s10530-013-0609-6

141. Tallamy DW. Do alien plants reduce insect biomass? Conserv Biol. 2004;18(6):1689–92. doi: 10.1111/j.1523-1739.2004.00512.x

142. Burghardt KT, Tallamy DW, Shriver WG. Impact of native plants on bird and butterfly biodiversity in suburban landscapes. Conserv Biol. 2009;23(1):219–24. doi: 10.1111/j.1523-1739.2008.01076.x

143. Morrison WE, Hay ME. Herbivore preference for native vs. exotic plants: generalist herbivores from multiple continents prefer exotic plants that are evolutionarily naïve. PLoS ONE. 2011;6(3):e17227. doi: 10.1371/journal.pone.0017227

144. Ballard M, Hough-Goldstein J, Tallamy DW. Arthropod communities on native and nonnative early successional plants. Environ Entomol. 2013;42(5):851–59. doi: 10.1603/EN12315

145. Burghardt KT, Tallamy DW. Plant origin asymmetrically impacts feeding guilds and life stages driving community structure of herbivorous arthropods. Divers Distrib. 2013;19(12):1553–65. doi: 10.1111/ddi.12122

146. Burghardt KT, Tallamy DW. Not all non-natives are equally unequal: reductions in herbivore β-diversity depend on phylogenetic similarity to native plant community. Ecol Lett. 2015;18(10):1087–98. doi: 10.1111/ele.12492

147. Zhang M, Ni Y, Li M. Evaluation of the growth, adaption, and ecosystem services of two potentially-introduced urban tree species in Guangzhou under drought stress. Sci Rep. 2023;13(1):3563. doi: 10.1038/s41598-023-30782-x

148. Riley CB, Herms DA, Gardiner MM. Exotic trees contribute to urban forest diversity and ecosystem services in inner-city Cleveland, OH. Urban For Urban Green. 2018;29:367–76. doi: 10.1016/j.ufug.2017.01.004

149. Farrell C, Livesley SJ, Arndt SK, Beaumont LJ, Burley HM, Ellsworth DS, et al. Can we integrate ecological approaches to improve plant selection for green infrastructure? Urban For Urban Green. 2022;76:127732. doi: 10.1016/j.ufug.2022.127732

150. Cregg BM, Rouse R, Ellison-Smith D. Genotypic variation in water relations and gas exchange of urban trees in detroit, Michigan, USA. Urban For Urban Green. 2023;81:127858. doi: 10.1016/j.ufug.2023.127858

151. Marchin RM, Esperón-Rodríguez M, Tjoelker MG, Ellsworth DS. Understanding urban tree heat and drought stress by tracking growth and recovery following an extreme year. Landsc Urban Plan. 2025;261:105394. doi: 10.1016/j.landurbplan.2025.105394

152. Watson G, Hewitt A, Custic M, Lo M. The management of tree root systems in urban and suburban settings ii: a review of strategies to mitigate human impacts. Arboric Urban For. 2014;40(5):249–71. doi: 10.48044/jauf.2014.025

153. Bartens J, Wiseman PE, Smiley ET. Stability of landscape trees in engineered and conventional urban soil mixes. Urban For Urban Green. 2010;9(4):333–38. doi: 10.1016/j.ufug.2010.06.005

154. Grabosky J, Bassuk N. Seventeen years' growth of street trees in structural soil compared with a tree lawn in New York city. Urban For Urban Green. 2016;16:103–9. doi: 10.1016/j.ufug.2016.02.002

155. Ow LF, Ghosh S. Growth of street trees in urban ecosystems: structural cells and structural soil. J Urban Ecol. 2017;3(1):jux017. doi: 10.1093/jue/jux017

156. Smiley ET, Urban J, Fite K. Comparison of tree responses to different soil treatments under concrete pavement. Arboric Urban For. 2019;45(6):303–14. doi: 10.48044/jauf.2019.027

157. Escobedo FJ, Kroeger T, Wagner JE. Urban forests and pollution mitigation: analyzing ecosystem services and disservices. Environ. Pollut. 2011;159(8–9):2078–87. doi: 10.1016/j.envpol.2011.01.010

158. Benjamin MT, Sudol M, Bloch L, Winer AM. Low-emitting urban forests: a taxonomic methodology for assigning isoprene and monoterpene emission rates. Atmos Environ. 1996;30(9):1437–52. doi: 10.1016/1352-2310(95)00439-4

159. Sousa-Silva R, Smargiassi A, Kneeshaw D, Dupras J, Zinszer K, Paquette A. Strong variations in urban allergenicity riskscapes due to poor knowledge of tree pollen allergenic potential. Sci Rep. 2021;11(1):10196. doi: 10.1038/s41598-021-89353-7

160. Brown P. Race, class, and environmental health: a review and systematization of the literature. Environ Res. 1995;69(1):15–30. doi: 10.1006/enrs.1995.1021

161. Brulle RJ, Pellow DN. Environmental justice: human health and environmental inequalities. Annu Rev Public Health. 2006;27(1):103–24. doi: 10.1146/annurev.publhealth.27.021405.102124

162. O'Neill MS, Jerrett M, Kawachi I, Levy JI, Cohen A, Gouveia N, et al. Health, wealth, and air pollution: advancing theory and methods. Environ Health Perspect. 2003;111(16):1861–70. doi: 10.1289/ehp.6334

163. Neier T. Austrian air–just clean for locals: a nationwide analysis of environmental inequality. Ecol Econ. 2021;187:107100. doi: 10.1016/j.ecolecon.2021.107100

164. van den Brekel L, Lenters V, Mackenbach JD, Hoek G, Wagtendonk A, Lakerveld J, et al. Ethnic and socioeconomic inequalities in air pollution exposure: a cross-sectional analysis of nationwide individual-level data from the Netherlands. Lancet Planet Health. 2024;8(1):e18–29. doi: 10.1016/S2542-5196(23)00258-9

165. Ash M, Fetter TR. Who lives on the wrong side of the environmental tracks? Evidence from the EPA's risk-screening environmental indicators model. Soc Sci Q. 2004;85(2):441–62. doi: 10.1111/j.0038-4941.2004.08502011.x

166. Fecht D, Fischer P, Fortunato L, Hoek G, Hoogh Kd, Marra M, et al. Associations between air pollution and socioeconomic characteristics, ethnicity and age profile of neighbourhoods in england and the netherlands. Environ Pollut. 2015;198:201–10. doi: 10.1016/j.envpol.2014.12.014

167. Alvarez CH, Calasanti A, Evans CR, Ard K. Intersectional inequalities in industrial air toxics exposure in the United States. Health Place. 2022;77:102886. doi: 10.1016/j.healthplace.2022.102886

168. Fonzo D, Fabri A, Pasetto R. Distributive justice in environmental health hazards from industrial contamination: a systematic review of national and near-national assessments of social inequalities. Soc Sci Med. 2022;297:114834. doi: 10.1016/j.socscimed.2022.114834

169. Chakraborty T, Hsu A, Manya D, Sheriff G. Disproportionately higher exposure to urban heat in lower-income neighborhoods: a multi-city perspective. Environ Res Lett. 2019;14(10):105003. doi: 10.1088/1748-9326/ab3b99

170. Tuholske C, Caylor K, Funk C, Verdin A, Sweeney S, Grace K, et al. Global urban population exposure to extreme heat. Proc Natl Acad Sci USA. 2021;118(41):e2024792118. doi: 10.1073/pnas.2024792118

171. Hsu A, Sheriff G, Chakraborty T, Manya D. Disproportionate exposure to urban heat island intensity across major US cities. Nat Commun. 2021;12(1):2721. doi: 10.1038/s41467-021-22799-5

172. Aznarez C, Kumar S, Marquez-Torres A, Pascual U, Baró F. Ecosystem service mismatches evidence inequalities in urban heat vulnerability. Sci Total Environ. 2024;922:171215. doi: 10.1016/j.scitotenv.2024.171215

173. Mennis J. Socioeconomic-vegetation relationships in urban, residential land. Photogramm Eng Remote Sens. 2006;72(8):911–21. doi: 10.14358/PERS.72.8.911

174. Clarke LW, Jenerette GD, Davila A. The luxury of vegetation and the legacy of tree biodiversity in Los Angeles, CA. Landsc Urban Plan. 2013;116:48–59. doi: 10.1016/j.landurbplan.2013.04.006

175. Jenerette GD, Miller G, Buyantuev A, Pataki DE, Gillespie TW, Pincetl S. Urban vegetation and income segregation in drylands: a synthesis of seven metropolitan regions in the southwestern United States. Environ Res Lett. 2013;8(4):044001. doi: 10.1088/1748-9326/8/4/044001

176. Landry SM, Chakraborty J. Street trees and equity: evaluating the spatial distribution of an urban amenity. Environ Plan A Econ Space. 2009;41(11):2651–70. doi: 10.1068/a41236

177. Gerrish E, Watkins S. The relationship between urban forests and income: a meta-analysis. Landscape and Urban Planning. 2018;170:293–308. doi: 10.1016/j.landurbplan.2017.09.005

178. Pereña-Ortiz JF, Salvo-Tierra ÁE, Cozano-Pérez P, Ruiz-Valero Á. Propagating uncertainty in urban tree trait measurements to estimate socioeconomic inequities in ecosystem service accessibility: a machine learning and simulation framework. Environ Sustain Indic. 2025;27:100864. doi: 10.1016/j.indic.2025.100864

179. Ruiz-Valero Á, Cozano-Pérez P, Ortiz JP, Guerrero-Serrano PM, Tierra ÁES. Tree structural traits as a key element for ensuring socio-economic equitable access to ecosystem services. Trees For People. 2025;21:100899. doi: 10.1016/j.tfp.2025.100899

180. Johnson LR, Johnson M, Aronson MFJ, Campbell LK, Carr ME, Clarke M, et al. Conceptualizing social-ecological drivers of change in urban forest patches. Urban Ecosyst. 2020;24(4):633–48. doi: 10.1007/s11252-020-00977-5

181. Sevianu E, Maloş C, Arghiuş V, Bican-Brişan N, Bădărău AS, Moga MC, et al. Mainstreaming ecosystem services and biodiversity in peri-urban forest park creation: experience from eastern Europe. Front Environ Sci. 2021;9:618217. doi: 10.3389/fenvs.2021.618217

182. Aguiar JTD, Brun FGK, Higuchi P, Bobrowski R. Although it lacks connectivity, isolated urban forest fragments can deliver similar amounts of ecosystem services as in protected areas. CERNE. 2023;29:e-103193. doi: 10.1590/01047760202329013193

183. Brandt LA, Lewis AD, Fahey RT, Scott L, Darling L, Swanston CW. A framework for adapting urban forests to climate change. Environ Sci Policy. 2016;66:393–402. doi: 10.1016/j.envsci.2016.06.005

184. Gordeeva E, Weber N, Wolfslehner B. The new eu forest strategy for 2030—an analysis of major interests. Forests. 2022;13(9):1503. doi: 10.3390/f13091503

185. Lier M, Köhl M, Korhonen K, Linser S, Prins K, Talarczyk A. The new eu forest strategy for 2030: a new understanding of sustainable forest management? Forests. 2022;13(2):245. doi: 10.3390/f13020245

186. McGann TC, Schattman RE, D'Amato AW, Ontl T. Climate adaptive management in the northeastern united states: common strategies and motivations of rural and urban foresters. J For. 2022;121(2):182–92. doi: 10.1093/jofore/fvac039

187. Mina M, Messier C, Duveneck MJ, Fortin M, Aquilué N. Managing for the unexpected: building resilient forest landscapes to cope with global change. Glob Change Biol. 2022;28(14):4323–41. doi: 10.1111/gcb.16197

188. Ludvig A, Schmid B, Öllerer B, Nikinmaa L, Hurtado P, Rodriguez-Ogea M, et al. Increasing climate-related resilience in the forest-based value chains? a policy perspective. For Policy Econ. 2024;168:103314. doi: 10.1016/j.forpol.2024.103314

189. Xie H, Chang M, Wang GG, Tang Y, Jin S. Integrating climate-smart practices in forestry: insights from Europe and America. Front Plant Sci. 2025;16:1583294. doi: 10.3389/fpls.2025.1583294