Ecological Informatics 97 (2026) 103943

Contents lists available at ScienceDirect

Ecological Informatics

journal homepage: www.elsevier.com/locate/ecolinf

Functional traits and ecosystem services across urban greenery, urban forests, and forests in nature-based solutions: A review

Margherita Paladini [a], Bruno Lasserre [a], Mario Pagano [b], Alessio Giovannelli [b], Claudia Cocozza [c,*]

[a] Department of Biosciences and Territory, University of Molise, 86090 Pesche, Italy
[b] Institute of Research on Terrestrial Ecosystems (IRET), National Research Council (CNR), 50019 Florence, Italy
[c] Department of Agriculture, Food, Environment and Forestry, University of Florence, 50121 Florence, Italy

ARTICLE INFO

Keywords:
Ecosystem service
Biodiversity
Forest
Urbanization
Functional traits
Ecosystem function
Green infrastructure

ABSTRACT

Understanding how plant functional traits influence ecosystem functioning is essential for implementing effective nature-based solutions in both urban and forest contexts. In this study, 80 papers (12.1% of the initially identified literature) were systematically reviewed using the SPIDER selection method to examine how traits mediate resilience, adaptation, and ecosystem service delivery across urban greenery, urban forests, and forests. The analysis revealed that functional traits mediate the relationship between biodiversity and ecosystem service provision, and that their expression is strongly context-dependent, shaped by management intensity, species selection, and environmental stressors. The discussion highlights the importance of trait-based approaches for restoration planning, urban forestry, and ecosystem management, underscoring the need for standardized measurements, mechanistic models, and long-term monitoring to optimize ecosystem service delivery and strengthen resilience.

1. Introduction

Nature-based solutions (NBS) are increasingly recognized as essential because they offer multifunctional responses to complex urban environmental challenges that conventional infrastructure often cannot fully address (Silva Luz et al., 2024). They represent a cost-effective approach to delivering environmental, social, and economic benefits while enhancing the resilience of urban ecosystems (Kong et al., 2021; Prieto et al., 2022). Through biodiversity enhancement, NBS help maintain the biological foundations necessary for human well-being and ensure the provision of ecosystem services (Wellmann et al., 2023). In this perspective, diverse ecosystems, such as forests with higher tree diversity, can increase ecological resilience and, at the same time, support long-term physical and mental health benefits, linking ecosystem management to public health needs (Gillerot et al., 2024). Moreover, major environmental and societal trends have helped place NBS in the spotlight. Projections indicate that approximately 70% of the population will live in cities by 2050 (Czaja et al., 2020). This trend leads to gradual biological depletion and increased human exposure to environmental stressors, particularly in urban systems (Silva Luz et al., 2024). Since the early 21st century, NBS have evolved into a widely used concept within the climate change research community (Kong et al., 2021) and have been a major topic in various policy agendas. For example, the United Nations conceptualizes NBS as actions that work through the protection, restoration, and sustainable management of natural or modified ecosystems to address social, economic, and environmental challenges, while creating benefits for human well-being, ecosystem services, resilience, and biodiversity (United Nations Environment Programme, 2022). Forests are integral to NBS because they contribute to climate mitigation and biodiversity protection within sustainable landscape management strategies (Solano et al., 2025). Urban forests are defined as systems comprising all woodlands, a group or individual trees located in urban and peri-urban areas, including forests, street trees, parks, and gardens (Salbitano et al., 2016), which play a significant role in decreasing air and land surface temperatures, mitigating the effects of heat islands (Love et al., 2025), and enhancing city livability (Scartazza et al., 2025). Within the NBS framework, forest ecosystems deliver services through a cascade effect, linking biophysical structures to ecological functions and human benefits (Andersson-Sköld et al., 2018). In this setting, the study of tree functional traits is fundamental to

* Corresponding author.
E-mail address: claudia.cocozza@unifi.it (C. Cocozza).

https://doi.org/10.1016/j.ecoinf.2026.103943
Received 8 March 2026; Received in revised form 16 July 2026; Accepted 17 July 2026
Available online 19 July 2026

improving NBS in urban and forest ecosystems, as they define plant functions and enable the integration of services into ecological restoration programs (Aubin et al., 2024; Prieto et al., 2022). Although ecological restoration and NBS are closely related and mutually supportive, their primary focus differs; restoration seeks to recover the structure and functioning of ecosystems, whereas NBS are explicitly designed to address societal needs and challenges (Waylen et al., 2024).

Functional traits are measurable morphological or physiological characteristics that influence plant fitness and performance, including growth and survival (de Bello et al., 2010; Sarker et al., 2021). Valorizing trees by considering their functional traits may be the best way to select suitable plants for specific environments, providing adequate processes at the plant level that have direct and beneficial effects on the ecosystem (Miedema Brown and Anand, 2022; Šímová et al., 2019). Despite recognition of NBS and the importance of forests in addressing environmental challenges (Love et al., 2025), gaps persist in understanding functional traits across contexts. Focusing on plant functions is important for determining how they contribute to the delivery of ecosystem services (Behm et al., 2022). Furthermore, functional traits are essential for enhancing resilience to disturbance and the multifunctionality of urban forests (Love et al., 2025). Although these topics have been increasingly studied, previous works remain fragmented, often focusing on single traits, specific services, or specific contexts. This fragmentation limits a comprehensive understanding of how plant functional traits simultaneously influence ecosystem service delivery and ecological resilience within integrated nature-based solutions frameworks. Moreover, only limited efforts have systematically compared these relationships across forest, urban forest, and urban greenery contexts, despite their markedly different ecological dynamics and management objectives.

From a methodological perspective, recent studies highlight the use of satellite-based remote sensing in environmental researches. Multispectral, hyperspectral, and thermal data support large-scale assessments of urban forests and related ecosystem services, yet they have limitations in capturing fine structural traits and therefore often require integration with tools such as Light Detection and Ranging (LiDAR), a remote sensing technology based on laser pulses (Sharma et al., 2025). Similarly, satellite imagery can be used for river morphology analysis; however, its accuracy decreases in complex, forested terrain (Szombara et al., 2020). Overall, satellite approaches are effective at broad scales, with current satellite imagery reaching sub-meter spatial resolution, but benefit from integration with ground-based data to achieve higher precision. This is particularly relevant because vegetation under stress may have reduced capacity to provide ecosystem services. To address these gaps, this study provides a synthesis that explicitly links plant functional traits, ecosystem services, and resilience within the NBS framework across multiple environmental contexts. Unlike previous studies that typically analyze these single gaps alone, this review adopts an integrative perspective, offering a unified analysis of their interactions.

Therefore, this study aims to investigate how plant functional traits contribute to ecosystem service provision and resilience within NBS across forest and urban contexts. Specifically, this review addresses the following research questions:

(i) How are plant functional traits used as indicators of ecosystem functioning, resilience, and adaptation?
(ii) How do these relationships vary across forest, urban forest, and urban greenery contexts?
(iii) How are functional traits integrated into NBS to support ecosystem service delivery?

From this perspective, we conducted a systematic review to examine how NBS, ecosystem services, and plant functional traits are interrelated in urban and forest contexts. We designed this review using the SPIDER framework to structure the analysis of the included literature, providing an innovative approach for systematic reviews by enabling an integrative synthesis of studies across diverse contexts.

2. Methods

This review systematically analyzed how plant functional traits are used in the context of NBS across forest and urban systems. To structure the analysis, we adopted the SPIDER framework for the included bibliographic literature. SPIDER was selected for its efficiency with qualitative and mixed-methods research questions (Cooke et al., 2012).

The guiding research question was: *"How are plant functional traits used to support ecosystem service provision and resilience within NBS across forest and urban contexts?"*

The SPIDER framework was used to define the scope of the review by identifying: (1) the types of systems analyzed (sample), (2) the main focus of the studies (phenomenon of interest), (3) the study designs included, (4) the evaluation criteria, and (5) the research approaches considered. Accordingly, the components were defined as follows:

Sample size (S): forest and urban systems within NBS and ecosystems-based approaches, including context exposed to environmental contaminants and pollution stresses.

Phenomenon of interest (PI): functional traits as indicators of resilience, adaptability, and mitigation.

Design of the study (D): case studies, secondary research, reviews.

Evaluation (E): ecological and functional indicators such as growth, productivity, tree ring characteristics, biomass increment, and responses to pollution or environmental stress.

Research type (R): mixed research approaches, quantitative large-scale analysis, and qualitative site-specific studies.

To address the review aims, a systematic bibliographic search was conducted using a combination of keywords related to three main components: plant functional traits, nature-based solutions and ecosystem services, and environmental context (forest and urban systems). The initial search query used was:

("functional trait" AND ("tree" OR "plant")) AND ("nature-based solution" OR "ecosystem-based approach" OR "ecosystem service") AND ("forest" OR "urban") AND ("growth" OR "productivity" OR "tree ring" OR "environmental contaminant" OR "environmental pollution").

The literature search was carried out across six scientific databases (CABI Digital Library, FAO AGRIS, Google Scholar, PubMed, Scopus, and Web of Science) with the following filters applied consistently:

Publication period: 2000–2025.

Language: English.

Document type: research articles and review papers.

The literature search identified 661 records across the six selected databases. Google Scholar provided the highest number of records ($n = 298$), followed by Web of Science ($n = 187$), Scopus ($n = 72$), PubMed ($n = 52$), CABI Digital Library ($n = 38$), and FAO AGRIS ($n = 14$). These results were retrieved through keyword search strategy before any screening or eligibility filtering.

The study selection process followed a stepwise screening procedure based on title, abstract, and full-text assessment (Fig. 1).

Following the initial search and duplicate removal, the remaining records were gradually screened. Titles were first evaluated for relevance to NBS and ecosystem-based approaches in forest or urban contexts, while abstracts were examined to identify studies aligned with the review scope and SPIDER framework criteria. Full texts were then assessed in detail, focusing on the indicators used and their consistency with the review objectives. Through this process, the number of relevant studies was progressively reduced, and 80 papers were ultimately retained, corresponding to 12.1% of the initially identified literature. The final set provides a representative synthesis of the available scientific literature relevant to the scope of the review.

Two reviewers conducted the screening process independently, and discrepancies were resolved through discussion until consensus was reached. At the full-text stage, studies were excluded if they: (i) did not

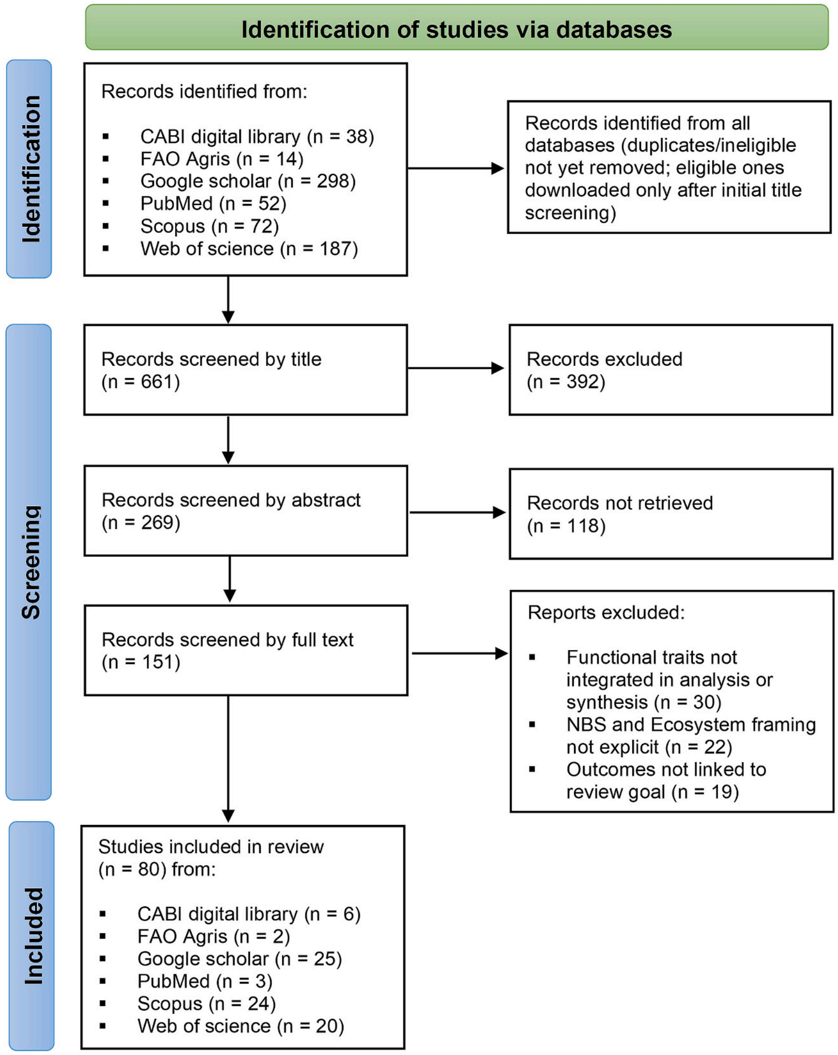

Fig. 1. PRISMA flow diagram summarizing the identification, screening, and inclusion of the studies in the review.

address plant functional traits, (ii) were not conducted in forest or urban contexts, (iii) did not explicitly relate to ecosystem services or resilience, or (iv) lacked sufficient methodological detail to support data extraction and comparison.

A structured database was created using spreadsheet software to extract and organize information from the selected studies. The database included the following variables: ID, source database, title, authors, year of publication, country or region, study type, objective, methods, sample, and main findings.

Each study was classified by its thematic focus: nature-based solutions (NBS), functional traits (FTs), and ecosystem services (ES). In addition, studies were assigned to a specific context: forest, urban greenery, or urban forest, based on the system investigated.

To further characterize the conceptual structure of the selected literature, the final set of 80 papers was analyzed using *VOSviewer* (Van Eck and Waltman, 2023). Bibliometric mapping was employed to identify major research themes and their interrelationships, providing a data-driven framework that complemented the qualitative synthesis of the literature and supported the interpretation of the review questions.

Given the varied terminology used across the NBS literature, it is crucial to establish clear definitions for the terms discussed in this review (Table 1). Although these categories may overlap conceptually in the literature, street trees were assigned to the urban forest category because they represent tree-dominated urban ecosystems.

Table 1
Key terminology and definitions used in this review, including forest, urban forest, and urban greenery, as adopted from FAO (Food and Agriculture Organization of the United Nations, 2020), Salbitano et al. (2016), and Aslanoğlu et al. (2025).

Terminology	Definition	Use in this review
Forest	Land spanning more than 0.5 ha with trees higher than 5 m and a canopy cover of more than 10%, or trees able to reach these thresholds in situ (Food and Agriculture Organization of the United Nations, 2020).	Natural or managed forest ecosystems outside urbanized settings.
Urban Forest	Woodlands, groups of trees, and individual trees located in urban and peri-urban areas; they therefore include forests, street trees, trees in parks and gardens, and trees in derelict corners (Salbitano et al., 2016).	Tree-dominated systems in urban and per-urban environments.
Urban Greenery	Green infrastructure, such as street trees, vertical and rooftop gardens, and living walls (Aslanoğlu et al., 2025)	Small-scale green infrastructure elements in urban areas.

3. Results

The network map (Fig. 2) identified five keyword clusters based on co-occurrence patterns, revealing major thematic domains within the literature. The green cluster highlights studies linking functional traits and forest management, while the remaining clusters are centered on ecosystem services and functions (yellow), global change and nature-based solutions (red), biodiversity and biomass (blue), and functional diversity (purple).

The bibliometric results provide a structured overview of the current literature by identifying both the main research areas and existing knowledge gaps. This mapping acts as a practical bridge between the quantitative results and the qualitative synthesis. Specifically, the network analysis highlights three dominant thematic clusters within the selected studies: nature-based solutions, Ecosystem Services, and Functional Traits. By extracting these topics directly from the data, the VOSviewer analysis provides a clear and logical foundation for the discussion (Bukar et al., 2023; Van Eck and Waltman, 2023).

3.1. Geographical distribution

The selected records included 47 case studies with defined study areas, after excluding review papers. They span five continents and 18 countries, underscoring the topic's global relevance. China accounted for 15 of the 47 case studies and was followed by Brazil and the USA with five studies each. Canada and Italy contributed four studies each, whereas France and Portugal contributed two studies each. The remaining 11 countries were represented by a single study each (Australia, Austria, Bangladesh, Belgium, Bulgaria, Chile, Colombia, Iran, Japan, Poland, Sweden). The 47 case studies were distributed across 18 countries and five continents, providing coverage of multiple environmental and socio-ecological contexts and enabling comparison among different regional research approaches.

The papers were classified, based on the previously mentioned spreadsheet, into three categories: urban greenery (including green roofs, gardens, living walls), forest (pure or mixed stands), and urban forest (as defined in more than one study, mainly in large cities) (Figs. 3 and 4).

The concentration of studies in China (31.9% of case studies) and, to a lesser extent, in Brazil and the USA (10.6% each) indicates that research efforts have been unevenly distributed geographically, with greater attention devoted to regions experiencing rapid urbanization or significant forest management challenges. This indicates that the evidence base is geographically distributed and shaped by context-specific drivers that influence the selection of the study approach.

3.2. Functional traits

Within the selected records, the analysis of functional traits (FTs) reveals a heterogeneous structure, with a clear distinction between leaf traits and plant characteristics. Leaf functional traits were mainly associated with the leaf economics spectrum (49.5% of the leaf trait records), which ranges from species with light, fast-growing leaves to species with dense, more durable, and slow-growing leaves (Simovic et al., 2024). This category includes traits such as specific leaf area (SLA), leaf mass per area (LMA), leaf dry matter content (LDMC), leaf nutrient concentrations (N, P, C) and ratios (C: N), isotopic composition, and pollutant accumulation. In addition, traits related to leaf size and morphology accounted for 28% of the observations, which include leaf area index (LAI), leaf length and width, lamina area, and shape. By contrast, leaf traits such as photosynthetic rate, stomatal conductance, transpiration, relative water content (RWC), and leaf water potential (LWP) represented only 6.5% of all leaf trait records. Finally, traits related to leaf structure, defense, and phenology (e.g., leaf thickness, texture, hairiness, succulence) accounted for 16.1% of all observations (data not shown).

This indicates that current research favors traits that are easy to measure at scale or via remote sensing, which may come at the expense of understanding complex processes such as stress resilience and overall ecosystem functioning.

Plant functional traits encompass a broader set of distinctive characteristics. Plant height traits represented 21.4% of records in the reviewed studies. Traits related to xylogenesis and stem structural characteristics, including wood density and biomass allocation,

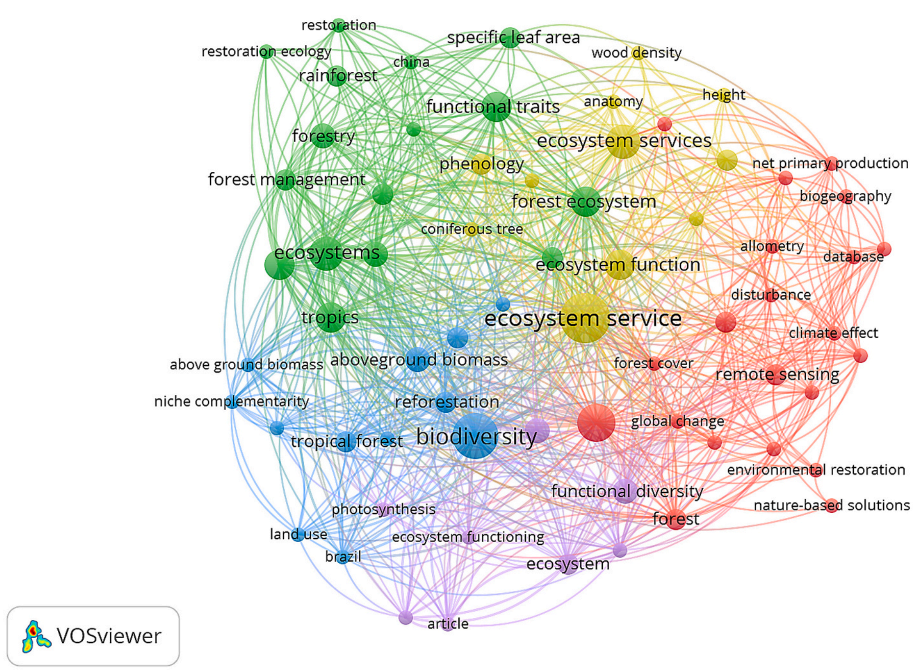

Fig. 2. Keyword co-occurrence network of the 80 selected papers created with *VOSviewer*. Items are represented by labels and circles, with the circle size proportional to keyword occurrence in the selected literature. Colors indicate thematic clusters, and lines represent the strongest links among keywords within the selected studies.

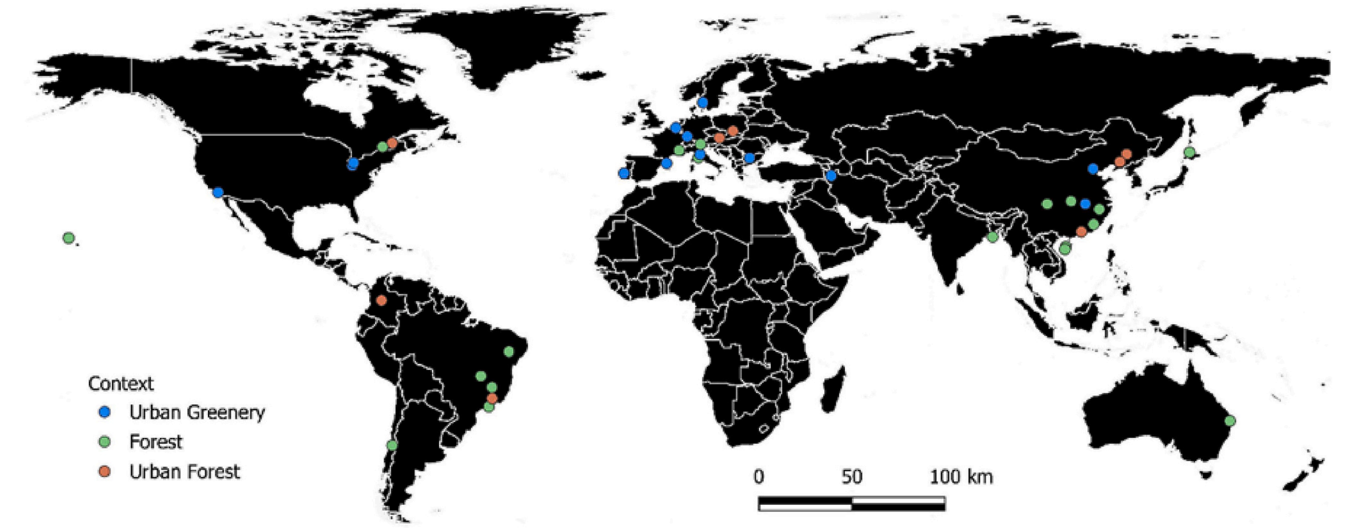

Fig. 3. Geographic map showing the distribution of case studies by country, filtered by context: urban greenery, forest, and urban forest. The map provides an overview of the worldwide spatial distribution of the research.

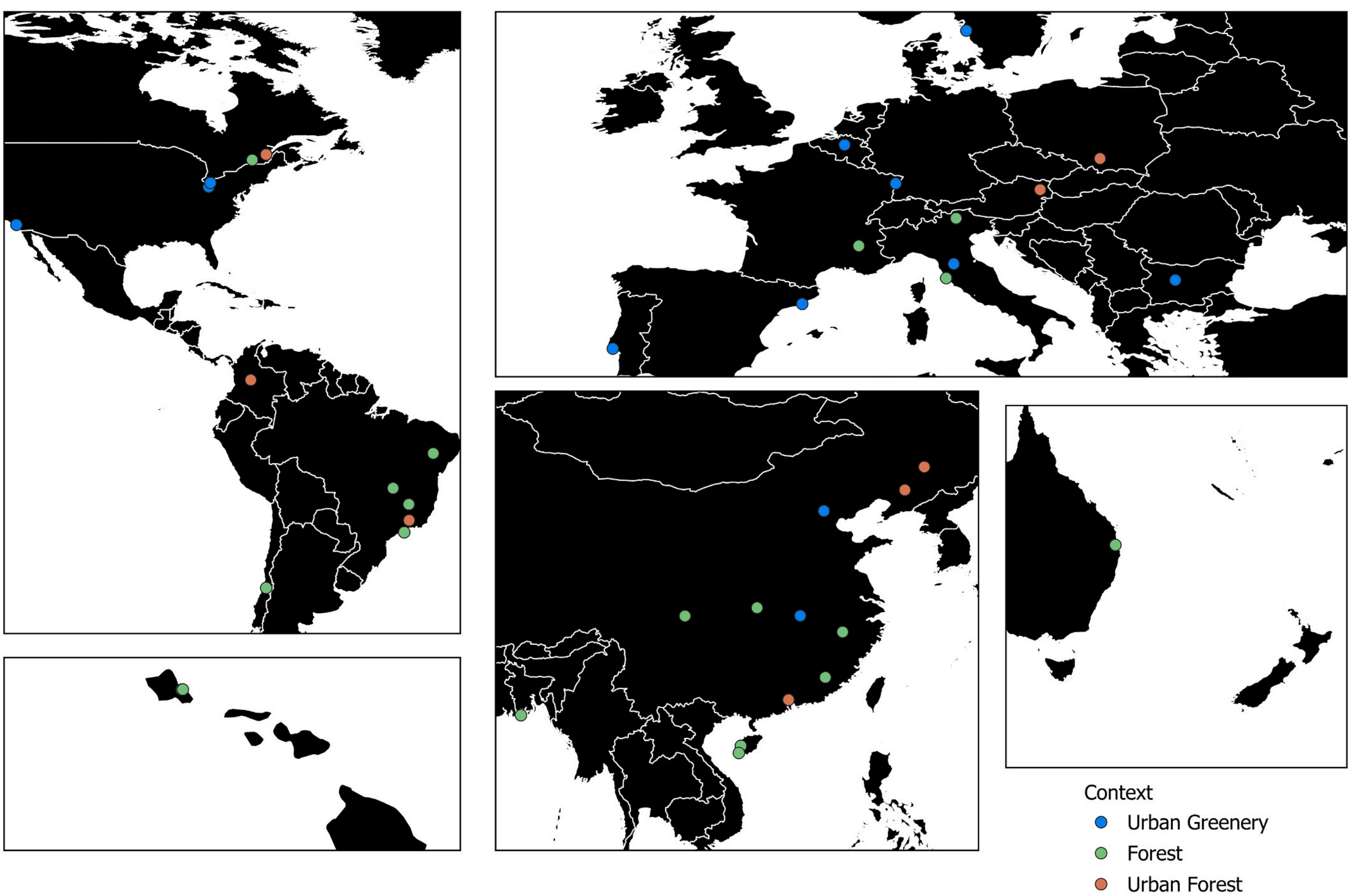

Fig. 4. Detailed sections of the global map at the country level. These insets provide country-level detail, highlighting regions with higher concentrations of case studies and others with limited representation, thereby offering a clearer visualization of the uneven spatial distribution of research across urban greenery, forests, and urban forests worldwide.

accounted for 23.8% of all records. Canopy-related traits (e.g., canopy size, cover, and density) represented 10.7% of the observations. Traits related to growth dynamics (growth rate, phenology, dominance, performance), reproductive traits (seeds, fruit type, flowering characteristics), and dispersal-related traits (e.g., seed dispersal mode and dispersal distance)accounted for 31.1%, 15.5% and 6.0% of plant trait records. Lastly, traits associated with below-ground investment and root expansion (root biomass, root type, root depth), accounted for 9.5% of the records (data not shown).

This creates a fragmented view of plant strategies, as it prioritizes visible architecture over the hidden, yet essential, processes of nutrient acquisition and environmental adaptation.

4. Discussion

The bibliometric analysis shows that the selected literature centers on a limited set of dominant themes, represented by keywords such as ecosystem services, biodiversity, forests, urbanization, functional traits, ecosystem functions, and green infrastructure (Fig. 2). The geographical patterns identified in the reviewed literature, together with the distribution of functional traits in the studies, provide important insights for interpreting the role of functional traits in ecosystem service delivery and Nature-Based Solutions across different environmental contexts.

These keywords reflect the main research focus and provide the basis for the discussion, which is organized around three themes: nature-based solutions, ecosystem services, and functional traits. Within this framework, this synthesis examines the use of functional traits in linking ecosystem services to nature-based solutions, focusing on their consistency, limitations, and context dependence.

In addition, the global distribution of case studies (Fig. 3) and the detailed regional insets (Fig. 4) highlight a marked spatial imbalance, with a higher concentration of studies in China, Brazil, and the USA, while other regions remain underrepresented. This spatial imbalance may indicate that regional research priorities and socio-environmental contexts strongly influence the current understanding of NBS, ES, and FTs. Similar geographic biases have been reported in global trait and ecosystem service databases (Aubin et al., 2024; Tsujii et al., 2020), indicating that empirical evidence and synthesis studies may be influenced by data availability. This has important implications for the transferability of findings across regions, particularly in the context of global environmental change.

The analysis shows that functional traits are increasingly used as a unifying framework, yet their application remains uneven and often oversimplified across studies.

4.1. Nature-based solutions

NBS are consistently framed as multifunctional approaches that integrate ecosystem services, green infrastructure, and ecological restoration, although their operationalization varies across contexts and methodologies. While NBS are broadly defined as solutions inspired by nature that deliver environmental, social, and economic benefits (European Commission, 2020), the literature reveals substantial differences in their implementation (Kong et al., 2021; Silva Luz et al., 2024).

Our results indicate that NBS are primarily approached through three complementary perspectives: policy frameworks, management tools, and measurable systems (as in Kong et al., 2021). This classification aligns with previous studies that describe NBS as socio-ecological-technological systems, integrating ecological processes with social and technological components (Wellmann et al., 2023). Some studies emphasize participatory co-production and governance, such as the EU Biodiversity Strategy 2030 and the UN Decade on Ecosystem Restoration (Hastings et al., 2020), while others rely on quantitative modeling and simulations to assess environmental impacts (Kong et al., 2021; Yang et al., 2015). This variability reflects that NBS work through complementary approaches rather than a single unified framework. Moreover, NBS can operate using functional and morphological traits to guide species selection in urban planning policies (Silva Luz et al., 2023). They can also be applied as management tools, for example, in agroforestry, hybrid restoration, or decision-support systems that combine remote sensing and vulnerability mapping (Hastings et al., 2020; Wellmann et al., 2023). Finally, NBS can be implemented using a measurement-based approach, employing biomonitoring and NDVI to assess tree vitality and functional diversity (Jakubiak et al., 2025; Wellmann et al., 2023). Indeed, our keyword analysis confirms that NBS research bridges policy, management, and monitoring (Fig. 2). The conceptual framing is consistent across the selected studies. At the same time, operational approaches differ in scale and methodology, particularly regarding participatory co-production models, as reported by Hastings et al. (2020).

Literature conceptualizes the relationships among NBS, functional traits, and ecosystem services through trait-based frameworks, in which biological characteristics function as mediators between biodiversity and societal outcomes (Hastings et al., 2020). NBS are considered management actions, and their effectiveness depends on the functional traits of the individual species involved. Traits are interpreted as predictors of ecological processes related to service provision: climate regulation, carbon sequestration, pollution mitigation, and soil stabilization (Jakubiak et al., 2025; Wellmann et al., 2023). At broad spatial scales, morphological and taxonomic traits are used as proxies for assessing functional capacities, effectively serving as shortcuts for assessing ecosystem services (Silva Luz et al., 2024). In addition, technological approaches are used, employing remote sensing and spectral traits to track NBS performance under environmental stressors (Abelleira Martínez et al., 2016; Wellmann et al., 2023). Overall, functional diversity is consistently associated with enhanced resilience, as response diversity stabilizes ecosystem service delivery under changing environmental conditions, as also observed by Wellmann et al. (2022).

Despite these advantages, our analysis also highlights that NBS are promoted as tools to enhance urban ecosystem resilience, although their actual efficiency may be constrained by limitations and risks. Widely acknowledged limitations include vulnerability to climate change, such as heat or drought, which cause damage, leading to early tree senescence, leaf abscission, or mortality. This directly affects ecosystem services, such as shading, cooling, and carbon sequestration (Wellmann et al., 2022).

Some studies also address biological disservices in urban configurations, for instance, when limited air circulation reduces the efficiency of air purification or when a high proportion of allergenic species is planted in residential areas (Grote et al., 2016; Kong et al., 2021). Moreover, a growing concern is the tendency toward monospecific plantings in urban tree composition, in which species selection is primarily driven by human decisions, aesthetic preferences, or the cultural significance of trees (Grilo et al., 2025; Rodríguez-Santamaría et al., 2022). This practice decreases plant resilience and exposes trees to a greater risk of pathogens and diseases (Silva Luz et al., 2023). Additionally, species selection may limit the use of drought-adapted species, which provide lower cooling benefits (Wellmann et al., 2022), while deciduous species fail to deliver the expected services during dormancy (Silva Luz et al., 2023). Importantly, leaf phenology influences carbon-biodiversity, and understanding these differences among phenological groups is crucial for identifying species that can maximize multiple ecosystem services under climate change, as highlighted by Rodrigues et al. (2023). However, further gaps identified in the analyzed studies include the limited availability of functional and species-level data in highly biodiverse and forested areas (Rayome et al., 2019) and the insufficient assessment of potential biological disservices (Hastings et al., 2020). These gaps reflect a geographic bias that leaves our understanding of NBS uneven and difficult to scale in underrepresented ecosystems.

4.2. Ecosystem services

Ecosystem services are central to the reviewed studies and are used to assess the effectiveness of NBS. Studies focus on quantifying, optimizing, and valuing specific services, such as carbon sequestration, air purification, and stormwater regulation (Amini Parsa et al., 2019), or treat them as explicit targets in restoration programs to deliver functional benefits (Carlucci et al., 2020). They provide a framework for understanding the pathway from ecological functions to human benefits, often conceptualized through a cascade model and applied to urban and ecological systems (Andersson-Sköld et al., 2018). This comprehensive set of services improves the world's environmental quality, underscoring benefits that extend beyond humans to wildlife as well, consistent with O'Brien et al. (2022). ES are used as primary evaluation metrics to compare management practices and identify configurations that maximize multiple benefits (Ranalli and Lundholm, 2008; Wood and Dupras, 2021), or they are the result of a combination of management paths that provide the desired services (Gadow et al., 2007). In some studies, they are treated as secondary outcomes of ecological processes, with ecosystem stability and biodiversity functioning maintained (Ali, 2023; Dolezal et al., 2020). Measurements rely on a broad spectrum of methods, including indirect indicators such as land cover (Miedema Brown and Anand, 2022), as well as approaches ranging from biophysical assessments to monetary valuation and social surveys (Shome et al., 2023). This methodological diversity reflects the heterogeneity observed in our dataset but also highlights a key limitation: despite a shared sustainability goal, the use of different tools and scales makes it difficult to integrate findings into a coherent understanding of multifunctionality (Ali, 2023; de Bello et al., 2021).

Ecosystem services analysis across the case studies shows uneven attention to service categories. Regulating services represent a major focus in urban contexts, with a focus on climate regulation, air quality improvement, water regulation, and heat mitigation, according to Liang and Huang (2023). This category is often quantified using measurable metrics, such as leaf area or wood density (Andersson-Sköld et al., 2018; Borges et al., 2021). Supporting services are also widely considered and, as support for the other services, include soil fertility, nutrient cycling, and primary production (Everard, 2018; Miedema Brown and Anand, 2022). In contrast, cultural services, although acknowledged as relevant to human well-being, are difficult to define and quantify and are limited to aesthetic or recreational aspects, as observed in Shome et al. (2023) and Fontana et al. (2014). Provisioning services also receive reduced focus in the studies, being addressed only in managed contexts such as agriculture or timber production (as in Gadow et al., 2007). This imbalance suggests that measurable, trait-linked ecosystem services are prioritized, while other services remain marginal in ecosystem services assessments (Aubin et al., 2024).

In the analyzed case studies, it emerges that improving ecosystem service research and integrating it into management and planning require conceptual and methodological advances (Vohland, 2009). At the conceptual level, a distinction among the terms used is needed to avoid ambiguity and double counting when they are used interchangeably (ecosystem processes, functions, or final services) (Ali, 2023; Basnou et al., 2015). In addition, ecosystem services should be outlined as outcomes of social-ecological coproduction, emphasizing their multifunctionality and the ability of ecosystems to provide bundles of services under changing conditions (Everard, 2018; Weiskopf et al., 2024). From a methodological perspective, the literature documents a shift from descriptive to mechanistic, process-based models, enabling causal links among traits, environmental drivers, and ecosystem services (Aubin et al., 2024; Bu et al., 2019). Recent studies suggest moving beyond total tree biomass measurements by focusing on vegetation layers and including shrubs, herbs, the canopy, and belowground tree organs to better understand how traits affect the provisioning of ecosystem services (Wang et al., 2024). This shift aligns with the growing role of functional traits identified in our analysis and underscores the need for more comprehensive, multi-layered data. Another priority is addressing data gaps for understudied species, for which trait information is often incomplete. This is particularly evident for rare species or those occurring in regions with limited access, or scarce resources. Consequently, global trait databases tend to include common species, leaving less abundant species underrepresented (Aubin et al., 2024; Tsujii et al., 2020). This gap is also evident for belowground traits, which are rarely measured but are important for ecosystem processes. Roots and fine roots are essential for water and nutrient uptake and help plants cope with environmental stress, such as drought. In urban environments, root traits reflect how trees adapt to limited water and harsh conditions (Zhang et al., 2023). Despite their importance for ES (e.g., soil stabilization, water regulation, and nutrient cycling), root traits remain poorly documented in global databases (Aubin et al., 2024). In green roof infrastructure, root traits indicate how plants respond to resource gradients and are used as indicators of plants' strategies (Rolhauser et al., 2023). Therefore, the limited integration of belowground traits represents a critical gap in current trait-based ES research, with implications for both modeling accuracy and NBS design.

4.3. Functional traits

Ecologists increasingly use plant functional traits (FTs) to predict changes in communities and ES by linking fundamental biological processes to ecosystem functioning (de Bello et al., 2010; Sarker et al., 2021). In line with patterns emerging from our analysis, FTs are a central analytical tool across the reviewed studies, particularly in contexts affected by environmental change and disturbance. Investigating how disturbance affects variation in functional traits is essential for understanding ecosystem functioning in disturbed forests, as demonstrated by Ding et al. (2012). Similarly, environmental changes associated with urbanization, including soil acidification, nutrient filtering, and heavy metal pollution, influence plant functional traits and forest community composition (Huang et al., 2013; Yu et al., 2018). For example, foliar C:N varies across species and climates in urban forests, indicating environmental effects on traits (Wei and He, 2021). In the case studies considered, these traits are used as a framework for combining, with distinct roles ranging from descriptive variables to predictive mechanisms (Carmona et al., 2016; Pataki et al., 2013). Traits are often used to characterize plant and community responses to environmental changes and stressors, including urbanization, drought, and disturbance regimes (Ilyas et al., 2021; Pereira de Oliveira et al., 2020). Consequently, the ecological strategies through which plant species manage environmental restraints can be identified by assessing plant functional traits (Song et al., 2019). Enhancing forest ecological resilience to unknown disturbances can be achieved by promoting functional traits and structural diversity (Mina et al., 2022). This is particularly relevant for ecological restoration, where identifying appropriate species remains an important goal for delivering ES (Tsujii et al., 2020). Accordingly, afforestation and reforestation should prioritize native species suited to the site's ecological and biogeographical conditions (Quaranta et al., 2025). Therefore, focusing on FTs rather than taxonomic identity allows practitioners of ecosystem restoration to target ES rather than attempting to recreate conditions that may no longer be feasible due to climate change (Manhães et al., 2025). In these contexts, traits are operationalized as management tools to guide species selection in urban forestry, restoration planning, and agroforestry (as in Carlucci et al., 2020). Plant FTs vary considerably across studies, reflecting different trait definitions (Streit and Bellwood, 2023). Consistent with patterns observed in the ecosystem services section (4.2. 2), there is a tendency to use easy- to- measure soft traits (e. g., seed mass) rather than hard traits (e. g., competition or colonization abilities) as proxies for studying trait mechanisms (Carlucci et al., 2020).

Studies conceptualize the pathways linking plant FTs to ecosystem functioning and service provision in urban ecosystems using a response-effect framework (Goodness et al., 2016). The provision of ES through plant FTs depends on the underlying ecosystem processes (Pan et al., 2022). In addition, traits function as mediators that connect the morphological characteristics of organisms to ecosystem services (Green et al., 2022; Guo et al., 2022). Specifically, traits are attributes of an organism that determine its contribution to ecosystem processes and the associated services it provides, which are subsequently translated into services valued by the community (Goodness et al., 2016). For regulating services, such as carbon storage, air purification, and decomposition, related traits (wood density, tree height, and leaf area) have been linked to measured ecosystem processes (Falster et al., 2011; Rodrigues et al., 2023). Therefore, evaluating functional traits is essential for biodiversity conservation, restoration programs for degraded forests, and monitoring the provision of ES (Ayma-Romay et al., 2021; Han et al., 2021).

Functional trait-based approaches have conceptual and empirical limitations. For example, FTs may have limited predictive power for survival during the early establishment phase in restoration programs, when initial plant size exerts a stronger influence, according to Gardiner et al. (2019). Furthermore, data availability is largely concentrated in Europe and the Americas, leaving a considerable gap in understanding species traits in other geographic regions (Goodness et al., 2016). This bias echoes the spatial imbalances in our results, highlighting the difficulty of generalizing trait-based models.

Moreover, the reliance on species-level data often overlooking intraspecific trait variability, which shapes community responses to stressors (Ding et al., 2012). Models often overlook interactions among FTs, the microclimate, management practices, and species competition, all of which can influence tree growth (Simovic et al., 2023). Trait-based functional diversity of tree species influences ecosystem multifunctionality, yet its effects remain poorly understood. Future research should incorporate additional factors (e.g., root traits, soil microbial diversity, and biodiversity) to achieve a more comprehensive understanding of the mechanisms driving multifunctionality in urban forests (Wang et al., 2025a; Wang et al., 2025b). These needs align with the gaps identified in our analysis, particularly the limited representation of belowground processes and complex trait interactions. The term "functional trait" is sometimes used without quantifiable evidence of a trait's impact on an ecosystem function (Streit and Bellwood, 2023).

4.4. NBS, ES, and FTs in urban greenery, urban forests, and forests

4.4.1. NBS across landscapes

Our results indicate that the role and implementation of NBS vary systematically across landscape contexts, even though the overarching goal of enhancing resilience is consistent. Across the analyzed studies, clear differences emerge among urban greenery, urban forests, and non-urban forests, reflecting variations in management intensity, ecological processes, and spatial scale. Urban greenery refers to intensively managed structures, such as green roofs, gardens, and lawns (Rolhauser et al., 2023; Wellmann et al., 2023), and is considered a tool for delivering social, cultural, and microclimate benefits (Jakubiak et al., 2025). Its operation relies on elevated levels of management and includes herbs and shrubs, which are valued for evaporative cooling and for mitigating surface and air temperatures in constrained urban environments (Silva Luz et al., 2024). Urban forests, by contrast, represent an integrated system of woody vegetation around cities and are considered a social, ecological, and technological system that connects people and urban infrastructure (Jakubiak et al., 2025). Their structure and functioning are influenced by the intensity of urbanization, measured, for example, by urbanized area, traffic volume, and air pollution, which can affect ecosystem service delivery (Petrova and Petkova, 2023; Yan et al., 2025) and reflect human-related environmental degradation that generates urban stressors (Czaja et al., 2020). In this context, NBS are implemented through tree-based ecosystems that address specific urban challenges, such as reducing flood risk and stormwater runoff, and mitigating heat (Kong et al., 2021). By contrast, forests outside urban areas and in natural (undisturbed) areas are treated as contiguous ecosystems, where NBS are associated with long-term processes of ecosystem recovery, biodiversity conservation, and carbon sequestration (Hastings et al., 2020; Jakubiak et al., 2025). This gradient highlights a shift from engineered urban greenery to process-based natural forests, mirroring the diverse ways NBS are operationalized.

4.4.2. Ecosystem services delivery

ES delivery varies across urban greenery, urban forests, and forests, shaped by differences in management intensity and ecological traits. This gradient reflects broader patterns identified in our analysis, showing how NBS shift from engineered urban solutions toward more process-based forest systems. In urban greenery, ES are primarily regulating and cultural (Andersson-Sköld et al., 2018). Service delivery is constrained by strong abiotic stressors in dense urban environments, such as heat stress, soil compaction, and reduced rooting volume. At the same time, these systems offer opportunities to integrate ecological and engineering systems, including sustainable urban drainage systems and green roofs that promote urban rewilding (Li et al., 2023; Salman et al., 2019). In cities, the interaction between "brown infrastructure" (urban soil) and "green infrastructure" (vegetation) supports resilience and the capacity to provide ES (Scartazza et al., 2025). Through the provision of multiple ES, urban forests, individual trees, or groups of trees play a significant role in mitigating the negative impacts of urbanization (Zhang et al., 2023). Urban forests operate at an intermediate scale and deliver complex and durable ES, including air quality regulation, carbon sequestration, and habitat continuity (Andersson-Sköld et al., 2018; Jakubiak et al., 2025). Moreover, their effectiveness can be limited by spatial fragmentation and vulnerability to pests and diseases, which weaken the tree canopy structure (Weiskopf et al., 2024). Forests are considered the primary providers of supporting and provisioning services, given their role in nutrient cycling, soil formation, and climate regulation (Gadow et al., 2007). These ecosystems hold enormous potential for large-scale restoration, strict protection, and rewilding (Solano et al., 2025). Overall, these differences reinforce the imbalance identified in our results, where regulating services dominate urban studies, while supporting and provisioning services are strongly associated with less disturbed ecosystems.

4.4.3. Functional traits depending on context

Our analysis further highlights that the role of functional traits is strongly context-dependent (Didion-Gency et al., 2021), with this dependency becoming more pronounced along the gradient from forests to urban forests to urban greenery (Simovic et al., 2024). In natural and semi-natural forests, ecosystem functioning is shaped by biophysical limitations and long-term ecological processes, so functional traits often arise from niche complementarity, in which functional diversity enhances productivity and stability (Borges et al., 2021; Lin et al., 2016; Ma et al., 2021). In urban forests, by contrast, these relationships are shaped by selection effects, as ES delivery is driven by the traits of a limited number of dominant or selected planted species that reflect management priorities (Rodrigues et al., 2023). Therefore, traits serve as functional markers, linking species' characteristics to the ecosystem properties of urban forests (Cardou et al., 2020). This context dependency also applies to urban greenery, where intensive management allows species to persist outside their niches, weakening the links between response and effect traits (Goodness et al., 2016). Here, human interventions, such as fertilization and irrigation, can loosen environmental filters (Behm et al., 2022). As a result, trees selected for social or aesthetic reasons might have little relevance to expected plant-regulating functions, and trait performance itself might shift in response to urban-specific stressors, such as heat, altered light regimes, and environmental pollution (Camargo et al., 2024; Su et al., 2021). Transferring trait-based findings across contexts is challenging because of scale mismatches and intraspecific trait variability. Traits that show strong correlations at regional and global scales may differ when the scale gradient changes (Yang et al., 2015). Moreover, these difficulties are underscored by geographic and taxonomic inconsistencies in existing datasets and across disciplines, as described by Shome et al. (2023). These gaps highlight the need for more context-sensitive and integrative trait-based frameworks.

In summary, while functional traits can bridge ES and NBS, their current use is often overly simplified or context-specific, making them less predictive. This limits the extent to which findings can be scaled across urban and non-urban systems, highlighting the need for integrative models that account for ecological complexity.

5. Conclusions

This review highlights that nature-based solutions rely on plant functional traits to support the delivery of ecosystem services and to improve the resilience of urban and forest ecosystems. However, the role of specific traits varies with environmental context and the ecosystem services considered. In urban greenery, traits related to leaf morphology, canopy structure, and tree size are commonly associated with thermal regulation, shading, and air purification. In forest ecosystems, hydraulic, structural, and wood-related traits are commonly linked to drought tolerance, carbon storage, and long-term ecosystem functioning. Consequently, urban forests represent an intermediate condition in which ecological processes interact with management practices and urban stressors.

ES are central to NBS evaluation: regulating services (e.g., climate mitigation, air purification, and water regulation) are the dominant category assessed in literature. By contrast, cultural and provisioning services remain less quantified and are often evaluated through indirect indicators. This imbalance limits understanding of ecosystem multi-functionality and reduces the integration of non-tangible services into trait-based NBS planning.

Trait-based approaches can support targeted species selection for restoration and urban planning. By linking canopy structure and leaf-related traits to cooling and air purification in urban systems, and hydraulic and structural traits to drought resistance and carbon-related functions in forests, these approaches enhance resilience to climate change and urban stressors. However, transferring trait-service relationships across forest, urban forest, and urban greenery contexts remains challenging due to intraspecific variability and the influence of urban stressors. Indeed, context strongly influences trait expression and ecosystem service delivery, as these systems differ in management intensity, species selection, and environmental conditions.

Future NBS implementation should integrate mechanistic, trait-based models and consider species context during selection, particularly regarding environmental filtering and management intensity. Additionally, monitoring ecosystem multifunctionality remains a powerful tool for evaluating trade-offs among ecosystem services and for guiding biodiversity conservation and adaptive management in both urban and forest systems.

In conclusion, integrating FTs approaches into NBS planning and management provides a valuable framework for improving the ecological basis of resilient and multifunctional urban and forest ecosystems. However, the effectiveness of trait–service relationships remain highly context-dependent, shaped by environmental conditions, management intensity, and intraspecific variability across urban greenery, urban forests, and forest systems. These limitations highlight the need for a mechanistic, model-based approach to trait data that is standardized, inclusive of understudied species, and more representative of a broader ecological gradient. A related but distinct issue concerns alien species. Although they may contribute to specific ecosystem functions or be readily accessible and convenient for research or management, their use within NBS requires careful evaluation to avoid unintended impacts on native biodiversity.

Thus, applying plant functional traits as operational tools can support informed species selection, improve NBS assessment, and optimize ES delivery while conserving biodiversity across urban and forest contexts.

Declaration of AI-assisted technologies in the writing process

During the preparation of this work, the authors used Grammarly in order to improve the English language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Margherita Paladini: Writing – review & editing, Writing – original draft, Data curation. **Bruno Lasserre:** Writing – review & editing, Supervision. **Mario Pagano:** Writing – review & editing, Validation. **Alessio Giovannelli:** Writing – review & editing, Validation, Supervision. **Claudia Cocozza:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

Abelleira Martínez, O.J., Fremier, A.K., Günter, S., Ramos Bendaña, Z., Vierling, L., et al., 2016. Scaling up functional traits for ecosystem services with remote sensing: concepts and methods. Ecol. Evol. 6 (13), 4359–4371. https://doi.org/10.1002/ece3.2201.

Ali, Arshad, 2023. Biodiversity–ecosystem functioning research: brief history, major trends and perspectives. Biol. Conserv. 285, 110210. https://doi.org/10.1016/j.biocon.2023.110210.

Amini Parsa, V., Salehi, E., Reza Yavari, A., Van Bodegom, P.M., 2019. Analyzing temporal changes in urban forest structure and the effect on air quality improvement. Sustain. Cities Soc. 48, 101548. https://doi.org/10.1016/j.scs.2019.101548. July.

Andersson-Sköld, Y., Klingberg, J., Gunnarsson, B., Cullinane, K., Gustafsson, I., Hedblom, M., et al., 2018. A framework for assessing urban greenery's effects and valuing its ecosystem services. J. Environ. Manage. 205, 274–285. https://doi.org/10.1016/j.jenvman.2017.09.071.

Aslanoğlu, R., Kazak, J.K., Szewrański, S., Świąder, M., Arciniegas, G., Chrobak, G., et al., 2025. Ten questions concerning the role of urban greenery in shaping the future of urban areas. Build. Environ. 267, 112154. https://doi.org/10.1016/j.buildenv.2024.112154.

Aubin, I., Deschênes, E., Santala, K.R., Emilson, E.J.S., Schoonmaker, A.L., McIntosh, A.C.S., et al., 2024. Restoring Forest ecosystem services through trait-based ecology. Environ. Rev. 32 (4), 498–524. https://doi.org/10.1139/er-2023-0130.

Ayma-Romay, A.I., Bown, H.E., Pérez-Harguindeguy, N., Enrico, L., 2021. Trait similarity among dominant highly-competitive species rather than diversity increases productivity in semi-arid Mediterranean forests. For. Ecol. Manage. 486, 118969. https://doi.org/10.1016/j.foreco.2021.118969.

Basnou, C., Pino, J., Terradas, J., 2015. Ecosystem services provided by green infrastructure in the urban environment. CABI Rev. 1–11. https://doi.org/10.1079/PAVSNNR201510004.

Behm, J.E., Bélouard, N., Gleditsch, J.M., Phillips, P.M., Swartz, T.M., 2022. Trait-based approaches for understanding how biodiversity generates sustainable benefits in urban vegetated green infrastructure. Curr. Opin. Environ. Sustain. 57, 101204. https://doi.org/10.1016/j.cosust.2022.101204.

Borges, E.R., Dexter, K.G., Pyles, M.V., Bueno, M.L., dos Santos, R.M., Fontes, M.A.L., et al., 2021. The interaction of land-use history and tree species diversity in driving variation in the aboveground biomass of urban versus non-urban tropical forests. Ecol. Indic. 129, 107915. https://doi.org/10.1016/j.ecolind.2021.107915.

Bu, W., Huang, J., Xu, H., Zang, R., Ding, Y., Li, Y., et al., 2019. Plant functional traits are the mediators in regulating effects of abiotic site conditions on aboveground carbon stock-evidence from a 30 ha tropical forest plot. Front. Plant Sci. 9, 1958. https://doi.org/10.3389/fpls.2018.01958.

Bukar, U.A., Sayeed, M.S., Razak, S.F.A., Yogarayan, S., Amodu, O.A., et al., 2023. A method for analyzing text using VOSviewer. MethodsX 11, 102339. https://doi.org/10.1016/j.mex.2023.102339.

Camargo, M.A., Melgarejo, L.M., Faerito, G., Pérez, I., Salgado-Negret, B., 2024. Morphological and biochemical changes in *Quercus humboldtii* in response to warmer and polluted urban areas in a tropical Andean city. J. Urban Ecol. 10 (1), juae010. https://doi.org/10.1093/jue/juae010.

Cardou, F., Aubin, I., Bergeron, A., Shipley, B., 2020. Functional markers to predict Forest ecosystem properties along a rural-to-urban gradient. J. Veg. Sci. 31 (3), 416–428. https://doi.org/10.1111/jvs.12855.

Carlucci, M.B., Brancalion, P.H.S., Rodrigues, R.R., Loyola, R., Cianciaruso, M.V., 2020. Functional traits and ecosystem Services in Ecological Restoration. Restor. Ecol. 28 (6), 1372–1383. https://doi.org/10.1111/rec.13279.

Carmona, C.P., de Bello, F., Mason, N.W.H., Lepš, J., 2016. Traits without Borders: integrating functional diversity across scales. Trends Ecol. Evol. 31 (5), 382–394. https://doi.org/10.1016/j.tree.2016.02.003.

Cooke, A., Smith, D., Booth, A., 2012. Beyond PICO: the SPIDER tool for qualitative evidence synthesis. Qual. Health Res. 22 (10), 1435–1443. https://doi.org/10.1177/1049732312452938.

Czaja, M., Kołton, A., Muras, P., 2020. The complex issue of urban trees—stress factor accumulation and ecological service possibilities. Forests 11 (9), 932. https://doi.org/10.3390/f11090932.

de Bello, F., Lavorel, S., Díaz, S., Harrington, R., Cornelissen, J.H.C., Bardgett, R.D., et al., 2010. Towards an assessment of multiple ecosystem processes and services via functional traits. Biodivers. Conserv. 19 (10), 2873–2893. https://doi.org/10.1007/s10531-010-9850-9.

de Bello, F., Lavorel, S., Hallett, L.M., Valencia, E., Garnier, E., Roscher, C., et al., 2021. Functional trait effects on ecosystem stability: assembling the jigsaw puzzle. Trends Ecol. Evol. 36 (9), 822–836. https://doi.org/10.1016/j.tree.2021.05.001.

de Oliveira, A.C.P., Nunes, A., Rodrigues, R.G., Branquinho, C., 2020. The response of plant functional traits to aridity in a tropical dry forest. Sci. Total Environ. 747, 141177. https://doi.org/10.1016/j.scitotenv.2020.141177.

Didion-Gency, M., Bachofen, C., Buchmann, N., Gessler, A., Morin, X., Vicente, E., et al., 2021. Interactive effects of tree species mixture and climate on foliar and Woody trait variation in a widely distributed deciduous tree. Funct. Ecol. 35 (11), 2397–2408. https://doi.org/10.1111/1365-2435.13898.

Ding, Y., Zang, R., Letcher, S.G., Liu, S., He, F., 2012. Disturbance regime changes the trait distribution, phylogenetic structure and community assembly of tropical rain forests. Oikos 121 (8), 1263–1270. https://doi.org/10.1111/j.1600-0706.2011.19992.x.

Dolezal, J., Fibich, P., Altman, J., Leps, J., Uemura, S., Takahashi, K., et al., 2020. Determinants of ecosystem stability in a diverse temperate Forest. Oikos 129 (11), 1692–1703. https://doi.org/10.1111/oik.07379.

European Commission, 2020. Biodiversity and Nature-Based Solutions: Analysis of EU-Funded Projects. European Commission, Brussels, Belgium, p. 3.

Everard, M. (2018). Optimizing ecosystem services to deliver multiple benefits. *CABI Rev.*, January 31, 1–10. doi:https://doi.org/10.1079/PAVSNNR201712060.

Falster, D.S., Brännström, Å., Dieckmann, U., Westoby, M., 2011. Influence of four major plant traits on average height, leaf-area cover, net primary productivity, and biomass density in single-species forests: a theoretical investigation. J. Ecol. 99 (1), 148–164. https://doi.org/10.1111/j.1365-2745.2010.01735.x.

Fontana, V., Radtke, A., Walde, J., Tasser, E., Wilhalm, T., Zerbe, S., et al., 2014. What plant traits tell us: consequences of land-use change of a traditional agro-forest system on biodiversity and ecosystem service provision. Agric. Ecosyst. Environ. 186, 44–53. https://doi.org/10.1016/j.agee.2014.01.006.

Food and Agriculture Organization of the United Nations, 2020. Global Forest Resources Assessment 2020: Terms and Definitions. FAO, Rome, Italy, p. 4.

Gadow, K.V., Kurttila, M., Leskinen, P., Leskinen, L., Nuutinen, T., Pukkala, T., 2007. Designing forested landscapes to provide multiple services. CABI Reviews. https://doi.org/10.1079/PAVSNNR20072038 ahead of print, September 5.

Gardiner, R., Shoo, L.P., Dwyer, J.M., 2019. Look to Seedling Heights, rather than functional traits, to explain survival during extreme heat stress in the early stages of subtropical rainforest restoration. J. Appl. Ecol. 56 (12), 2687–2697. https://doi.org/10.1111/1365-2664.13505.

Gillerot, L., Landuyt, D., Bourdin, A., Rozario, K., Shaw, T., Steinparzer, M., et al. 2024. Forest biodiversity and structure modulate human health benefits and risks. Preprint, in review, September 2. Doi:10.21203/rs.3.rs-4669329/v1.

Goodness, J., Andersson, E., Anderson, P.M.L., Elmqvist, T., 2016. Exploring the links between functional traits and cultural ecosystem services to enhance urban ecosystem management. Ecol. Indic. 70, 597–605. https://doi.org/10.1016/j.ecolind.2016.02.031.

Green, S.J., Brookson, C.B., Hardy, N.A., Crowder, L.B., 2022. Trait-based approaches to global change ecology: moving from description to prediction. Proc. R. Soc. B Biol. Sci. 289 (1971), 20220071. https://doi.org/10.1098/rspb.2022.0071.

Grilo, F., McPhearson, T., Aleixo, C., Santos-Reis, M., Branquinho, M., 2025. Urban trees through a functional traits' lens: exploring the interplay between tree functional groups and social-ecological factors. Urban For. Urban Green. 107, 128749. https://doi.org/10.1016/j.ufug.2025.128749.

Grote, R., Samson, R., Alonso, R., Amorim, J.H., Cariñanos, P., Churkina, G., et al., 2016. Functional traits of urban trees: air pollution mitigation potential. Front. Ecol. Environ. 14 (10), 543–550. https://doi.org/10.1002/fee.1426.

Guo, C., Yan, E.R., Cornelissen, J.H.C., 2022. Size matters for linking traits to ecosystem multifunctionality. Trends Ecol. Evol. 37 (9), 803–813. https://doi.org/10.1016/j.tree.2022.06.003.

Han, X., Huang, J., Yao, J., Xu, Y., Ding, Y., Zang, R., 2021. Effects of logging on the ecological strategy spectrum of a tropical montane rain forest. Ecol. Indic. 128, 107812. https://doi.org/10.1016/j.ecolind.2021.107812.

Hastings, Z., Ticktin, T., Botelho, M., Reppun, N., Kukukea-Shultz, K., Wong, M., et al., 2020. Integrating co-production and functional trait approaches for inclusive and scalable restoration solutions. Conserv. Sci. Pract. 2 (9), e250. https://doi.org/10.1111/csp2.250.

Huang, L., Chen, H., Ren, H., Wang, J., Guo, Q., 2013. Effect of urbanization on the structure and functional traits of remnant subtropical Evergreen broad-leaved forests in South China. Environ. Monit. Assess. 185 (6), 5003–5018. https://doi.org/10.1007/s10661-012-2921-5.

Ilyas, M., Liu, Y.Y., Shah, S., Ali, A., Khan, A.H., Zaman, F., et al., 2021. Adaptation of functional traits and their plasticity of three ornamental trees growing in urban environment. Sci. Hortic. 286, 110248. https://doi.org/10.1016/j.scienta.2021.110248.

Jakubiak, M., Panek, E., Urbański, K., Victória, S.S., Lach, S., Maciuk, K., et al., 2025. Nature-based solutions in sustainable cities: trace metal accumulation in urban forests of Vienna (Austria) and Krakow (Poland). Sustainability 17 (15), 7042. https://doi.org/10.3390/su17157042.

Kong, X., Zhang, X., Xu, C., Hauer, R.J., 2021. Review on urban forests and trees as nature-based solutions over 5 years. Forests 12 (11), 1453. https://doi.org/10.3390/f12111453.

Li, X., Li, Y., Zhang, S., Lin, R., Chen, M., Feng, Li., 2023. Driving effects of land use and landscape pattern on different spontaneous plant life forms along urban river corridors in a fast-growing city. Sci. Total Environ. 876, 162775. https://doi.org/10.1016/j.scitotenv.2023.162775.

Liang, D., Huang, G., 2023. Influence of urban tree traits on their ecosystem services: a literature review. Land 12 (9), 1699. https://doi.org/10.3390/land12091699.

Lin, D., Anderson-Teixeira, K.J., Lai, J., Mi, X., Ren, H., Ma, K., 2016. Traits of dominant tree species predict local scale variation in Forest aboveground and topsoil carbon stocks. Plant and Soil 409 (1–2), 435–446. https://doi.org/10.1007/s11104-016-2976-0.

Love, N.L.R., Althaus, K., Esperon-Rodriguez, M., Ossola, A., Johns, J., Pawlak, C., et al., 2025. Genetic diversity in urban forests and their potential role in conserving the world's threatened tree species. Ann. Bot., mcaf238,. https://doi.org/10.1093/aob/mcaf238.

Ma, S., Wang, X., Miao, W., Wang, X., Sun, H., Guo, Z., 2021. Relative influence of environmental, stand factors and functional traits on allocation of forest productivity during the restoration of subtropical forests in Central China. For. Ecol. Manage. 482, 118814. https://doi.org/10.1016/j.foreco.2020.118814.

Manhães, A.P., Saavedra, M., Pansonato, M.P., Andrade, M.T., Camelo, B., Machado, F. S., et al., 2025. Applying a functional trait-based approach for ecological succession monitoring and species management in areas under active restoration in a tropical forest. Environ. Manage. 75 (12), 3156–3169. https://doi.org/10.1007/s00267-025-02264-5.

Miedema Brown, L., Anand, M., 2022. Plant functional traits as measures of ecosystem service provision. Ecosphere 13 (2), e3930. https://doi.org/10.1002/ecs2.3930.

Mina, M., Messier, C., Duveneck, M.J., Fortin, M.J., Aquilué, N., 2022. Managing for the unexpected: building resilient Forest landscapes to cope with global change. Glob. Chang. Biol. 28 (14), 4323–4341. https://doi.org/10.1111/gcb.16197.

O'Brien, L.E., Urbanek, R.E., Gregory, J.D., 2022. Ecological functions and human benefits of urban forests. Urban For. Urban Green. 75, 127707. https://doi.org/10.1016/j.ufug.2022.127707.

Pan, Q., Wen, Z., Wu, T., Zheng, T., Yang, Y., Li, R., et al., 2022. Trade-offs and synergies of forest ecosystem services from the perspective of plant functional traits: a systematic review. Ecosyst. Serv. 58, 101484. https://doi.org/10.1016/j.ecoser.2022.101484.

Pataki, D.E., McCarthy, H.R., Gillespie, T., Jenerette, G.D., Pincetl, S., 2013. A trait-based ecology of the Los Angeles urban Forest. Ecosphere 4 (6), 1–20. https://doi.org/10.1890/ES13-00017.1.

Petrova, Sl., Petkova, M., 2023. Plant traits of *Tilia tomentosa* Moench, *Fraxinus excelsior* L., and *Pinus nigra* J.F. Arnold as a proxy of urbanization. Forests 14 (4), 800. https://doi.org/10.3390/f14040800.

Prieto, P.V., Bukoski, J.J., Barros, F.S.M., Beyer, H.L., Iribarrem, A., Brancalion, P.H.S., et al., 2022. Predicting landscape-scale biodiversity recovery by natural tropical forest regrowth. Conserv. Biol. 36 (3), e13842. https://doi.org/10.1111/cobi.13842.

Quaranta, L., Di Marzio, P., Fortini, P., 2025. Quercus Cerris leaf functional traits to assess urban Forest health status for expeditious analysis in a Mediterranean European context. Plants 14 (2), 285. https://doi.org/10.3390/plants14020285.

Ranalli, M., Lundholm, J., 2008. Biodiversity and ecosystem function in constructed ecosystems. CABI Rev. https://doi.org/10.1079/PAVSNNR20083034 ahead of print, June 25.

Rayome, D., Di Manno, N., Ostertag, R., Cordell, S., Fung, B., Vizzone, A., Pante, P., Tate, R., 2019. Restoring Ecosystem Services Tool (REST): a program for selecting species for restoration projects using a functional-trait approach. Gen. Tech. Rep. PSW-GTR-262. US Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, 47 p. 262.

Rodrigues, A.C., Silla, F., Meira-Neto, J.A.A., Gomes, L.P., Villa, P.M., Neri, A.V., 2023. Carbon and biodiversity cobenefits of second-growth tropical forest: the role of leaf phenology. For. Ecol. Manage. 546, 121377. https://doi.org/10.1016/j.foreco.2023.121377.

Rodríguez-Santamaría, K., Zafra-Mejía, C.A., Rondón-Quintana, H.A., 2022. Macro-morphological traits of leaves for urban tree selection for air pollution biomonitoring: a review. Biosensors 12 (10), 812. https://doi.org/10.3390/bios12100812.

Rolhauser, A.G., MacIvor, J.S., Roberto, A., Ahmed, S., Isaac, M.E., 2023. Stress-gradient framework for Green roofs: applications for urban agriculture and other ecosystem services. Ecological Solutions and Evidence 4 (2), e12227. https://doi.org/10.1002/2688-8319.12227.

Salbitano, F., Borelli, S., Conigliaro, M., Chen, Y., 2016. Guidelines on urban and peri-urban forestry. In: FAO Forestry Paper, 178. Food and Agriculture Organization of the United Nations.

Salman, I.N.A., Schindler, B., Agra, H., Bawab, O., Friedman-Heiman, A., Kadas, G.J., et al., 2019. Green roof research towards enhancing urban biodiversity, storm-water retention and air pollution abatement. CABI Rev. 1, 1–14. https://doi.org/10.1079/PAVSNNR201813039. January.

Sarker, S.K., Reeve, R., Matthiopoulos, J., 2021. Solving the fourth-corner problem: forecasting ecosystem primary production from spatial multispecies trait-based models. Ecological monographs 91 (3), e01454. https://doi.org/10.1002/ecm.1454.

Scartazza, A., Vannucchi, F., Peruzzi, E., Macci, C., Scatena, M., Manzini, J., et al., 2025. Nutrient interaction in the soil-plant system and tree physiological functional traits in an urban Green infrastructure. J. Soil Sci. Plant Nutr. 25 (2), 2829–2845. https://doi.org/10.1007/s42729-025-02301-6.

Sharma, G., Morgenroth, J., Richards, D.R., Ye, N., 2025. Advancing urban forest and ecosystem service assessment through the integration of remote sensing and I-tree eco: a systematic review. Urban For. Urban Green. 104, 128659. https://doi.org/10.1016/j.ufug.2024.128659. February.

Shome, A., Phartyal, S.S., Maharana, P., Verma, A., 2023. Mapping peer-reviewed scientific studies on plant trait–service linkages across ecosystems: a bibliometric analysis. Anthr. Sci. 2 (1), 19–30. https://doi.org/10.1007/s44177-023-00048-2.

Silva Luz, C.L., Reale, R., Candido, L.F., Zappi, D., Locosselli, G.M., 2024. Using morphological characters to support decision-making in nature-based solutions: a shortcut to promote Urban Plant biodiversity. Urban Sci. 8 (4), 233. https://doi.org/10.3390/urbansci8040233.

Šímová, I., Sandel, B., Enquist, B.J., Michaletz, S.T., Kattage, J., Violle, C., et al., 2019. The relationship of woody plant size and leaf nutrient content to large-scale productivity for forests across the Americas. J. Ecol. 107 (5), 2278–2290. https://doi.org/10.1111/1365-2745.13163.

Simovic, M., Mueller, K.E., McMahon, S.M., Medeiros, J.S., 2024. Functional traits and size interact to influence growth and carbon sequestration among trees in urban greenspaces. Functional Ecology 38 (4), 967–983. https://doi.org/10.1111/1365-2435.14505.

Solano, F., Mansi, C., Baliva, M., Canestrelli, D., Chiarucci, A., Manicone, R., et al., 2025. Mediterranean strictly protected forests are cooler. Agric. For. Meteorol. 375, 110858. https://doi.org/10.1016/j.agrformet.2025.110858. December.

Song, G., Wang, J., Han, T., Wang, Q., Ren, H., Zhu, H., et al., 2019. Changes in plant functional traits and their relationships with environmental factors along an urban-rural gradient in Guangzhou, China. Ecol. Indic. 106, 105558. https://doi.org/10.1016/j.ecolind.2019.105558.

Streit, R.P., Bellwood, D.R., 2023. To harness traits for ecology, let's abandon 'functionality.'. Trends Ecol. Evol. 38 (5), 402–411. https://doi.org/10.1016/j.tree.2022.11.009.

Su, Y., Cui, B., Luo, Y., Wang, J., Wang, X., Ouyang, Z., et al., 2021. Leaf functional traits vary in urban environments: influences of leaf age, land-use type, and urban–rural gradient. Front. Ecol. Evol. 9, 681959. https://doi.org/10.3389/fevo.2021.681959. December.

Szombara, S., Lewińska, P., Żądło, A., Róg, M., Maciuk, K., 2020. Analyses of the Prądnik riverbed shape based on archival and contemporary data sets—old maps, LiDAR, DTMs, Orthophotomaps and cross-sectional profile measurements. Remote Sens. 12 (14), 2208. https://doi.org/10.3390/rs12142208.

Tsujii, P.K., Coutinho, A.G., Medina, A.M., Kraft, N.J.B., Gonzalez-Melo, A., Higuchi, P., et al., 2020. How many and which species to plant? A multi-trait-based approach to select species to restore ecosystem services. Preprint. Ecology. https://doi.org/10.1101/2020.10.29.359455. October 30.

United Nations Environment Programme, 2022. In: United Nations Environment Programme (Ed.), United Nations Environment Assembly of the United Nations Environment Programme: Fifth Session, Nairobi (Hybrid), 22–23 February 2021 and 28 February–2 March 2022.

Van Eck, N.J., Waltman, L., 2023. VOSviewer Manual. Univeristeit Leiden. http://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.1.pdf.

Vohland, K., 2009. Impacts of climate change on biodiversity - consolidated knowledge and research gaps. CABI Rev. 1–11. https://doi.org/10.1079/PAVSNNR20083086.

Wang, Y., Dai, X., Chen, X., Zhang, D., Lin, G., Zhou, Y., et al., 2024. Effects of urbanization and forest type on species composition and diversity, forest characteristics, biomass carbon sink, and their associations in Changchun, Northeast China: implications for urban carbon stock improvement. J. For. Res. 35 (1), 36. https://doi.org/10.1007/s11676-023-01688-1.

Wang, J., Manning, P., Peñuelas, J., Brearley, F.Q., Shi, X., Leng, P., et al., 2025a. Tree functional strategies and soil microbial communities regulate Forest ecosystem services. J. Appl. Ecol. 62 (6), 1544–1554. https://doi.org/10.1111/1365-2664.70045.

Wang, R., Xu, S., Gao, K., Zhang, Y., He, X., 2025b. Functional evenness and community-weighted mean traits jointly drive ecological multifunctionality in urban forests. J. Plant Ecol. 18 (4), rtaf059. https://doi.org/10.1093/jpe/rtaf059.

Waylen, K.A., Wilkinson, M.E., Blackstock, K.L., Bourke, M., 2024. Nature-based solutions and restoration are intertwined but not identical: highlighting implications for societies and ecosystems. Nature-Based Solutions 5, 100116. https://doi.org/10.1016/j.nbsj.2024.100116.

Wei, H., He, X., 2021. Foliar C/N stoichiometry in urban Forest trees on a global scale. Journal of Forestry Research 32 (4), 1429–1443. https://doi.org/10.1007/s11676-020-01188-6.

Weiskopf, S.R., Lerman, S.B., Isbell, F., Morelli, T.L., 2024. Biodiversity promotes urban ecosystem functioning. Ecography 2024 (9), e07366. https://doi.org/10.1111/ecog.07366.

Wellmann, T., Andersson, E., Knapp, S., Lausch, A., Palliwoda, J., Priess, J., et al., 2023. Reinforcing nature-based solutions through tools providing social-ecological-technological integration. Ambio 52 (3), 489–507. https://doi.org/10.1007/s13280-022-01801-4.

Wood, S.L.R., Dupras, J., 2021. Increasing functional diversity of the urban canopy for climate resilience: potential tradeoffs with ecosystem services? Urban For. Urban Green. 58, 126972. https://doi.org/10.1016/j.ufug.2020.126972.

Yan, X., Li, P., Wu, X., Wang, J., Wang, Z., Xu, J., et al., 2025. Variations in the leaf economics spectrum, anatomical, ultrastructural, and stomatal traits of five tree species in the urban-rural air pollution environment. Journal of environmental sciences (China) 155, 177–192. https://doi.org/10.1016/j.jes.2024.08.009.

Yang, Y., Zhu, Q., Peng, C., Wang, H., Chen, H., 2015. From plant functional types to plant functional traits: a new paradigm in modelling global vegetation dynamics. Progress in Physical Geography: Earth and Environment 39 (4), 514–535. https://doi.org/10.1177/0309133315582018.

Yu, K., Van Geel, M., Ceulemans, T., Geerts, W., Ramos, M.M., Serafim, C., et al., 2018. Vegetation reflectance spectroscopy for biomonitoring of heavy metal pollution in urban soils. Environ. Pollut. 243, 1912–1922. https://doi.org/10.1016/j.envpol.2018.09.053.

Zhang, M., Ni, Y., Li, M., 2023. Evaluation of the growth, adaptation, and ecosystem Services of two Potentially-Introduced Urban Tree Species in Guangzhou under drought stress. Sci. Rep. 13 (1), 3563. https://doi.org/10.1038/s41598-023-30782-x.