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# Global Spatiotemporal Dynamics and Ecosystem Services of Urban Forests: A Systematic Review

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**ABSTRACT**

*Rapid urbanization and climate variability have intensified interest in urban forests and their role in sustainable city development. Urban trees, including those in parks, streets, and peri-urban woodlands, provide essential ecosystem services such as carbon sequestration, temperature regulation, stormwater management, air purification, biodiversity conservation, and human well-being. This review synthesizes findings from peer-reviewed studies published between 2005 and 2025, drawing on bibliometric analyses, thematic reviews, and major international research projects. Research output has increased substantially since 2010, with significant contributions from Europe, North America, and East Asia. Advances in remote sensing, LiDAR, and modeling techniques have improved the assessment of urban tree cover and ecosystem services. Findings indicate that urban forests effectively mitigate climate impacts by storing carbon, reducing urban heat, filtering pollutants, and decreasing runoff. Additionally, access to green spaces enhances physical and mental health. However, unequal distribution of urban greenery remains a major challenge, particularly in socioeconomically disadvantaged communities, highlighting the need for equitable urban greening strategies.*

***Keywords:*** *Urban forestry; ecosystem services; spatiotemporal dynamics; LiDAR; environmental justice; 3-30-300 rule.*

## INTRODUCTION

More recently the role of urban trees changed from decorative and aesthetic element to being essential for urban survival during heat waves, floods and other such problems as it was confirm by many researches and researchers. Street trees mix with backyards, leftover forest patches, public lawns, and school grounds - each piece tangled into roads, policies, and community habits. Benefits pile up where canopies grow: they trap soot, lower summer highs, hold rain runoff, shelter birds, and sequestering atmospheric carbon. People feel better near them too, though scientists still debate how much.

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A growing body of empirical research shows that leafy neighborhoods do more than look quiet - they shape livability without saying it out loud.

Between 2005 and 2025, big shifts happened in how the world handles environmental challenges - think ecosystem reviews, climate deals, city green plans - all shaping new ways to work with nature in towns and cities (Qiu et al., 2024; Pauleit et al., 2024). Even with gains, problems still linger. Cities in Europe and North America grab most research attention, leaving many rising urban areas across the Global South overlooked - studies by Zhang and others in 2022 plus Wang's team show this gap. A mix of different ways to measure green benefits makes it tough to match findings across projects, recent papers highlight. Not every neighborhood gets equal access to trees and cooling shade, raising fairness issues as heat, dirty air, and poor greenspace hit some groups harder - Gerrish alongside Watkins noted such patterns years ago, later echoed again by Zhang's group.

This paper pulls together studies from 2005 to 2025 about city trees, looking at where they grow, how they change over time, and what nature benefits they offer. It gathers findings on how often such work appears, which topics come up most, and which parts of the world get attention - then shifts into newer ways scientists measure tree shapes and their roles in cities. Here, the numbers are important, particularly those related to storing carbon and cooling neighborhoods and city concrete with shade and evaporation. Hard facts and data align with research on what it means to be fair about allocating green spaces, who is excluded and included, and how rules have an impact on control and access to greens. But it does not stop there and continues to point forward to undetermined priorities of future and it helps us find new goals so we can see how the world will change by 2030.

## Methods

### 2.1 Search strategy and data sources

In the period 2005-2025, this is the period under review is divided into two decades (2005-2015, 2016-2025) to show the evolution of thinking on city and its nature specially considering green spaces over 20 years and its key concepts, including the importance of benefits from green areas and natural solutions (Qiu et al., 2024; Pauleit et al., 2024). Significant works on trees, parks, and trees functions in cities were searched using word sets in two large science libraries, Web of Science and Scopus, in a careful and selective way (Zhang et al., 2022; Wang et al., 2022). These scans were led by the following key phrases and words: urban forest, street tree, tree cover in towns, City Park, natural benefit, stored carbon, hot spot effect, local climate, nature based solution (NBS), and fair access to nature, green spaces, and urban vegetation. These words were found where they are needed most; titles, summaries, and tag listings (Zhang et al., 2022).

In addition, the extra searches included with the "urban green space" concepts related to health, well-being, movement in everyday life, environment justice, biodiversity, since trees are often rooted within a larger urban green space (Zhang et al., 2022; Wang et al., 2022). In addition to top-tier reviews and praised real-world studies, citation trails aided in the discovery of important work that was not retrieved or searched via traditional search methods (Soga et al., 2024 and Nowak & Greenfield, 2018). The literature on urban trees and nature based solutions was not systematically wanted, but when necessary or needed, papers and other manuscripts to support guidance and planning were recovered around the globe, such as those concerning the 3-30-300 concept explained above and other important studies, (Konijnendijk, 2021; Nature Based Solutions Institute, 2021).

The systematic review protocol was created and used in adherence to PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) to be transparent and reproducible. Primary literature was collected from Web of Science and Scopus using a standardized Boolean search string: (urban forest or street tree) and (ecosystem service or spatiotemporal dynamics).

**2.2 Inclusion and exclusion criteria**

Those paper that were published in a peer-reviewed journal during the years 2005-2025, were selected. The main theme was created on a popular idea among the green zones in cities, known as "urban forests" or "city trees", located either in the cities ( parks, open grounds, street etc.) or present in outskirts. For each they were required to either measure, simulate or evaluate an ecosystem benefit fact, feature in a wooded area or an effect on ecosystem and society which was linked to such vegetated areas. Studies on grasses or shrubs not included. Research studies on remote vegetated areas also did not apply unless linked meaningfully with urban or city areas. Only English language reports were analyzed. This decision was based on the model and proven methods adopted by other large databases and studies, the analysis showing how these databases were cited and used in the recent years that contributed to the development of this overview.

The study includes summaries of good existing practice, as well as real-world examples, guiding from previous studies. It does not begin from ground zero, rather it looks globally over the last 30 years on the subject of parks, green spaces and includes some important themes and trends in publications from that time.

**2.3 Analytical approach**

Formal analysis across all service categories was not feasible: the studies differ too much in how they were built, what they measured, not to mention where they took place - so pulling one big number out across services doesn't work (Almasi et al., 2024; Qiu et al., 2024). What happens instead? The review leans on storytelling with data, grouping findings by shared themes like movement through time and space, carbon and climate roles, regulation beyond those, human experience including culture and well-being, fairness and control systems - all shaped using reference points pulled from earlier wide-reaching analyses and broad fieldwork (Zhang et al., 2022; Nowak & Greenfield, 2018; Zardo et al., 2021).

**3.1 Studies the Growth and geography of urban forest research (2005–2025)**

Urban forest research and urban ecological planning was explored spatially with regard to its growth and geography (2005-2025).Investment in city parks or vegetated areas has been growing rapidly in recent years particularly since 2010, when there was a sharp increase in production ( Zhang et al., 2022; Wang et al., 2022). A large-scale study of the relationship between green spaces and human behaviour around health and well-being provided an overview of 607 articles published from 2002 to 2021 where clear trends could be seen, with growing overlaps between study disciplines and subjects, such as the ecology, urban design and medicine fields (Zhang et al., 2022). Research outcomes from urban forestry studies can be published in specific journals on urban forestry/urban greening (e.g. Urban Forestry & Urban Greening), but also in broader, city planning or environment related journals on trees and green spaces in cities as well as in geography related journal of urban planning, town planning and more (Pauleit et al., 2024; Soga et al., 2024). The trees were organized into clusters of general services and ecosystem services, rather than just topics, indicating a strong relationship between tree science and discussions on livable and resilient cities, as presented by the patterns of keywords, such as the ecosystem services, urban planning, urban heat island, carbon sequestration, air quality, biodiversity and public health (Zhang et al., 2022; Wang et al., 2022).

There is a substantial 'geographical bias' present despite growth in the world. Based on bibliometric data, 61% of the research conducted in Sub-Saharan region of the world is done only in 5 countries that are Ethiopia, Kenya, Tanzania, Madagascar, and Ghana. Furthermore, in Latin American contexts, urban forest dynamics are frequently a legacy of 'superimposing European aesthetic criteria' on native landscapes, often neglecting indigenous biodiversity and local water constraints. Transitioning toward a 'decolonized' approach in urban forestry is essential for achieving climate justice in rapidly urbanizing regions.

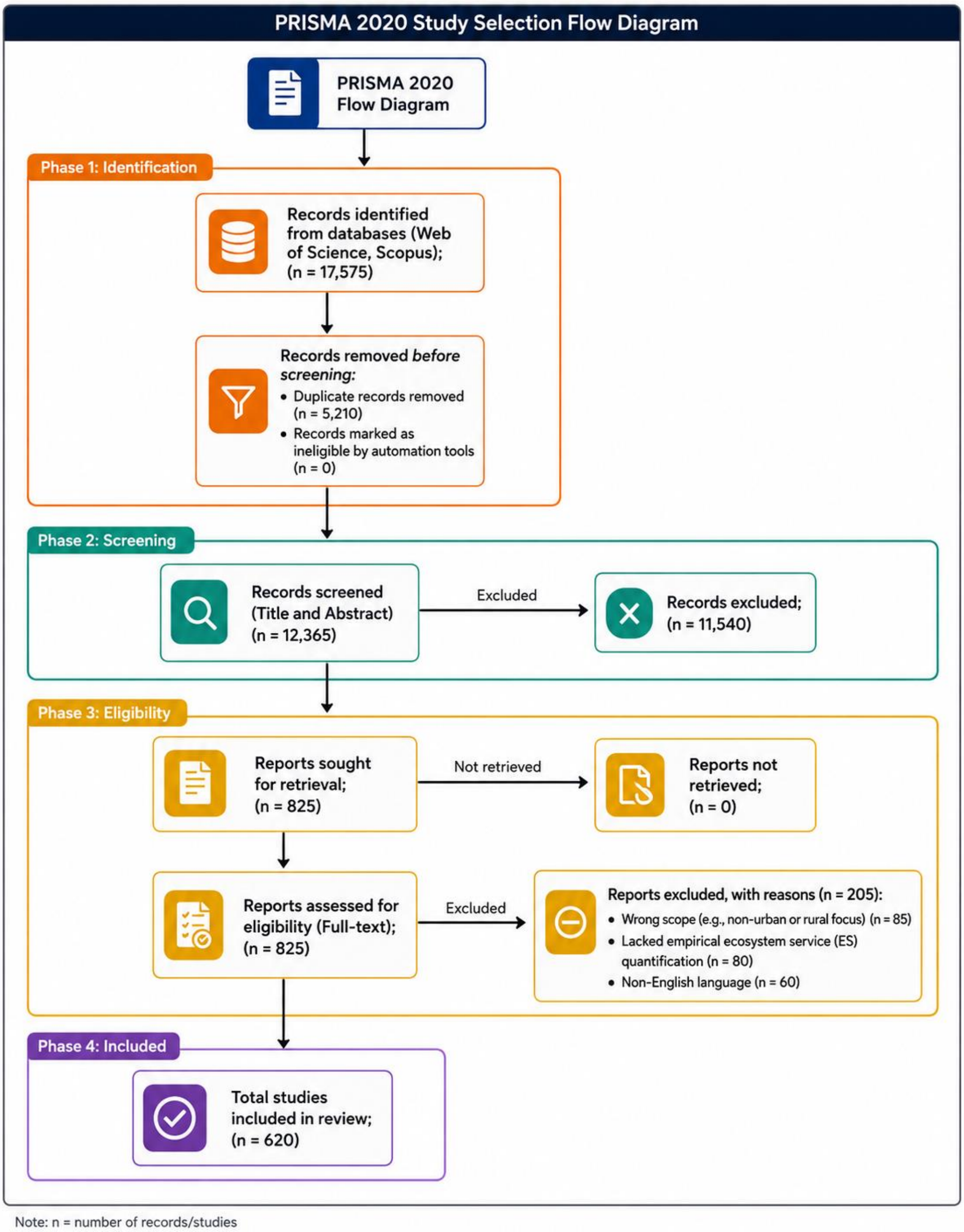


**Figure 1: PRISMA flow diagram**

### 3.2 Methodological developments

#### 3.2.1 Ecosystem services and nature based solutions structures

It is a standard approach to view city trees from the perspective of ecosystem services and categorizing their functions into different types such as climate regulation, resource provisioning, cultural values, health benefits and background services (Almasi et al., 2024; Qiu et al., 2024). Urban forests continuously do important jobs it cycle and store carbon, sequester heat, purify air, reduce rainwater runoff, provide better health, provide habitat for wildlife and open green space for recreation and community interaction (Almasi et al., 2024, Wang et al., 2022). With the development of the concepts of NbS (Nature base solutions) as solutions, the roles of green spaces were merged with water work in urban city areas by the 2010s (Qiu et al., 2024; Pauleit et al., 2024).

City vegetation's do two things, helping to cool the urban environment and sequester carbon, as well as welcome birds into paving depleted neighbourhoods (Qiu et al., 2024; Soga et al., 2024). Although there are benefits, it sometimes leads to disservices from species, such as the potential to stir allergies, and create problems in times of natural disasters like storm and flood (Almasi et al., 2024; Pauleit et al., 2024).

#### 3.2.2 The Use of Remote sensing LIDAR and modelling

With studies of trees and vegetation within cities researchers nowadays rely primarily on precise perspective data from satellites and laser scans rather than ground based observations, field surveys and grainy photographs (Pauleit et al., 2024; Qiu et al., 2024). Mid-range satellites and the presence of basic plant signals with modern tools were the primary sources for defining green zones, canopy cover, and making estimates of the amount of trees removal in the area was counted on for most of the past work (Almasi et al., 2024). Gradually from the early 2010s, 3D (full 3D) measurements like tree height, crown size and layering became possible, primarily using aerial laser measurements, remote sensing, ultra clear space photos and drone shots (Pauleit et al., 2024; Zardo et al., 2021).

Since these developments, others tools had emerged to detect trees, sketch the outline of their canopy, and even differentiate tree species in the context of diverse urban matrices using the support of object based image analysis and smart algorithms like random forests, support vector machines and convolutional neural networks etc., with the help of different online and offline tools (Pauleit et al. 2024; Qiu et al. 2024). These methods are intensive enough to be tightly tied to ground based allometric models and actual data from plots to further refine biomass and carbon measurements, as well as provide understanding into the layout, variety and gaps of the canopy (Nowak & Greenfield, 2018; Nowak et al., 2013).

Meanwhile, there was growing expansion of tools for quantifying the benefits provided by nature. At the same time, tools for measuring nature's benefits also increased and strengthened. There are platforms available, such as i-Tree Eco and i-Tree Canopy, that use information from the city forest structure to provide estimates for carbon capture, cleaner air, reduced storm drain flow, etc., based on Nowak & Greenfield's 2018 research and others. But observed from another perspective, scientists use heat and energy models and real world data to understand how trees influence the temperature and energy requirements of houses and buildings during their life cycle as demonstrated in 2021 by Zardo and associates and then by Almasi and colleagues in 2024 study.

### 3.3 Science of spatiotemporal dynamics of urban forests

#### 3.3.1 Extent, composition and change

By assessing the city scale tree counts, it gives an indication of the existing green space and its quality, but at the same time of how vulnerable it is. In one major study in the U.S. there are nearly 5.5 billion trees on nearly two in five developed acres within urban regions. These plants provide annual benefits of approximately 18.3 billion dollars benefits such as cleaner air, reduced power usage, stored carbon, flood control and reduced greenhouse gas emissions as reported by previous studies. The researchers tracked the trend and practices over time, and, if planning practices don't change, the area of spreading development and dying treetops could decline significantly by 2050 reported by past study in U.S.

In urban areas scientists sometimes measure changes in tree cover from year to year by remote sensing, analyzing air photos or laser scans. Even though underserving quality maintenance requirements and other important practices, many trees are planted around towns, others lose coverage either due to building expansion, road development, the introduction or spread of insect pests, or from storms damaging trees and greenery and by cutting etc.

**3.3.2 The study of Division, Connectivity and Configuration**

The spatial configuration of urban forests is as important as total canopy cover. When green spaces breaks or converted into small, scattered patches, wildlife struggles especially animals which needs large vegetated areas, despite having decent overall tree coverage. Big clusters and linked green zones tend to help birds and insects move around more freely. Streets lined with trees, joined park systems, and natural strips along rivers often boost chances for walking, lower heat, and create consistent shade.

Out past city edges trees get split apart when buildings move in. Along roads and new neighborhoods woods break into pieces because of housing that grows without a plan. Factories go up too, cutting through what used to be connected forest areas. Canopies shrink as these spaces disappear piece by piece. Services nature once gave freely start fading with them. One way forward lies in weaving tree-covered zones into how cities lay out their space.

**3.4 Ecosystem services of urban forests**

**3.4.1 Carbon storage and sequestration**

In cities, trees hold plenty of carbon within trunks, roots, branches, and soil - feeding into broader efforts to balance carbon at local and national levels, plus serving as visible reminders of environmental responsibility through education (Nowak & Greenfield, 2018; Nowak et al., 2013). A study in U.S. led by Nowak's team found urban tree foliage stores approximate to 44 million metric tons of carbon, pulling significant volumes of carbon from the air every year, which gives financial benefits worth several billion when judged against societal damage and loss costs (Nowak & Greenfield, 2018). While these cuts are comparatively negligible in relation to pollution levels nationwide but their impact is more pronounced within municipal planning, where a strict focus is placed on concrete measures for emissions reduction (Nowak & Greenfield, 2018; Qiu et al., 2024).

Based on the material in Almasi et al., 2024, and Pratiwi et al., 2023, studies the average amount of carbon stored on i-Tree Eco tree tool is typically between 10 and 20 tons per hectare. Trees that are measured in a big city or metro city typically store between a few dozen to almost two hundred tons of carbon per hectare.

**3.4.2 Study of microclimate regulation and thermal comfort**

Tree covered areas in hundreds of European cities stayed noticeably cooler than city zones during summer heat, according to many studies yet how much cooler depended on local weather patterns, rainfall, surrounding greenery, plus urban layout and planning (Zardo et al., 2021). In some tight spaces like sheltered yards or small narrow lanes, shade from trees reduced temperature by as much as 10–12 °C, elsewhere, across broader neighborhoods and wide lane areas temperature drops ranged between 1–5 °C near ground level (Qiu et al., 2024; Almasi et al., 2024). New studies highlights moisture supply as key when trees lack water, their pores shut, limiting natural cooling while leaf arrangement, plant type, along with nearby structures are critical factors (ETH Zurich, 2025; Almasi et al., 2024).

**3.4.3 Better air and smarter water flow**

The ability of tree canopy to catch rain water, the role of trees roots in absorbing water into the ground, and the evaporating effect of the ground are among the important benefits of water flow control (Almasi et al., 2024; Pratiwi et al., 2023). Practical and real world applications illustrated that planting urban trees and vegetation reduces flood peaks and reduces flood water runoff, particularly in the presence of landscape strategies like vegetated ditches, planted basins or permeable surfaces (Pratiwi et al., 2023; Qiu et al., 2024). There are several methods for quantifying these benefits, ranging from local observation and survey of how many rainfall events are captured, how much ground infiltration occurs, to broad scale water movement simulations which, however, do not have a clearly agreed upon technique or method for tracking water capture and infiltration (Almasi et al., 2024; Pauleit et al., 2024).

#### 3.4.4 The conservation of biodiversity, health and cultural services.

In urban landscapes with the dense growing of trees, life flourishes as birds hide in the foliage, insects chirp, little animals crawl around, bees buzzing and plants grow beneath. These patches will connect particular wilder areas and allow creature and big animal’s movement from one patch to another through built up areas. Studies conducted in various metropolitan regions reveal that green plots are more likely to be associated with a greater number of nature's species both animal and birds in close proximity. However, the extent and quality of the natural vegetation depends more on the integrity of management of the city than on its leafy cover.

### 3.5 Environmental justice, equity and governance

In recent years, urban forestry research has given importance with more emphasis on environmental justice. This is the myth now that richer neighborhoods don't have more trees in the sky but instead they have more tree rich. Money is important factor to make an area green. Communities of color, or impoverished communities are frequently excluded from urban parks and green spaces. They experienced reduction of tree-lined sidewalks, less shade overall. Parks that aren’t as well kept show up again and again in these findings.

Researches record findings, make cross neighborhood comparisons, refine goals, and more. A study, conducted in Toronto, analyzed local data patterns. Another group of researcher looked at similar efforts in countries in Europe. Numbers tell the story about who gets what, who gets nothing and who has more in terms of accessibility. Unfortunately, many such city tree initiatives are fraught with difficulties with respect to responsibilities of who does what and how, and this invariably confuses implementation when it comes time to make decisions and planning. In practice, a diversity of groups or more people from diverse fields is often responsible for city tree efforts which results in messy coordination around who does what and how, as this was illustrated by Pauleit et al. and Soga et al. (2024). Street crews, park teams, power companies, housing offices, government departments even property owners take care of various components of trees (from planting through maintenance to removal), mostly without good cooperation, and long term tree upkeep is rarely as attractive as flashy tree plantings and has less funding (Almasi et al., 2024; Pauleit et al., 2024). In recent years some practitioners are experimenting with new approaches and methods, such as local choice in tree placement, neighbourhood care teams, and local planning for trees within, or tied to, climate related policy and public health frameworks, to plug those gaps in, but with limited evidence on effectiveness on ground to date (Zhang et al., 2022; Konijnendijk, 2021).

**Table 1: Core Journal Selection Strategy of Journals**

| Journal Title | Impact Factor | Citation Authority | Strategy |
|---|---|---|---|
| Sustainable Cities and Society | 12.0 | Very High | Target for policy-heavy reviews |
| Landscape and Urban Planning | 9.2 | Extreme (5,000+) | Target for design/planning focus |
| Urban Forestry & Urban Greening | 6.7 | High (1,800+) | Primary venue for forest management |

**Table 2: Technological Methodology Evolution**

| Technology | Application | Data Precision |
|---|---|---|
| Airborne LiDAR | Individual tree attribute extraction | High (RMSE < 0.1m) |
| AI / CNN | Automated species mapping | 92.5% Ground-truth accuracy |
| Digital Twins | Predictive "Cyber-physical" modeling | Bidirectional/Real-time |

## 4. Research gaps and future roadmap (to 2030)

The study of the past 50 years helps us identify some gaps and helps us further direct the actions needed next.

There are several studies that demonstrate why long term tracking of trees is important, in terms of better understanding of how city trees benefit nature and people. Research could benefit not only from only snapshots of conditions at a particular point in time, but from setups and managements where conditions are compared before and after a change occurs. Some more recent attempts already consider real life solutions with greenery such as spontaneous projects, evaluating their impacts over the years with both pros and cons. Where feasible, these methods should be considered, in particular where tree cover is being added or planning to add in to an area. It could be used to uncover more layers of pattern with repeated field sites and satellite images. Their inclusion with other details at the community level brings a clearer picture of how it works. Then the findings will be on a better foundation with less guesswork and more scientific evidence.

One more thing, there is still a certain amount of work to be done to estimate the value of nature, particularly in terms of demonstrating the benefit when it is uncertain (Nowak & Greenfield, 2018; Pauleit et al., 2024). Such that, if we focusing on cleaner air or local climate impacts, there are multiple different models, each has specific rules, starting points or values, method which result in different outcomes (Nowak & Greenfield, 2018; Nowak et al., 2013; Zardo et al., 2021). Control of rainwater, diversity of species and social value of green spaces. Those areas do not have an easily repeatable benchmark to compare and with which to measure them, and the comparisons between cities is challenging (Almasi et al., 2024; Wang et al., 2022). More comprehensive and descriptive accountings of model and method selection explicit discussions of model uncertainty, and benchmarking model against model testing might facilitate better action in the real world for funding and planning (Pauleit et al., 2024; Qiu et al., 2024).

Fairness, engagement, equality and allowing people to remain involved over time is a way for cities to move forward on urban forest studies and development. Trees rather than extras are addressed by researchers instead, in terms of local measures that indicate tree equity when they are given fairly distributed across the various neighborhoods with various financial background. Governance models receive attention too in particular those supporting sustainable care and management of green spaces in an equitable manner. Some work identifies how neighborhood groups, First Nations and others affect the placement and type of trees. Combining mapping efforts, interviews, surveys and public participation identifies who influences, which values are valued by folk, conflicts between alternative values if there. That combination is conducive to plans that are opening up doors for more voices and justice in the city. This mixture seems to be supported by many studies, emphasizing that understanding can be achieved by combining methods.

## CONCLUSION

Research continues to uncover unequal tree cover and unequal benefits from the trees, and poor management can often have adverse impacts on long term gains to city ecosystem (Gerrish & Watkins, 2018; Zhang et al., 2022; Konijnendijk, 2021). The improvement is not so much based on the development of new tools and devices, but on improved rules, planning and decisions, as well as sustained care over time (Qiu et al., 2024; Pauleit et al., 2024). In the future (to 2030), priorities include a mix of long term studies with real tests, proper upkeep and follow up, measurement of urban value in the context of uncertainties, incorporation of fairnessness and justice into city forest control, and thoughtfully utilizing the new technologies and methods( Zhang et al., 2022; Qiu et al., 2024).

However, following these paths could make urban vegetation into more resilient and equitable city systems and more resilient to move into, in order to live in, and simultaneously ecologically fit for all living beings.

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