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EDITORIAL

The science of urban trees to promote well-being

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Abstract

Key message **Urban trees and forests are one of the main tools available in cities to face current and future environmental challenges and ultimately promote well-being.**

Abstract More than half of the world's population lives in cities nowadays. This rural exodus to cities resulted from a pursuit of better life quality. However, the urban population increase led to new levels of complexity. Such complexity calls for multifunctional solutions such as Nature-based Solutions (NbS). Trees are at the core of NbS, for all the ecosystem services they provide. Nevertheless, managing them is challenging and requires both the empirical knowledge of practitioners and a deep scientific understanding of the tree's structure and function. This special issue on "Urban Trees" advances our knowledge of their ecosystem services, tolerance and resilience to the urban environment, their possible disservices, and steps forward on new proposals for managing urban trees. It is clear from the current literature and the studies in this special issue that decision-making on urban trees must be supported by scientific evidence to promote well-being in cities.

Keywords Ecosystem services · Disservices · Management · Nature-based solutions · Biodiversity

The urban world

Urbanization is a strong tendency in this stage of civilization. The human population has grown steadily in cities since the Industrial Revolution and exponentially after the end of World War II. A turning point in human history occurred in 2007 when more than half of the world's population became urban (Baklanov et al. 2016), currently reaching more than 55% (UN 2020). This urban expansion reflects a pursuit of a better quality of life since access to essential services and professional opportunities increases by 15% when cities double their size (West 2017). Although cities indeed display qualities for supporting society, the growth of populations in cities, sometimes reaching dozens of millions of people, has pushed inherent urban challenges to a new level of complexity (Fig. 1).

The fact that more than half of the world's population inhabits only 2% of the terrestrial land (Fig. 1, Pincetl 2017) makes cities one of the main drivers of global changes (Fig. 2). Significant environmental, social, and economic changes occur within and outside cities as they grow in size and complexity. Heat islands are amongst the most iconic urban environmental issues (Zhao et al. 2014; Manoli et al. 2019) that affect thermal comfort, health, and well-being of citizens, especially under a global warming climate (Gasparrini et al. 2015, 2017). Economic losses and poor livelihood are also a result of the higher vulnerability of cities to extreme precipitation events. Either for the effects of droughts combined with the high demand for water resources or the effects of floods because of constraints in water percolation and volume of natural reservoirs, and increased surface runoff (Marengo et al. 2020). Floods are the main natural hazard in cities leading to health issues and economic losses that affect more than two billion people worldwide (Gu et al. 2015). Urban populations also face high air, water, and soil pollution from urban activities. Exposure to environmental pollution

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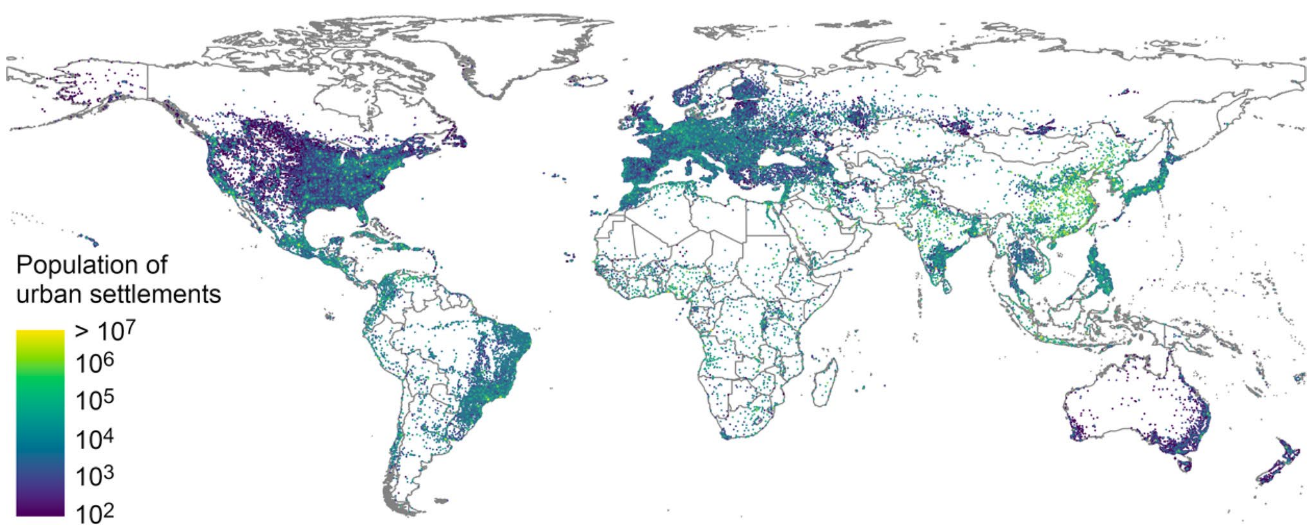

Fig. 1 Geographical distribution of urban settlements and their respective population size (World Cities Database Pro, v1.75, Pareto Software LCC)

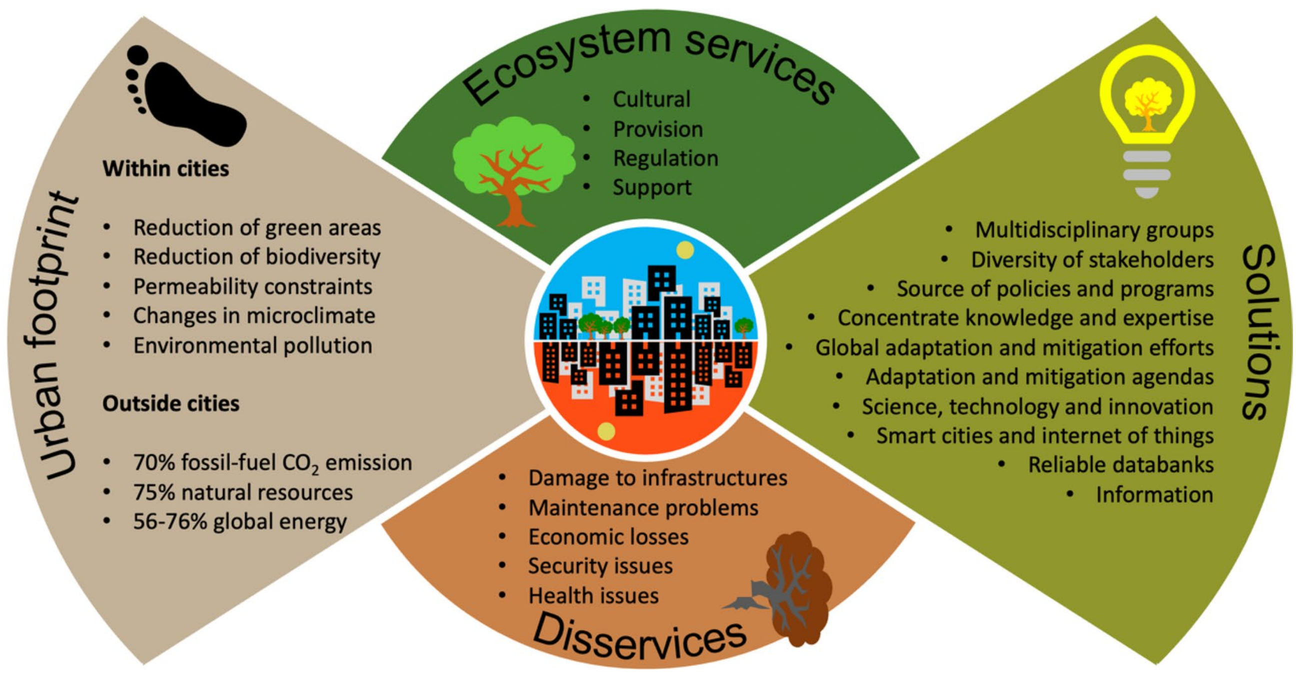

Fig. 2 Cities are the epicenter of global changes for their intrinsic activities, footprints, and emerging solutions. Trees are regarded as a transversal tool that requires a balance between services and disservices for optimum use to solve urban problems

frequently exceeds the recommended levels by competent authorities, and air pollution alone is considered the fourth cause of premature death worldwide (Health Effects Institute 2020). Cities are also responsible for over three-quarters of global natural resources and energy consumption, and are responsible for two-thirds of global greenhouse gas emissions from fossil fuel burning (Gurney et al. 2015; Pincetl 2017) significantly contributing to local and global changes.

There is now a consensus that cities are a primary source of solutions to address these problems (Bai et al. 2018; Rosenzweig et al. 2010). Such solutions may arise from the diversity of stakeholders, know-how, and city political power. The diversity of actors leads to new ideas being implemented, monitored, and reassessed in a continuous learning process. International, national, and regional agendas already consider the relevance of cities and urban activities in pursuing solutions and well-being. Cities are leading the way in tackling climate change, especially by proposing adaptation-related solutions (Rosenzweig et al. 2010).

Nature-based Solutions (NbS) arose from the need of stakeholders and decision-makers to find reliable alternatives to usual monofunctional heavy engineering solutions that are becoming inadequate to cope with the complex environmental, social, and economic challenges of cities. The term NbS comprises multifunctional solutions built upon well-established concepts such as green- and blue-infrastructures, ecosystem-based adaptation, and ecosystem services, but that takes co-creation as the heart of innovation. These solutions comprehend actions "inspired by, supported by, or copied from nature" to address environmental, social, and economic problems (ECDG 2015). Thus, it relies on more than just the latest technological advances but on the use of tools developed during thousands to millions of years of the evolution of the world's biodiversity (Miyahara et al. 2022).

Trees as part of the solution

Nature-based Solutions rely on complex tools from the world's natural environments to promote multifunctional benefits, and trees are at the core of these solutions for cities. Cities may benefit from well-known ecosystem services that trees can provide (Fig. 2). They are: (I) regulatory services for controlling climate conditions, air and water quality, drainage, and natural risks; (II) support, including biogeochemical cycles and biodiversity, (III) cultural, which encompasses immaterial aspects of the green infrastructure; and (IV) provision, mostly related to the delivery of essential goods. The contribution of trees to the provision of ecosystem services has a vast literature built over the last few decades.

Trees are known for their contribution to the mitigation of global climate change. This large carbon sink and storage take place through plant assimilation, allocation, and mobilization. While urban forests cannot keep to the levels of the carbon stocks of natural forests simply because they cover only a portion of the global land, they can achieve nearly 14% of natural forests' assimilation in some countries (Heath et al. 2011; Nowak et al. 2013). Increasing global urban vegetation by 50% would double the contribution of urban forests to the global carbon sink (Churkina 2016). The carbon sink potential of urban forests depends on the biology of various species of urban biodiversity (Weissert et al. 2017) and the extent of green cover. It is not only through assimilation and storage that urban forests contribute to the mitigation of climate change but also through the reduction of direct and indirect urban greenhouse gas emissions supported by other ecosystem services like climate regulation.

Ecosystem services largely depend on intrinsic characteristics of tree species. The contribution of trees to thermal comfort depends on their potential to provide shading and sensible heat conversion during evapotranspiration (Ferreira and Duarte 2019; Shao et al. 2019; Manoli et al. 2019). This potential usually increases with crown height and width (Gage and Cooper 2017), and diversity of tree species (Arcos-LeBert et al. 2021; Wang et al. 2021). Trees also contribute to stormwater control through the interception of rainwater along leaves and stems, water storage and transpiration, and reduction of through fall and surface runoff speed (Stan 2018). Water interception varies significantly with the morphology of different species, reaching up to 90% of the rainfall volume under light rain, and 50% under heavy storms (Alves et al. 2018; Aydin et al. 2018; Holder and Gibbes 2017; Kermavnar and Vihar 2017; Nycht et al. 2019). The potential contribution of trees to air pollution control also varies among tree species according to the characteristics of leaves (Leonard et al. 2016; Shao et al. 2019; Wang et al. 2015), like the presence of hairs (Leonard et al. 2016), their phenology (Cai et al. 2019), and stem bark morphology (Locosselli et al. 2021). All these services point to the actual contributions of trees not only to mitigation but also mainly to the adaptation of cities to current and future environmental changes.

All these services can only be fully provided if trees develop well, which can be challenging in cities. Urban trees face warmer and evaporative demanding conditions because of heat islands. Urban trees also need to deal with air pollution, shading within the urban canyons, artificial light, conflicts with the surrounding infrastructure, and paved and compacted soils, all of which may affect their growth and development, thus limiting the ecosystem services delivery (Locosselli et al. 2019). These adverse environmental conditions may impact the biological mechanisms of trees responsible for the delivery of ecosystem services. According to their tolerance, some species may decline while others may thrive.

More than just the ecosystem services of urban trees and their resilience to the altered urban environment need to be known for the efficient use of trees as part of the solution because trees themselves may be a part of the problem (Lyytimäki and Sipilä 2009; Roman et al. 2021). Many tree disservices have been reported in cities worldwide (Fig. 2). They include the seasonal production of allergenic pollen, contribution to air pollution, maintenance cost, and tree failure (Escobedo et al. 2011; van Haafen et al. 2021; Manfra et al. 2022). The latter is especially critical because it represents a risk to cities' infrastructure and citizens' health and a potential threat to urban tree cover and ecosystem services delivery. Thus, properly managing trees requires balancing services, tolerance, resilience, and disservices.

Advances in the science of urban trees

The use of urban forests to address current and future social, economic, and environmental challenges builds on the fact that urban forests can be optimized according to needs. In contrast to natural areas that may require ecosystem restoration of natural biodiversity and biological processes fully, urban forests allow poetic license in ecosystem restoration. The fact that natural processes will unlikely fully recover in cities should not be seen as a caveat but rather an opportunity to employ urban trees and forests to promote well-being.

Managing trees and urban forests for well-being requires deepening the knowledge about their structure and function to make decisions based on accurate evidence (e.g., Miyahara et al. 2022). Promoting the knowledge of tree functioning has been at the core of Trees, Structure, and Function, which has largely contributed to the dissemination and discussion of many aspects of urban trees over the years (Lütge and Buckeridge 2023). This special issue brings the theme "Urban trees" to the center of the discussion as a critical tool for promoting cities' well-being. The studies published in this special issue advance our knowledge of ecosystem services, resilience and disservices and propose guidelines for the efficient management of urban trees.

There is no question that urban trees contribute to well-being by providing ecosystem services that vary between native and exotic species (Arcos-LBert et al. 2021), including heat island control as highlighted by Ribeiro et al. (2023) in the cities of São Paulo and Curitiba, Brazil. However, trees can only deliver if they are resilient to adverse urban conditions. For instance: cities are renowned for extensive impervious cover, which is an artificial condition that may limit tree growth due to high surface and soil temperature and altered soil moisture (Cui et al. 2021). Even though warmer urban conditions may favor the growth of trees in cold-limited sites, such as *Pinus sylvestris* in Stockholm, heatwaves can severely affect water storage dynamics and limit the growth of trees in drought-sensitive sites, according to the study by Rocha and Holzkämper (2023). The effects of high urban temperature on photosynthesis, more specifically on quantum yield and thermal optimum, seems to be species-specific which calls for a deep understanding of the performance of different species to be planted in cities (Hara et al. 2021).

Recent reports of increasing frequency and intensity of droughts also raise the flag about the development of urban trees because they are exposed to impermeable and compacted soil, and high levels of Vapor Pressure Deficit (VPD). Under such adverse conditions, trees must adopt a fine control of transpiration through stomatal regulation to maintain their hydraulic status (Chen et al. 2023). Chen et al. (2023) show that *Pinus tabulaeformis* adopt this strategy to reduce the risk of hydraulic impairment and dysfunction, allowing trees to survive urban droughts in Hohhot, China. Drought recovery is another important aspect of tree resilience, according to the study by Horike et al. (2023). Although drought limits photosynthesis, water use efficiency, leaf mass per area, and other biological processes, some species can quickly reach pre-drought status. In contrast, other species cannot recover quickly from water stress making them less suitable for future urban climates (Horike et al. 2023). Thus, photosynthesis is a seasonal (Kinoshita et al. 2021) key trait in understanding the impacts of drought in urban trees, and Kar et al. (2021) propose a new method to assess these impacts through photosynthesis measurements in excised leaves.

Air pollution is another intrinsic characteristic of cities worldwide that has the potential to limit tree development and ecosystem services delivery. High exposure to pollutants such as particulate matter can reduce the growth of urban trees by more than 30% (Locosselli et al. 2019). In Dehradun/India, Singh (2023) observed a significant increase in leaf thickness, water use efficiency, soluble sugars, and ascorbic acid. They also observed a decrease in assimilation rate, transpiration, stomatal conductance, and relative water content in trees of *Alstonia scholaris* exposed to roadside air pollution. Such fine-tuning in biological processes allows them to withstand high levels of air pollution and thus be used in roadside plantations to mitigate air pollution (Singh 2023). Bezerra et al. (2023) and Silva et al. (2023) also observed tree plasticity changes. They report significant changes in wood anatomy, leaf chemistry, and cytotoxic effects along natural to urban gradients in Rio de Janeiro, Brazil.

A key question regarding the resilience of trees is: [are] "…there any synergistic effect of urban stressors on the growth of trees?". Hirsch et al. (2023) try to answer this question by examining the combined effects of drought and air pollution on the stem diameter growth rate of five tree species from the German cities of Karlsruhe and Rheinstetten. Tree growth was negatively affected by drought events to different degrees according to species. However, the exposure to traffic emissions did not result in altered tolerance to water stress for any of the five analyzed species. Therefore, these observations led to the conclusion that no synergistic effects between drought and air pollution exist in these species.

The poor resilience of trees to urban stressors can tip the balance in favor of disservices. Because of recent reports of increasing frequency and intensity, tree failure is a matter of great concern in many cities (van Haafen et al. 2021). Tree failure largely depends on the mechanical stability of trees and their interaction with adverse weather conditions. As urban trees generally lack canopy protection of neighboring trees (Gonçalves et al. 2023) and may face low-pressure zones and increased wind speed related to the urban canyons (Manfra et al. 2022), they are highly vulnerable to wind gusts and storm events (Locosselli et al. 2021). The wind drag forces on the canopy of trees were reviewed in depth by Gonçalves et al. (2023). Drag forces on tree canopy are strongly related to wind speed, but the magnitude of the drag force depends mainly on the crown architecture of trees (Gonçalves et al. 2023). Thus, any intervention like incorrect pruning and possible conflicts with the urban infrastructure may threaten trees' stability and favor their collapse.

For instance, conflicts between overhead power cables and the crown of trees are a known issue in many cities that calls for proper management actions. However, managing trees over the entire city is challenging. Many studies address this challenge using artificial intelligence algorithms that can learn patterns and support informed decision-making (Araújo et al. 2021). For instance, Oliveira et al. (2023) used deep learning and images from Google Street View imagery to assess tree and wire entanglements in São Paulo, Brazil. With relatively high accuracy (ca.75%) compared to other studies (e.g., Araújo et al. 2021), the algorithm can detect possible conflicts between the power cable and the crown of street trees, representing a significant step forward in supporting management and decision-making.

Proper urban tree management must also consider the impacts of plant diseases on the mechanical stability of trees, especially those related to fungal infection. This is the narrative highlighted by Kimic et al. (2023), who assessed the presence of fungal diseases on the leaves and stems of trees and shrubs from Warsawian squares, Poland. The authors propose guidelines for proper management to avoid the degradation of the health of these species that will affect ecosystem services delivery, plant fitness, and costs of green infrastructure maintenance.

So far, the management of trees is challenging in the cities, but it is necessary to guarantee and optimize ecosystem services delivery, avoiding disservices. Pretzsch et al. (2023) adapted the concept of sustainable forestry, long used for the maintenance of the wood stocks in natural and planted forests, to the urban environment, aiming not at wood yield but the delivery of ecosystem services. This sustainable delivery of ecosystem services requires continuous maintenance of the tree populations so that a constant stock of urban trees is guaranteed. The authors propose that the distribution of age classes in the urban forest should follow a regressively decreasing distribution. Any deviation from this distribution could cause a decrease in ecosystem services or lead to higher maintenance costs. According to the simulations, the authors recommend constantly planting and replacing trees instead of replanting after tree failure.

Fig. 3 Control panel for tweaking trees phenological, morphological, physiological, and biochemical features to promote the optimization of ecosystem services and disservices in urban forests. (Age: longevity of trees, Gr: growth rate, A: assimilation, g_s: stomatal conductance)

Tweaking trees for the well-being

It is clear from the literature and this special issue that the management of urban trees is rather challenging and requires not only the empirical knowledge of practitioners but also a much deeper understanding of the structure and function of trees. As a tool for Nature-based Solutions, urban forests can improve ecosystem services while mitigating disservices. This requires fine-tuning some critical biological processes such as phenology, morphology, anatomy, physiology, and metabolism to make interventions as efficient as possible (Fig. 3). In this context, highly diverse areas are in a favorable condition for having many possible tools already available to construct functional urban forests (Miyahara et al. 2022). On the one hand, because South American countries contain 43% of all tree species (Gatti et al. 2022), many cities in this region might assume key roles regarding urban trees as solutions based on natural processes. On the other hand, this biodiversity also poses an enormous scientific challenge as little is known about species' potential benefits, resilience, and possible disservices. As it stands, cities also benefit from a pool of exotic tree species.

This special issue, seen together with the available literature, suggests that much more work needs to be done on urban trees, looking at their structure and function and their role in cities. The science of urban trees has the potential to support evidence-based decision-making in cities to promote well-being.

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Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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