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Barriers and opportunities for resilient and sustainable urban forests

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Manuel Esperon-Rodriguez [1,2] ✉, Rachael Gallagher[1], Carlo Calfapietra[3,4], Paloma Cariñanos [5,6], Cynnamon Dobbs [7], Ana Alice Eleuterio[8], Diego Esperon Rodriguez [9], Ali Jahani [10], Elizaveta Litvak[11], Stephen J. Livesley[12], Gabriel Manoli [13], Renee M. Marchin[1], Timon McPhearson [14,15,16], Christian Messier[17,18], Johan Östberg[19], Lara A. Roman[20], Alessio Russo [21], Maryam Saffariha[22], Charlie Shackleton[23], Henrik Sjöman[19,24,25], Ingjerd Solfjeld[26], Jonah Susskind[27], Jens-Christian Svenning [28], Natalie van Doorn [29], Björn Wiström[19], Jun Yang [30] & Mark G. Tjoelker [1]

As cities heat up and expand in area and population, urban forests offer a nature-based solution to enhance liveability and reduce rising temperatures in cities. However, urban forests are vulnerable to climate change and face costly establishment and maintenance challenges. Here we explore four key ecological and socioeconomic barriers to achieving resilient urban forests: species selection, tree supply, tree life cycle (establishment and maintenance, including irrigation) and community engagement. We discuss how integrating traditional urban forestry practices with emerging technology offers a holistic approach to creating resilient, sustainable urban forests that can adapt to climate change while meeting community needs.

Climate change and urbanization are rapidly reshaping the urban experience[1]. People worldwide are already experiencing record heatwaves, drought and extreme events, and global policy failures have placed the planet on a track for 2.5–2.9 °C of warming by 2100 (ref. 2). Global average temperatures in 2024 were the warmest on record, about 1.34 °C above the twentieth-century average[3]. Cities face one-off catastrophic events and are increasingly subject to sequences of compounding hazards (for example, droughts, floods and storm surges) that require climate change risk assessment, adaptation and mitigation policies[4]. By their design and structure, cities also exacerbate heat effects from climate change[5]. However, cities also possess expertise, innovative capacity and wealth to develop and implement adaptations to cope with climate change[6]. The transition to sustainable cities requires active urban design and strategic planning, and stewardship by governments and communities to create and maintain liveable cities. The adaptation of urban landscapes to future impacts of climate change is a necessary step toward greater resilience—that is, increased capacity to recover from, or to mitigate vulnerability to, climate-related events[7].

A major challenge, however, is in designing resilient cities given accelerating rates of climate change, increasing biotic risks and urbanization. Consideration of complex and often interacting ecological and socioeconomic factors to identify and overcome barriers is required to achieve sustainability and resilience to climate change. To this end, urban forests—that is, naturally occurring and planted trees and other vegetation growing throughout a city in streets, parks, woodlands, vegetated plots, residential yards and roadside verges[8]—are broadly used as a nature-based solution. Urban forests contribute to sustainable urban development by improving human thermal comfort and liveability through positive effects on human health[9]. Urban forests also help to mitigate the effects of increased temperatures through evapotranspiration and shading and, hence, improve building energy savings[10,11]. However, urban forests are vulnerable to climate change and other biotic stressors. Rising temperatures, changing precipitation patterns and other extreme events associated with climate change (for example, heatwaves, drought, ice storms and floods) can lead to stress in urban trees, cause direct physical damage and increase susceptibility to pests and diseases[12–14] (Fig. 1).

A full list of affiliations appears at the end of the paper. ✉e-mail: m.esperon-rodriguez@westernsydney.edu.au

As complex ecosystems, urban forests function in close interaction with human society and urban infrastructure. The management, allocation and utilization of resources in urban forests often reflect a legacy of nonsustainable decisions[15]. Past practices and decisions (for example, widespread monoculture tree plantings (such as American elm, *Ulmus americana*, in some US cities) and invasive species plantings) are no longer suitable for current and future urban forest planning and management. Importantly, management during the tree establishment phase (ranging from 2 to 10 years after planting) and long-term maintenance should consider potential negative effects both inside and outside cities, such as the depletion of other environmental resources. For example, in water-scarce regions, irrigation used for newly planted trees and maintaining urban forests may compete with other urban and peri-urban needs (for example, agriculture, consumption and industry)[16]. Thus, it is critical to consider the potential for increased water demand for tree care to place strain on local water resources[17].

Identifying barriers and setting attainable goals for achieving resilient and sustainable urban forests requires a comprehensive understanding of environmental and social processes that can support (or jeopardize) the survival of these forests and the benefits they provide. We outline a path toward urban forest resilience and sustainability by reviewing four ecological and socioeconomic barriers to healthy and thriving urban forests: species selection, tree supply, tree life cycle (establishment and maintenance, including irrigation) and community engagement (Fig. 2). These barriers directly affect the survival, growth and long-term health of urban forests and collectively determine the success of urban forestry programs. We further discuss limitations and opportunities of ongoing and emerging technology for overcoming these barriers.

Fig. 1 | Examples of urban tree vulnerabilities to extreme weather events across the globe. a, Tree damage associated with a cyclone in Padua, Italy. **b**, Leaf damage after an extreme heatwave and drought event in Sydney, Australia. **c**, A tree uprooted by a wind storm in Foz do Iguaçu, Brazil. **d**, Tree collapse resulting from ice formation in the tree canopy in Nanchang, China. Photographs by A.R. (**a**), M.E.-R. (**b**), A.A.E. (**c**) and J.Y. (**d**).

Species selection and a diverse tree community

Climate change combined with unfavorable urban conditions (for example, limited soil and water volume[18]) can affect tree growth and the health of many species through drought and heat extremes as well as pest and disease outbreaks[14,19]. This results in many tree species experiencing poor health, high mortality and the consequent reduction or loss of ecosystem services[20]. Thus, one key challenge in urban greening projects is the identification and selection of resilient species that are well suited to current and future site growing conditions and resistant to pests and diseases[21].

Using more stress-resilient tree species, however, can have some unwanted consequences. Trade-offs between stress resilience and other growth characteristics may influence species choice. Some stress-resilient species exhibit more robust and long-lived plant parts (for example, leaf and wood structure) than less resilient species, which often comes at the expense of rapid growth[22]. Other stress-resilient species invest more biomass into roots, including surface roots for accessing water[23], which can affect urban built infrastructure. These growth strategies imply that many species with great potential for use in stressful urban environments may also have slower growth and perhaps require longer time periods for establishment and attaining desired size in the landscape[24]. Furthermore, the risk of selecting only stress-resilient species can reduce species and functional trait diversity, leading to greater biotic homogenization and, hence, risks to sustainable ecosystem service provision[25]. Thus, strategies promoting resilience against climate change and other risks should seek to reduce functional redundancy[26] and increase species and genetic diversity, which helps to provide resilience to environmental stressors and facilitates ecological interactions[27].

Selection of a greater diversity of species that can thrive amid extreme and changing conditions will require substantial changes in local, regional and national policies to guide arborists, greenspace designers and landscape architects to consider and select new or underused tree species[28]. This will probably require policies and practices to guide and incentivize adoption by property owners and residents. A holistic approach is imperative, allowing resilience and diversity to become central concepts in urban design and decision-making processes[29]. Conservation practices can be enriched by linking biodiversity with geodiversity[30] and considering the importance of nutrient cycling in maintaining urban soil microbiomes[31]. In certain settings (for example, abandoned industrial sites, urban river corridors and floodplains), spontaneous tree recruitment in rewilded urban greenspaces may be feasible in contributing a natural approach to urban greenspace management akin to forest succession[32], but this will need to account for limitations (for example, invasiveness, infrastructure conflicts, lack of management and social perceptions)[33]. Furthermore, opportunities to integrate traditional and Indigenous knowledge to improve social connection and sense of place can be sought in urban greenspaces. For example, the 2023 Street Master Plan from Sydney, Australia, incorporated Indigenous knowledge to increase the use of local plant species important to Traditional Owners. This resulted in a high diversity of species in the city's urban forest[34]. However, increased diversity will be effective only if selected species are also resilient to climate change.

The promotion of resilient tree species also involves designing plantings with a diverse population structure and demographic classes and including varied species and growth rates[35]. Depending on the planting context, having a mix of fast-growing and slow-growing tree species can create a multilayered or multiaged forest structure, enhancing biodiversity and ensuring continuous provision of ecosystem services over time as different species reach maturity at different rates. This approach enhances not only resilience but also overall ecological functionality[25] and can be achieved by matching the choice of planting material to sites, a long-recognized approach within forestry and silviculture[36]. Understanding the effect of species as well as cultivars, ecotypes or seed provenances on stress resilience may be crucial in selecting the most suitable planting material for specific locations[19].

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New approaches that consider stress resilience and the capacity to deliver ecosystem services need to be integrated with more traditional horticultural and botanical interests in meeting the objectives of future urban plantings. Through the establishment of urban forest marteloscopes (that is, forest plots for monitoring and training[37]), new species and cultivars can be tested in cities and their performance can be monitored. A global urban tree trial database[38] can help to identify tree species most suitable for urban plantings in different climatic regions and local-scale contexts.

Adequate tree supply for diversity and resilience

The availability of tree species in nursery production and plant supply chains is a barrier to urban forest sustainability. Plant material is often not available in the numbers required and on timelines needed to meet demands of urban greening projects[28]. Nursery growers can be aware of the part they play in meeting the challenge of greening cities in a constantly changing climate[39]. However, the rapid rate of climate change is forcing nurseries to act quickly to maintain a supply of suitable tree species with sufficient adaptive capacity to current and future environmental conditions[19]. Unfortunately, there are few standardized strategies, protocols and guidelines integrating future climate change that can be widely implemented to guide plant production[19]. For example, most commercial nurseries in the USA have not yet explored the effects that climate change may have on their operations[40]. Thus, it is likely that the nursery industry will need to propagate a wider diversity of tree species, including species new to nursery production[41]. However, barriers exist to achieving this goal. Many years of production time are needed to bring new species or cultivars into market with no guarantee of selling the product when it is ready[42]. Changing the nursery stock exposes nurseries to economic risk if they do not have a fixed or contracted buyer, which may result in unsold plants remaining in nurseries and economic losses for growers. One potential solution is advanced procurement contracts; for example, the Million Trees New York City planting program used such contracts to diversify and scale up the production of stock needed for that massive planting effort[43].

Nurseries may have knowledge gaps with regard to the biology of less common species and their maintenance needs[19]. There are uncertainties around how tree species new to urban areas might respond to the full range of urban conditions, including pollution and soil compaction. Nurseries, therefore, need new research knowledge that is readily available to them on which new tree species might be able to adapt to future stresses[19]. Unfortunately, there is scarce research on species-specific tree stresses, and when available, this is not always in an accessible format. Information on future climate change projections and research on species' climatic tolerances in user-friendly formats can help to inform plant choices and knowledge sharing with nursery growers and consumers[19].

The propagation of new native and exotic species and a wider diversity of species will probably require overcoming commercial and regulatory barriers to safely and sustainably produce and distribute plant material[44]. Nurseries have contributed to the spread of invasive species, pests and diseases through global trade and transportation of stock[45]. Bringing new native and exotic species into nursery production will require strict protocols (for example, weed risk assessments) to evaluate the invasiveness potential and the risk of novel pests and pathogens[46], without reducing the ability for the nursery trade to supply stock into other countries, which could increase genetic diversity.

Another barrier in tree supply is the limited collaboration and information sharing between nurseries and researchers. This can result in inefficiencies, duplicated efforts and missed opportunities for collective learning and advancement in climate-adapted tree production[42,44]. Undertaking experimentation and trials as collaborative efforts between nurseries and governments can allow testing responses of new species and, in turn, fill knowledge gaps in species' biology and maintenance needs[44]. In many cities, work is already underway

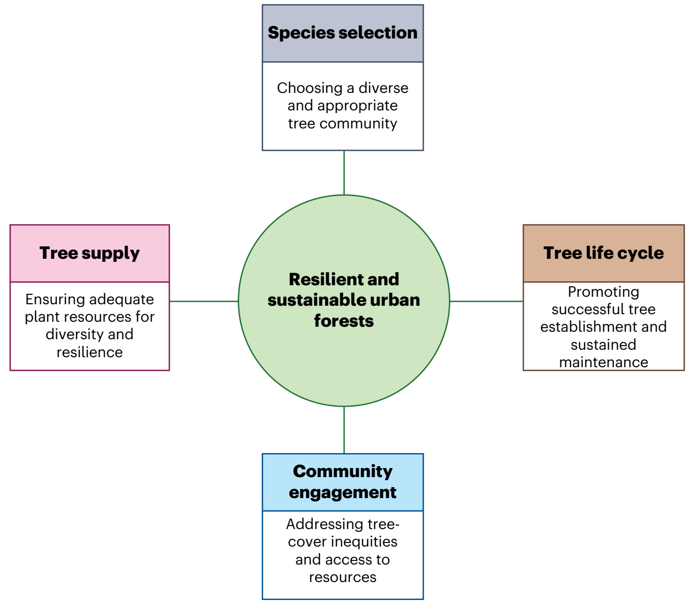

Fig. 2 | Four ecological and socioeconomic barriers to achieving resilient, sustainable urban forests. These barriers are species selection, tree supply, tree life cycle (establishment and maintenance, including irrigation) and community engagement.

to establish plans and strategies for adaptation to climate change, highlighting the role of municipal nurseries. Examples such as Adapta Biofilia in Badajoz, Spain, and the working group on Forest Genetic Resources of SilvaMediterránea (Food and Agriculture Organization Forestry Division) represent initiatives aiming to improve the public service of nurseries. These initiatives do so by incorporating adaptation to climate change as a criterion for the selection, production and supply of plants and then generating best-practices guidelines for sustainable nursery production with certification and harmonization to international standards[47,48].

Successful tree life cycle

The planting of urban trees, their long-term maintenance and their eventual removal require strong and long-term economic investment strategies, which compete for budget allocation with other urban services and infrastructure. Urban tree management can be daunting for local governments in both the Global North and South when they face increasingly limited public budgets[49,50]. In such situations, budget allocations to greenspaces can be minimal, particularly for small cities, post-industrial cities or jurisdictions that consequently rely on planting stock supply from the private sector, donations from nongovernmental organizations or larger, better resourced metropolitan centers[51]. Some small cities may lack designated departments or divisions to implement urban greening programs or have no staff to advance these strategies[52], although communities and volunteers can have an important role in urban greening programs[53].

Massive global tree-planting campaigns are sometimes framed around numerical targets to plant large numbers of trees; for example, millions (or many thousands) of trees (for example, the program 5 Million Trees for Greater Sydney in Australia and the Trees in Cities Challenge by the United Nations Economic Commission for Europe). However, funding for these tree-planting initiatives has typically gone mainly toward purchasing and perhaps tree planting, but not toward their subsequent establishment and maintenance[54]. These tree-planting initiatives can also put substantial pressure on nursery tree production, leading to the use of trees of an inadequate size or age class or even less-suitable tree species for certain planting sites, all of which may contribute to failure[55]. Furthermore, urban tree maintenance is often

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limited to a few years after planting, or in some cases no establishment 'aftercare' is provided, as is the case for tree-planting programs that depend on the public to plant trees[54].

Care and maintenance during establishment are not the only critical elements for ensuring tree survival and growth. Trees with insufficient space belowground or aboveground or species unsuited to a site's conditions may exhibit poor growth and health[56]. Although providing an extended period of irrigation and nutrient maintenance may keep trees alive, this is predicated on the continued intensive stewardship of the trees and subject to water availability, which is becoming more constrained in many regions[57]. Best practices for maintenance and establishment aftercare of trees also includes appropriate pruning (for example, early elevation and structural pruning), mulching and staking. Importantly, considering pest and disease outbreaks is essential for maintaining healthy and resilient urban forests[14]. Proactive, science-based management of these risks is a core part of urban forestry and green infrastructure planning[17]. Another key consideration is the physical space available for planting new trees, including space limitations related to underground pipes, overhead wires, roads and parking spaces, with additional issues related to soil compaction[56]. Space may be severely constrained in neighborhoods with high population density, historical city centers and cities adopting densification strategies[52], all areas where urban trees are most needed.

Selecting and planting species that suit the site's environmental conditions can limit the need for intensive maintenance. In a study of tree survival on private residential property in northern California, USA, a lack of maintenance was identified as the main cause of tree mortality, although failures could have been exacerbated by inappropriate species selection[58]. Beyond plant selection, sustainable technologies (for example, stormwater management systems and soil quality improvement technologies) can have a key role in ensuring the success of future urban forests under stressful conditions[59]. Basic tools, from watering bags (Fig. 3) to advanced automated systems (for example, smart irrigation and innovative tree pits for passive irrigation), can contribute to resilience and smart urban forestry[60]. However, their effective implementation requires supportive policies and finances. Cities exhibit different climates, land-use policies and morphological characteristics and thus will need to address unique challenges and find their best solutions at the lowest cost given their typically low maintenance budgets.

Fig. 3 | Examples of urban management practices and community engagement across the globe. a,**b**, The use of tree watering bags in London, UK, as a temporarily deployed preventive measure for climate resilience during periods of water limitation. **c**, Structure to support an established *Ficus* spp. tree in Malaga, Spain. **d**, Passive stormwater rain garden in Washington, DC, USA. **e**, Community engagement in an urban street planting project in the city of Newcastle, Australia. Photographs by A.R. (**a**,**b**), M.E.-R. (**c**,**e**) and J.Ö. (**d**).

Providing water via irrigation

Irrigation is generally considered a best practice in arboriculture, especially during the establishment years, and is an important component in the maintenance of urban forests[54]. Irrigation of urban forests is recommended in a variety of urban climate contexts[61], and will probably be required to alleviate future drought and extreme heat events[12]. However, it is increasingly an unsustainable practice in many arid and semi-arid cities where water security is paramount[57]. Thus, promoting the right species pool in terms of water-use efficiency will be key in these cities along with innovative systems to recycle urban wastewater to be used for watering purposes[62]. By contrast, in some cities, consideration of stormwater flows and use of greenspace is required to reduce risks from flooding[63].

Minimum water requirements of drought-resilient species are highly variable depending on species age, size, drought tolerance, landscape management, soil conditions and planting density, complicating the determination of water-use requirements[64]. However, urban trees can sometimes access deep groundwater or leaky water supply infrastructure. In these situations, irrigation may not be needed during droughts if roots can access available water at depth[65]. Importantly, during hot, dry conditions, the cooling benefits that trees can provide through evapotranspiration are most needed, but the trade-off may be the water they require. For example, irrigation of greenspaces in hot and dry cities aims to maintain aesthetics, provide shade and decrease air temperatures, while contributing to human well-being and local sustainability[66]. Nonetheless, minimizing water use of greenspaces is often necessary to confront water scarcity and preserve nonrenewable water resources[57]. Similarly, when strategically placed near buildings, tree shade can decrease the use of air conditioning and lower energy costs, contributing at the same time to avoiding emissions[67]. However, if reducing the irrigation of shade trees leads to reductions in the canopy cover or evaporative cooling function of trees, this poses a trade-off between water and energy conservation. These examples illustrate the importance of comprehensive, place-based analysis to identify and address trade-offs and potential conflicts on the way to achieving optimal solutions and developing efficient sustainability strategies.

Community engagement and access to resources

The distribution of tree canopy within cities can be highly uneven, such that certain neighborhoods have more urban greenspaces and tree cover than others, the so-called luxury effect. This often stems from legacy effects of historical patterns of urban development, discrimination, investment or land-use policy[68]. Residents of some neighborhoods often face challenges in accessing greenspaces owing to factors such as lack of public transportation, public access limits, urban sprawl or perceived safety concerns[68]. In Los Angeles, USA, for example, police departments can request the removal of trees if they interfere with aerial surveillance operations[69]. Furthermore, the lack of proximity to a greenspace contributes to inequity in opportunities for recreation, relaxation and social interaction[70], as well as disparities in air temperature regulation, air quality, aesthetics and mental and physical health benefits associated with urban forests[70]. Vulnerability to the effects of climate change, such as extreme heat events, can be higher in neighborhoods with limited green infrastructure and inadequate access to cooling effects provided by urban forests[71,72].

The quality and maintenance of urban forests also vary spatially within cities. Urban trees in disadvantaged neighborhoods may experience neglect or receive fewer resources for maintenance, leading to degraded greenspaces that are less appealing and less conducive to community well-being[73]. Furthermore, although urban revitalization can bring positive changes (for example, improved quality of urban forests or greater provision of green infrastructure overall), it can also lead to gentrification and may contribute to the displacement of low-income residents or amplify inequity in the provision of environmental services[74].

Globally, most urban planning is practiced by professionals and experts employed by governments or developers with limited input from local residents[75]. The selection and planting of trees in public spaces is generally conducted by professional arborists, horticulturalists, developers and landscapers, and the decisions made may not meet community expectations or reflect community preferences and needs[76]. Reducing green inequality requires a comprehensive, multifaceted and whole-of-governance approach that includes or is led by community members to address the root causes of environmental disparities[75]. Urban planning policies can be implemented to prioritize the equitable distribution of urban forests through both the preservation of large, established trees and the planting of new ones. Community needs and preferences should be considered in the planning process[77]. In some countries, it is reassuring to note that tree-planting plans are increasingly being presented to residents for their input. In South Korea, for example, the level of residents' satisfaction with urban trees influenced their engagement in different practices[78]. Thus, urban residents have critical roles in valuing and stewarding urban greenspaces[75].

Although a step in the right direction, community engagement processes typically occur toward the end of the planning process. Consequently, urban greening plans may not be fully embraced and championed by local communities as they were not empowered by being included at initial development[79]. This can lead to suboptimal support and even rejection or vandalism by residents[79]. Environmental justice scholarship and practice calls for the active inclusion of residents, particularly those of marginalized communities, throughout greening processes[80]. Residents' needs and priorities then become the very foundation of subsequent outcomes[81]. In Paris, France, urban trees are used to engage citizens in public consultation and for community participation[82]. Inclusion, then, can transform the interactions with residents from a community outreach exercise to one of coplanning and codesigning, through the provision of enabling grants and establishment of living laboratories or community gardens, activities that are typical of a nature-based solution approach[83].

In some cases, however, residents may not see the benefit in greening programs owing to other more pressing priorities or may harbor deep concerns about urban tree disservices (that is, negative effects of trees)[81] due to their lived experiences with municipal disinvestment or inadequate municipal tree care. Poor community engagement may not acknowledge the diversity of relational values of communities toward urban forests, following approaches of 'one size fits all'[84]. Community engagement processes and decisions are often made by negotiating between perceived trade-offs related to aesthetics and preference for native plants over exotic plants, for example, as opposed to environmental performance[85]. Hence, incorporating codesign and coproduction in urban forestry engagement and implementation is essential to understand and provide desired benefits from urban forests while decreasing tree disservices[86].

A path towards resilient and sustainable urban forests

Resilient and sustainable urban forests require comprehensive management plans to secure and support urban development. Such plans require promoting a high diversity of tree species, notably native ones, but also well-integrated exotic species, with support of spontaneous recruitment processes in appropriate areas, integration of geodiversity—including hydrology—in greenspace planning, community engagement and consideration of socioecological inequality in urban spatial planning. A collaborative effort among governments, urban planners, nurseries, researchers, environmental organizations and residents is essential for the successful execution of these plans. This may require a shift from large-scale tree-planting campaigns with a focus on numbers of trees to, instead, a focus on local priorities and outcomes[54]. Setting local goals based on relevant information can help in implementing actions, and monitoring and evaluation will provide information to adjust these goals.

Overcoming the barriers we have outlined requires an integrated urban forest resilience framework. Within this framework, a diverse portfolio of stress-resilient species needs to be developed for each region, with species selection based on climate projections and cultural preferences and local ecological knowledge[19]. Emerging technologies such as artificial intelligence (AI) and machine learning offer transformative potential for urban forestry, aiding in species selection by integrating real-time climate and environmental data to enhance adaptability. These tools can monitor tree health, optimize water usage and forecast tree growth, enabling proactive urban management and strategic planning. Virtual reality allows the visualization of future forest designs, and civic science and AI-driven image recognition can engage communities in tree identification and monitoring. The next step to resilient urban forests is a sustainable tree supply from nurseries, which should implement high-quality production standards and ensure a consistent stock of stress-resilient trees. Partnerships among governments, nurseries and research institutions are essential for forecasting demand and optimizing the supply chain. These collaborations can be complemented by local tree propagation programs to reduce transportation costs, support local economies and enhance the sustainability of urban forestry practices.

To ensure that urban trees thrive after planting, innovative establishment and maintenance strategies are needed. Innovative communication and monitoring strategies of urban forests have the potential to support improved establishment care and long-term maintenance. Although an added cost, technology is now available for each tree to have its own readable digital label (for example, QR code) for maintenance with information on origin, instructions for maintenance and cost of planting to inform the public of costs and benefits. In addition to promoting public interaction with urban trees, the communicated information can raise awareness of the value of trees and the consequences of neglected maintenance. Melbourne's urban forest in Australia, for example, has an email address and an interactive map with tree locations, and each tree has its own ID number. The purpose of the email was for members of the public to report incidents; however, people have used these emails to send personal letters and fan mail[87].

Long-term monitoring of urban forests that incorporates detailed data on growth and mortality over time can help to identify best maintenance and management practices, along with information on species and locations that are most vulnerable to failure[19]. By collecting and using failure data from different locations to train deep-learning algorithms, predictions of incidence of failures can used to track maintenance needs. New technologies, including AI-driven methods through proximal, deep-learning applications and remote-sensing techniques, along with other traditional methods such as digital phenology cameras, can be applied to assess tree condition and to monitor urban tree health, pest and disease outbreaks, and hazards (for example, fire) at various resolutions and scales, from individual trees to citywide canopy cover[88,89]. Monitoring can also be conducted using civic science and crowdsourcing of information gathering, enabled by various smartphone apps. However, to effectively manage urban forests, it is essential to use precise methods and criteria for monitoring and identifying aging and deteriorating trees and have a plan for what to do as trees senesce. Importantly, technology adoption may vary by location and availability of resources[90] as adoption can be prohibitively expensive. Instead, advanced techniques can be built from relatively simple approaches such as recurrent size measurements for long-term evaluation, involve the public in civic science efforts and provide valuable information to urban forest managers[19].

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Alternative water sources are crucial to providing sustainable water management for urban greening in the future. Smart irrigation systems that respond to real-time soil moisture data and use recycled sewage water, stormwater capture systems and small urban water storage bodies are available options to optimize water usage and address water scarcity, particularly in dry regions[91]. However, it is critical to ensure that any such water usage does not have negative effects on people or nontarget peri-urban ecosystems. Supplementary water can be provided to trees through active or passive irrigation. The implementation of passive irrigation systems, structural soil systems and permeable pavements can enhance root growth conditions in urban settings, contributing to healthier, more resilient trees.

Recycled sewage wastewater can offer a viable alternate or supplemental source of irrigation water[91]. Stormwater irrigation can also be wholly passive by simply redirecting stormwater runoff (often road gutters) toward greenspace swales or tree pits or depressions[92]. Alternatively, an engineered stormwater irrigation system can include harvesting of runoff from roads, parking lots and roofs into underground storage reservoirs that may be used to irrigate trees[93]. Other alternatives are gray and black water systems along with collection of condensate water from heating, ventilating and air conditioning systems, local rainwater detention systems and xeriscaping, especially in cities with arid and semi-arid climates. By using monitoring data, emerging technologies (for example, deep-learning techniques) can be used to track soil moisture levels. By enhancing remote-sensing image resolution, early warning signs of drought—such as canopy browning—can be detected through machine learning. AI-powered satellite, aircraft and drone-based remote-sensing observation and analysis can be used for real-time management and monitoring of irrigation practices.

Community-based tree stewardship programs can reduce maintenance costs by involving residents in long-term tree care, fostering a sense of ownership and ensuring sustained support for urban forests[75]. New digital platforms that integrate tree inventory data, climate risk assessments and community input may enable informed urban forest planning. Education programs are also essential to inform the public about the benefits of urban forests, emphasizing their role in climate change mitigation and adaptation. This will help to ensure that urban forestry decisions are transparent and data-driven, increasing public trust and involvement. Community engagement should ensure that residents' needs and preferences are better catered to with respect to species, spaces, activities and benefit flows and improve a sense of caring and stewardship (Fig. 3). To achieve this, it is crucial to actively involve local communities when developing inclusive and culturally relevant greening programs[82]. These activities may consider traditionally underrepresented groups in the decision-making processes related to urban forestry (for example, design, maintenance and use of greenspaces). Focusing investments on green infrastructure in historically underserved neighborhoods can have positive effects even if tree canopy cover increases are not immediately realized. Importantly, urban greening goals, although usually established top-down, may often benefit from incorporating bottom-up strategies.

The barriers described here represent some of the main issues that cities face on their path toward managing resilient and sustainable urban forests. However, there are other barriers related to competing urban priorities, urban planning and land-use policies, limited urban space, infrastructure conflicts and funding constraints that can further increase risk to urban forests. Further research is needed on context-specific barriers and policy solutions[94,95].

National and local governments may need to reassess opportunities to implement policies that incentivize and support the creation and maintenance of resilient urban forests. Governments may also need to allocate sufficient resources to support urban forestry initiatives as a public health and sustainability need. Although there are no universal solutions, the ideas discussed here provide a basis for addressing specific challenges faced by cities across the globe. Integrating these insights into new approaches to urban planning and development, together with collaborative and equity-focused policies, will contribute to creating more resilient, sustainable and liveable cities.

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Author contributions

M.E.-R., R.V.G. and M.G.T. conceived the article. The manuscript was written by M.E.-R. with contributions from C.C., P.C., C.D., A.A.E., D.E.R., A.J., E.L., S.J.L., G.M., R.M.M., T.M., C.M., J.Ö., L.A.R., A.R., M.S., C.S., H.S., I.S., J.S., J.-C.S., N.v.D., B.W. and J.Y. All authors, M.E.-R., R.G., M.G.T., C.C., P.C., C.D., A.A.E., D.E.R., A.J., E.L., S.J.L., G.M., R.M.M., T.M., C.M., J.Ö., L.A.R., A.R., M.S., C.S., H.S., I.S., J.S., J.-C. S., N.v.D., B.W. and J.Y., contributed to the discussion of the content and reviewed or edited the manuscript before submission. All authors, except for M.E.-R., R.G. and M.G.T., are listed alphabetically.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Manuel Esperon-Rodriguez.

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[1]Hawkesbury Institute for the Environment, Western Sydney University, Penrith, New South Wales, Australia. [2]School of Science, Western Sydney University, Penrith, New South Wales, Australia. [3]Research Institute on Terrestrial Ecosystems, National Research Council of Italy, Porano, Italy. [4]National Biodiversity Future Centre, Palermo, Italy. [5]Department of Botany, Faculty of Pharmacy, University of Granada, Granada, Spain. [6]Andalusian Institute for Earth System Research, University of Granada (IISTA-CEAMA), Granada, Spain. [7]Department of Natural Resources and the Environment, University of Connecticut, Storrs, CT, USA. [8]Instituto Latino-Americano de Economia, Sociedade e Política, Universidade Federal da Integração Latino-Americana, Foz do Iguaçu, Brazil. [9]Centro Universitario de Ciencias Sociales y Humanidades, Universidad de Guadalajara, Guadalajara, Mexico. [10]Faculty of Assessment and Environment Risks Department, Research Center of Environment and Sustainable Development, Tehran, Iran. [11]School of Sustainability, Arizona State University, Tempe, AZ, USA. [12]School of Agriculture, Food and Ecosystem Sciences, Faculty of Science, The University of Melbourne, Richmond, Victoria, Australia. [13]School of Architecture, Civil and Environmental Engineering, École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland. [14]Urban Systems Lab, The New School, New York, NY, USA. [15]Cary Institute of Ecosystem Studies, Millbrook, NY, USA. [16]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden. [17]Département des Sciences Naturelles, Institut des Sciences de la Forêt Tempérée, Université du Québec en Outaouais, Ripon, Quebec, Canada. [18]Centre d'Étude de la Forêt, Université du Québec à Montréal, Montreal, Quebec, Canada. [19]Department of Landscape Architecture, Planning and Management, Swedish University of Agricultural Sciences, Alnarp, Sweden. [20]Pacific Southwest Research Station, USDA Forest Service, Riverside, CA, USA. [21]School of Architecture and Built Environment, Queensland University of Technology, Brisbane, Queensland, Australia. [22]Department of Plant Sciences, University of California, Davis, Davis, CA, USA. [23]Department of Environmental Science, Rhodes University, Makhanda, South Africa. [24]Gothenburg Botanical Garden, Gothenburg, Sweden. [25]Royal Botanic Gardens, Richmond, UK. [26]Faculty of Landscape and Society, Norwegian University of Life Sciences, Ås, Norway. [27]SWA Group, Sausalito, CA, USA. [28]Department of Biology, Center for Ecological Dynamics in a Novel Biosphere (ECONOVO), Aarhus University, Aarhus, Denmark. [29]Pacific Southwest Research Station, USDA Forest Service, Vallejo, CA, USA. [30]Department of Earth System Science, Institute for Global Change Studies, Ministry of Education Ecological Field Station for East Asian Migratory Birds, Tsinghua University, Beijing, China. ✉e-mail: m.esperon-rodriguez@westernsydney.edu.au