Trees: structure and function and the challenges of urbanization

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Abstract

Key message Urban trees are passively subject to and actively mitigate urban environmental pressures. Suitable selection of tree species and appropriate management can make cities useful habitats for trees.

Abstract The urban environment is stressful not only because of pollution but also due to heat and drought, creating arid conditions. Trees are passively subject to the microclimate but are also actively modifying it, and they perform important urban ecosystem services. Trees function as bio-indicators of urban conditions by morphological features and by dendrochronology and dendrochemistry. Anchorage and mechanical stability need to be surveyed. Among the stresses in addition to deposition of metals, there is gaseous pollution of the atmosphere (SO₂, NO₂, and O₃). Reacting to that are leaf anatomy as well as even the fine-tuning of biochemical pathways, e.g., terpene synthesis. The significant urban stresses are heat and drought. They increase top dieback and lead to a decrease of life crown-top heights from the ground (LCTH), where water relations remain similar in the crowns at various heights. Statistics of dendrochronology allow identification of pointer years with exceptionally wide and narrow tree rings. The prevalence of pointer years helps the selection of species suited for plantation in cities. Measurements of water potential at the turgor-loss point, π_{lp} , indicative of the permanent wilting point also helped identifying whole-plant drought tolerance. Infection by wood-decay fungi is a hazardous urban problem, as wood-decay builds up over many years increasing the danger of tree fall. Ectomycorrhiza is hampered in urban soils having a low inoculum potential due to chemical and physical soil qualities regarding cation-exchange capacity, permanent wilting point, and availability of water. Management should be based on scientific investigations. Allometry modeling allows for quantifying ecosystem services. Surveying stability is possible for instance by noninvasive acoustic tomography. Practices are irrigation and mulching. With appropriate management, cities can be useful habitats for trees contributing to biological richness and the comfort of life in cities.

Keywords Biodiversity · Dendrochronology · Drought · Ecosystem service · Heat · Mulching · Mycorrhiza · Windthrow · Wood decay · Urban trees

Introduction

Challenges of urbanization

Urbanization displays a massively increasing trend. According to data of the UN, more than half of the world's population lives in urban areas and the prediction for 2050 is that 64% and 86% will be urbanized in the developing and the developed world, respectively. Because urbanization tends

to increase quickly at a planetary level, the effects of the global climate change will be critical in urban areas (Bazaz et al. 2018). The structure of the cities usually increases local temperature due to the condensation of constructions using concrete and asphalt. Thus, the elevation of temperature due to the global climate change poses a problem for the next decades since it will provoke several different impacts on urban areas, with consequences to human health, energy consumption, to name but a few. In the IPCC special report on the impacts of global warming of 1.5 °C, urban trees have been pointed out as one of the strategies to help to strengthen the global response to climate change (De Conink et al. 2018).

The distribution of trees in some major cities around the world has been examined using computational analyses

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based on the Google Street view (Li et al. 2015; Seiferling et al. 2017). Using available data banks for trees that occur in city streets, the authors calculated a Green View Index (GVI), which can be used to examine the percentage of distribution. Although data from only 27 cities are currently available, the analysis shown in Fig. 1 afforded a comparison between the percentage of tree coverage and population density, revealing distinctive characteristics of cities from America, Europe, Asia, and Oceania. A general tendency is an increase in tree coverage as the population density decreases. For large cities (above 1 Mio. inhabitants) such as New York, São Paulo, Paris, a lower percentage of tree coverage (< 15%) is observed. Some cities can be considered outliers, having, for instance, a large population density but at the same time high tree coverage (Singapore) (Fig. 1).

Articles in “Trees: Structure and Function” regularly cover relations between trees and urbanization. In this overview, we recall and summarize articles published in the Journal over the last years and, in some cases, correlate them to other references. In perspective, these articles provide a comprehensive coverage of the role of trees in

urban environments, their function as bio-indicators for environmental conditions and stress, their urban ecosystem services, their stability, and sensitivity in response to abiotic and biotic urban stresses and requirements of management. With their observational and experimental approaches, their interpretations, and bibliography, it is worth considering these articles in context for a broad view of Tree’s structure and function under challenges of urbanization. For the benefit of readers of the Journal, in the text, references of Trees are marked by a T behind the year of appearance.

Trees and urban environments

For trees, cities provide a broad diversity of contrasting growing sites, which modulate the biodiversity of trees we can find in cities. Naturally, this depends on the latitudinal and altitudinal location of cities as well as on their size. City-land use patterns range from industrial and main traffic areas with street canyons to plazas and parking areas, living quarters and parks, and gardens. Trees interact with

Fig. 1 Comparison between percentage of tree coverage and population density in 27 cities. After data compiled by the Massachusetts Institute of Technology to construct the website (Treepedia—<https://senseable.mit.edu/treepedia>)

the microclimate conditions of these localities both being subject to them and moderating them.

Generally, buildings and pavements may cause conditions analogous to arid environments with higher temperatures and lower air humidity (Kjelgren and Clark 1993-T). Stress factors prevailing at various intensities due to location in the land-use mosaic of cities are properties and scarceness of space, limitations of light and conditions of the air with gaseous and particulate pollution, coarseness, and compaction of soil with both low availability of nutrient minerals and mineral pollution, and limited water availability. Most of these challenges of trees are addressed in the various articles published in *Trees*.

Urban trees are also moderating urban microclimate and thereby pay vital services helping to control adverse conditions for life in cities when planted and managed correctly both considering the choice of the tree species and establishment in the mosaic. Among outstanding services are the control of air and surface temperature due to shading and transpiration. Trees reduce the urban-heat island effects, where by sun absorption of buildings and asphalt, temperature can be 1–3 °C warmer than in surrounding landscapes. Other services are increasing the air quality by absorbing pollutants from the gas phase and from rain water and by fixing particulate aerosol matter, sequestration and storage of carbon, storm and water management, providing windbreaks and reducing rainwater runoff by interception. A converse example of interaction of runoff with trees is using it for feeding drainage channels directed into city-surrounding mangroves for minimizing mosquito breeding habitats, as, e.g., at Darwin Harbour in Northern Australia (Moritz-Zimmermann et al. 2002-T). Urban development eliminates native species and invites nonnative species, which may become invaders. In managed suburban areas as well as unmanaged ruderal areas, early successional species are common. These habitats resemble savanna or grassland communities. Among their ecosystem services is the creation of conditions providing niches for animals such as birds and insects (McKinney 2002). Last but not least, tree aesthetics contribute to the well-being of city dwellers.

Trees as bio-indicators of stress in urban environments

Plants and their performance can serve as indicators for prevailing environmental conditions. Due to their longevity, trees are particularly suitable for this. Moreover, the tree rings in the wood provide archives of responses over time. Dendrochronology supported by dendrochemistry (Locosselli and Buckeridge 2017-T, Lüttge 2017-T) enables analysis of traces left behind by stress. Trees growing in urban environments are much used for diagnoses.

Betula pendula Roth. is tolerant to effects of industrial pollutants, including metals such as Zn and Pb, and it is even noted to be an invader of damaged areas. The leaves have a sticky surface, especially when young, and collect precipitation of aerosols and soil dust. This is the significant input of metals to the leaves, while the translocation of metals from the roots is limited. Samecka-Cymerman et al. (2009-T) have analyzed *P. pendula* trees in a study comparing a polluted area in the city of Wrocław (Poland) with a non-polluted area 36 km away.

Due to the traffic intensity, industrial facilities and non-negligible long-range input from industries in SW-Poland, the deposition of metals such as Co, Cu, Fe, Ni, and Pb in leaves was more abundant in the polluted area than in the control plots, which indicated a certain degree of metal stress. The high suitability of *B. pendula* as a bio-indicator for the environment derives from the fact that it displays a dimorphism producing short and long vegetative shoots. Over time, short shoots change to long shoots, but this development is inhibited by stress, e.g., through pollution, and short shoots eventually may even die. Therefore, under stress, the age and length of short shoots increase. In the study of Samecka-Cymerman et al. (2009-T), short shoot length was positively correlated with traffic intensity and Co, Cu, Fe, Ni, and Pb concentrations in the leaves. Thus, short shoot length is an excellent bio-indicator of environmental stress.

Locosselli et al. (2018) have studied the distribution of various metals, such as Cd, Cu, Hg, Na, Ni, Pb, and Zn, transported in the xylem vessels from root to shoot in the stem rings of the deciduous tropical tree species *Tipuana tipu* (Benth.) Kuntze (Fabaceae) in the central region of the city of São Paulo, Brazil, using a high-resolution laser ablation system. Hg was not detected. There was a decreasing trend of the other elements in the period from 1988 to 2016, especially for Pb, Cd, Cu, and Ni. The phase-out of lead in fuel explains the reduction of Pb. For the other metals, the decrease is correlated with deindustrialization in the city center and increasing the efficiency of vehicles diagnosing a particular improvement of the city environment.

Time-series of urban tree-ring data over more extended periods can be very complicated, because effects of climate change and anthropogenic pollution overlap each other. Political influences during history, causing pronounced fluctuations of human population sizes may result in temporal complexity. Tree growth captures such urban environmental variations, and tree ring width and deposition of pollutants, e.g., metals, in tree rings are indicators of past environmental changes. Chen et al. (2011-T) have performed an investigation of such complex interactions studying trees of the Chinese pine *Pinus tabulaeformis* Carr. at three locations with different pressure by pollution at the city of Sheyang in southern Northeast-China, namely

a metropolitan, a suburban, and a rural area. The trees were established before 1900, and dendrochronological recordings were made for the entire twentieth century. The human population was 100,000 in the 1840s. It rose to 250,000 by 1894 and due to mass migration to 1,880,766 by 1945. Post World War II and Chinese civil war reduced it to 992,155 by 1948, after which it rose to 6,850,000 by 2000 and is now > 7,000,000. Stress to the trees by urban agriculture and industrial activities and the sheer size of urban built-up area oscillated accordingly. The temporarily complex interactions between growth sites, human population density, climatic and non-climatic impacts, required sophisticated statistical correlation analyses of the dendrochronological fingerprints in the study of Chen et al. (2011-T). The effects of urban pollution as indicated by deposits of Zn, Cu, Pb, and Cd in the tree rings were stronger than those of climate. In the period of 1955 through 1969 when the highest anthropogenic interference was recorded due to abrupt population growth, the growth rate of the trees in the Shenyang area was significantly slowed down.

Stability, sensitivity, and mortality of trees in urban environments

The stability of anchorage of trees in the urban environments is of particular concern for safety reasons, especially in geographical regions with frequent windstorms, cyclones, and hurricanes, but with global change also given by recurring extreme weather events. Mechanical stability is an essential property of healthy trees necessarily required to be known. The problem is exacerbated when there is an additional mechanical strain on trees due to construction work and establishment of underground utility lines cutting part of their root system. For different tree species planted in cities and a sufficient variety of urban conditions, research must evaluate potential dangers of tree un-anchorage for supplying data for management of accident prevention.

The approaches needed are exemplified by Ghani et al. (2009-T) in a thorough, detailed study of 20-year-old trees *Eugenia grandis* (Wight) in an urban park at Kuala Lumpur. This tree is famous as an urban landscape tree throughout the tropical climate of Malaysia. The authors have used trenching damaging the root system at distances between 0.5 and 1.5 m from the stem base and winched the trees in bending tests. They related the responses of anchorage in these tests to root architecture. The trees of *E. grandis* produce a root–soil plate with lateral roots, and there is no taproot. However, there are sinker roots clustered together underneath the tree stem, which could function like a single large taproot acting as the dominant component of anchorage. Close to the trunk, they are not damaged by trenching. The effect of trenching on the critical turning moment and on tree anchorage rotational stiffness (TARS) in the winching tests

was only small, i.e., a loss of 13% TARS, when trenching at a distance of 0.5 m from the stem had cut off the roots. Thus, the severing of lateral roots had little effect on tree stability.

Cities are complex habitats for trees with a diversity of site characteristics such as along streets, on open squares, in parks, and at urban peripheries. Independent of and in addition to pollution, these have significant consequences for tree growth. In a 2-year study, Kjelgren and Clark (1993-T) have compared trees of *Liquidambar styraciflua* L. growing in a park and on a plaza in Seattle, Washington, USA, where soil properties differed. At the plaza site, the soil had a coarser texture and a shallow depth. The pH was less acid as often in cities due to alkaline leachates. The availability of water was lower and the air warmer and drier. At this site, the trees developed higher internal moisture deficits and a lower nutritional status, particularly concerning nitrogen. Due to the higher vapor pressure deficit of the air, the plaza trees showed prolonged stomatal closure. With these problems, the trees had limited growth with lowered yearly diameter increment and canopy size. Irrigation and still more so fertilization reduced these effects of the plaza conditions. The selection of trees suited for the arid city conditions and their maintenance are essential challenges for greening the city.

Helama et al. (2012-T) have been concerned about the conspicuous mortality of Scots pine (*Pinus sylvestris* L.) around Helsinki, Finland. For understanding the reasons for death in an urban park, they have compared two classes of pine trees, dead ones at the time of their study with sampling in July 2007 that had grown between 1831 and 2006 and still living ones grown between 1850 and 2007. They have related dendrochronology and climate, or severe weather conditions as they were. There were noticeable historical long-term growth differences between the living and in the 2007 already dead pines. Summer moisture appeared to be the most important agent for mortality. Over the full period of the analysis, the 2007 dead pines had been sensitive to summer droughts significantly longer than the still living ones. The pronounced drought late in the year 2002 and in the summer of 2003 elicited the most negative growth anomaly and led to tree death.

Responses of trees to urban stresses

Pollution

Plant leaves are complex structures exposed to their surrounding atmosphere and hence directly affected by air pollution. Their anatomical structures are fundamental for leaf function and sensitivity to environmental stresses. The cuticle is shielding the interior components. By closing movements of their guard cells, the stomata in the epidermis can restrict water loss under dry conditions, minimize uptake of toxic pollutant gases, and influence photosynthetic

capacity and water-use efficiency. The spongy parenchyma serves aeration, and the palisade parenchyma concentrates photosynthetic activity. Rashidi et al. (2012-T) addressed the question of to which extent and in which way these leaf structures respond to gaseous air pollution (SO_2 , NO_2 , and O_3) and climatic factors. They have studied numerous anatomical features of leaves of black locust tree (*Robinia pseudoacacia* L.) in the urban parks of seven municipal districts of Tehran, Iran. They found that the anatomy was affected by both air pollution and climate. Among the many traits recorded, reactions to air pollution were: development of a thicker upper cuticle, increase in density of stomata, and a concomitant reduction in stomatal size. These features conferred faster reactions to guard cell movements, which led to the exclusion of gaseous pollutants, especially those displaying fluctuating concentration. The thinner spongy mesophyll layer reduced aeration from the polluted atmosphere as it has a lower resistance to gas exchange than the palisade parenchyma. An increased ratio of palisade/spongy parenchyma lowers aeration from the polluted atmosphere.

Similar relations were observed with climatic factors where warming and reduced humidity increased stomatal density and leaf and mesophyll thickness, reactions considered as characteristics in response to water stress. The relationship between responses to gaseous air pollution and climate shows the similarity of mechanisms excluding pollutant gases from the leaves and minimizing water loss.

The fine-tuning of particular biochemical pathways can be affected by pollution. *Pinus nigra* (Arnold) is considered to be a resistant species suitable for urban environments. In a study of terpene contents, Supuka et al. (1997-T) have compared trees growing in an urban environment along a thoroughfare in the city center of Nitra and in the relatively clean environment of the Mlyňany Arboretum, in the Slovak Republic. While the type of changes in terpene spectra due to pollution noted in the literature is species dependent, the intra-specific comparisons of *P. nigra* reveal delicate metabolic responses. At the polluted site, there were a smaller number of terpene substances than at the clean site, i.e., 12 and 15, respectively, and the absolute amount was lower. Overall the α -pinene content declined, and the β -pinene content increased, so that the ratio α/β was 0.86 and 2.80 at the polluted and clean site, respectively. Nothing appears to be known, however, about the response mechanism and the possible adaptive eco-physiological consequences of this specific subtle stress reaction.

Environmental stresses of heat and drought

Heat is one of the most prominent urban stress factors. In the urban areas of the north of Nara Prefecture, central Japan, from 1900 to 1980, 5-year averages of temperature oscillated between 14.1 and 14.5 °C and then there was an

abrupt steep increase to about 15.2 °C in the 2 decades of 1980–2000 due to sudden urbanization and exacerbated by global warming. Concomitantly, annual precipitation has not changed over these 100 years. Japanese cedar trees, *Cryptomeria japonica* (L. f.) D. Don, in these low altitude urban plains shows increasing top dieback and is subject to height restriction. This is explained by water stress, which due to the role of gravity, tends to be more intense at the top of trees. Thus, decrease of live crown-top heights from the ground (LCTH) is the answer to temperature causing water stress. Most interestingly, leaf water relations remain similar in the crowns in the trees at various heights. Under the temperature-induced drought stress, they are regulated by LCTH (Ueda et al. 2006-T).

The width of individual tree rings depends on the prevailing weather conditions of the corresponding years; favorable and non-favorable conditions lead to broader and narrower rings, respectively. This allows dendrochronology to assess past effects of climate on trees. With statistics of dendrochronology, one can identify so-called pointer years with exceptionally wide and narrow tree rings, i.e., positive and negative pointer years, respectively. Gillner et al. (2014-T) have used the pointer-year concept in an assessment of the performance concerning drought of five tree species over 87 years (1920–2007), namely *Acer platanoides* L., *Acer pseudoplatanus* L., *Quercus petraea* (Mattuschka) Liebl., *Quercus rubra* L. and *Platanus × hispanica* Münchh., in Dresden, Germany. The over 90-year-old trees were growing in a residential area on the sidewalk along both sides of a street in a highly sealed urban environment.

Primarily, high above-average temperature inhibited, and average and above-average precipitation stimulated radial growth, but effects were dependent on season and species. Pointer years are species specific. For the whole period of 1920–2007, the two *Quercus* species had more frequent positive pointer years, while the other three species had more frequent negative pointer years. However, *P. hispanica* had the highest number of extremely positive pointer years. Since 1975, the two *Quercus* species had a declining frequency of both positive and negative pointer years, the *Acer* species had high numbers of negative pointer years, and *P. hispanica* had the highest number of extremely positive pointer years. In summary, the two *Acer* species showed significant growth reductions in drought years, while the other three species showed a high tolerance towards water deficits. They are more suited for urban applications as they are better adapted to highly sealed urban sites with low infiltration rates and a higher drought risk as well as to predict future climate than the drought-sensitive two *Acer* species.

In another study, eight genotypes of cultivars of the three deciduous *Acer* species, *A. platanoides* L., *A. pseudoplatanus* L., and *A. campestre* L., commonly utilized as urban street trees, were compared in a tree nursery in

Cambridgeshire, UK, for evaluating their suitability for tree selection in urban applications (Banks et al. 2019-T). Stress was applied by two weeks of whole-plant tree drought in summer and by dehydration of isolated leaves in vitro. Several measurements were performed to rank drought tolerance. Foliar dehydration and water potential at the turgor-loss point, π_{lp} , indicative of the permanent wilting point, identified whole-plant drought tolerance. There was a seasonal developmental element for tolerance acclimation, and, therefore, the ranking was not constant throughout the growing season. For instance, in the genotype “Negenia” of *A. pseudoplatanus*, drought tolerance was most pronounced in spring and lowered in summer and autumn, while, of course, the drought conditions are most severe in summer. But tolerance in spring is vital for the performance over the entire season. Among the three species, *A. platanoides* was most tolerant. The genotype “Princeton Gold” was more dehydration tolerant in the leaf tests while “Drummondii” having variegated leaves was more tolerant in the whole-tree drought tests.

Biotic stress by wood-decay fungi

Infection by wood-decay fungi can be increasingly hazardous for trees in cities because urban stresses reduce resistance. On the 8th of September 2004, a typhoon caused windthrow of many trees of Japanese elm in the city of Sapporo, Hokkaido Island, Japan. The elm, *Ulmus davidiana* var. *japonica* (Rehd.) Nakai, is the dominant tree in the urban green area of Sapporo. Fukui et al. (2018-T) have sampled several wood-decay fungi in the fallen trees after the typhoon, identified them mainly based on DNA-sequence data and provided an overview. The common fungus was *Polyporus squamosus* Fr. It causes white rot, hollowing big stems during many years of growth after infection. In the typhoon, the average failure height of elm in the windthrow was 6.4 m. Species compositions of wood-decay fungi are different in natural and urban environments. The infection of the trees in Sapporo is thought to have been accelerated by the rapid urbanization rate of the area. In 1886, the population size and urbanized areas were 15,000 people and 14 km², respectively. Urbanization speed increased after 1950, and the numbers reached 1,900,000 people and 1,121 km², respectively, in 2018. The wood decay in the trees spreads as they age, increasing the danger of trees falling. The fungus *P. squamosus* penetrates not through the roots but via wounds of the stem, including pruning cuts. Therefore, the timing of pruning is essential. It should be avoided in early summer and autumn when fungal fruit bodies are developed, and basidiospores are spread.

Urban mycorrhiza

Ectomycorrhiza, the symbiosis of trees with fungi for the supply of water and minerals to the trees and photosynthetic products to the fungi, was studied by Alzetta et al. (2012-T) in Padova, Italy, with linden trees (*Tilia vulgaris* Hayne). Linden is a favorite tree in this urban environment, with more than 3000 planted individuals. Studies with trees which were already 50 years old were performed at two sites, a roadside and a park-side or town-garden site. Two classes of decline of tree vitality were compared, i.e., moderately and strongly declining at the road site and moderately declining at the garden site, where the sharply declining class did not occur. The study provides a comprehensive census of 52 ectomycorrhizae as well as detailed soil analyses. The root tips were classified as non-vital (NV), vital non-mycorrhized (NM), and vital ectomycorrhized (ECM).

There were no differences among the trees at the same site and for the same decline class. The root tip vitality and ectomycorrhization degree did not differ between the different decline classes. Sites only differed in NM. The roadside site had more NM root tips (0.3%) than the park-side site (0.02%). However, both values were very low, so that root tips appear to have more chances to remain vital when ectomycorrhized. Colonization was generally low, presumably because of a low inoculum potential of the urban soil. Urban soils, classified as technosoils, are short of organic matter and provide inadequate nitrogen reserves. For most of the various chemical and physical soil qualities analyzed, the town-garden site had higher values. The measured variables, i.e., the different soil properties as characteristic of sites and decline classes, had pronounced effects on the species composition of the ectomycorrhizal community. Variation of soil properties as a whole may be responsible, where cation-exchange capacity, permanent wilting point, and available water appeared to be the most critical parameters.

Management

An essential basis of urban-tree management is the modeling of urban-tree growth and ecosystem services (Fukui et al. 2020). This can quantify the ecosystem services for assessment of the benefits of tree planting in cities by approaches of allometry. It depicts the dimensional development of major tree compartments, such as diameter at breast height (dbh), height, and crown dimensions.

In management, it is essential to assess the risk of stem failure to avoid unforeseen damages and injuries of property and people. One way of tree-stability assessment is non-invasive acoustic tomography of standing trees. It allows localization of structural effects inside tree trunks due to decomposition of heartwood and sapwood by decay fungi. It also shows cracks, ring shake, and hollows. Ostrovský

et al. (2017-T) have tested the results of acoustic tomography in comparison to visual inspection in five tree species of an urban environment in the city of Nitra, in the Slovak Republic, namely *Acer platanoides* L., *Castanea sativa* Mill., *Juniperus virginiana* L., *Cerasus serrulata* (Lindl.) G. Don, *Thuja plicata* D. Don ex Lamb. For the comparison, thick stem disks were cut from the trees. Visual inspection showed extensive damage in all disks, which was remarkably reproduced by the tomography, the precision of which in the various examples of disks is evaluated in the article.

An example of potential management practices is mitigation of water stress at the dry urban sites. Because of sealing and soil compaction, moderate soil water stress is a significant and most frequent stress of trees in the urban habitats. Effective management is important. A study by Kagotani et al. (2016-T) aimed at assessing the potential of irrigation and mulching managements. *Ginkgo biloba* L. and *Prunus yedoensis* Matsum. are favorite species as roadside trees in Japan. The authors evaluated 4-year- and 3-year-old trees maintained in containers under controlled conditions mimicking the climate of Kyoto. They tested irrigation and organic mulching with shredded pruned material from the landscape trees. Mulching reduced soil evaporation. Mulching and irrigation enhanced soil water content by 18–20 and 63–70%, respectively. In summer but not in the rainy season, both treatments increased photosynthetic carbon assimilation at saturating photosynthetic photon flux density (PPFD) of $1500 \mu\text{mol m}^{-2} \text{s}^{-1}$ (A_{sat}) and stomatal conductance (g_s) in both species. The effects were more pronounced in *G. biloba* than in *P. yedoensis*. In *G. biloba*, g_s was small and decreased in response to high temperature and vapor pressure deficit of the air (VPD). The effective stomatal control helped to maintain turgor under a wide range of soil water contents.

In comparison to this conserved water use of *G. biloba*, *P. yedoensis* was more opportunistic and long-term water-use efficiency (WUE) decreased. The photosynthetic machinery in *G. biloba* was more suited to severe water stress than in *P. yedoensis*. As a result, *G. biloba* displayed a higher drought resistance than *P. yedoensis*.

The selection of tree species concerning their tolerance of the dry urban environment together with the management methods helps to support urban tree planting. However, many variables have to be considered and some key points are relevant regarding the choice and management of urban tree populations: (1) species behave differently according to the region where the city is located; (2) the physiological behavior and structural features may change in a given species when it is grown in a urban area in comparison with its natural habitat; (3) some species are able to develop in many different regions of the world and work well as exotic urban trees; (4) native species to the region where the city is located may not tolerate urban conditions; (5) increasing biodiversity of trees may be an option, especially in the tropical cities. However, this can make management very complicated and elevate its cost.

Understanding how stress factors interact, affecting tree health and longevity in urban areas is quite relevant since an increase in longevity will decrease management costs. By knowing longevity features and understanding what diseases might be opportunistic and take advantage of stress conditions, one can design procedures of “urban tree care” that could minimize stress effects, increasing longevity and avoiding tree fall.

Outlook

The aesthetic appeal of urban tree greenery is an enormous cultural value. It radiates human sensation and may contribute to safety and well-being of life in cities. Indeed it has been reported that urban trees decrease the levels of depression and stress (for example Beyer et al. 2014). Urban trees are vividly embedded because they both are passively subject to urban environmental impacts and actively mitigate these pressures. With a suitable selection of tree species for planting in cities, urban biodiversity can build up and can contribute to biological richness.

In relative terms, urbanization in the period from 2001 to 2015 played a minor role in the loss of global forest area due to various types of disturbance. However, in absolute terms, the forest area lost by urbanization in considerable (Table 1). As a counterbalance appropriate management,

Table 1 Global disturbance and loss of forest area in the period of 2001–2015. Data from Curtis et al. (2018)

Dominant disturbance type	Qualification	Contribution to total disturbance (%)	Area (Mha)
Total		100	314
Deforestation	Development (agriculture including oil palms, mining, and energy infrastructure)	27 ± 5	84
Forestry	Managed forests and tree plantations	26 ± 4	81
Shifting agriculture	Forest conversion for agriculture	24 ± 3	75
Wild fire	Burning of forest vegetation	23 ± 4	72
Urbanization	Forest conversion for development of urban centers	0.6 ± 0.3	2

especially controlling drought effects and mechanical stability and anchorage, can make cities useful habitats for trees. This requires continued intensive research, as exemplified by the articles summarized above, for understanding the role of structure and function of trees under the challenge of urbanization and for providing hand-outs to urban planners.

Nevertheless, although presenting data for a rather small number of cities, Fig. 1 shows that the inequality regarding the benefits of urban trees to human populations seems to increase with city size and with population density. In São Paulo, for instance, such “green inequality” of tree cover has been shown (Buckeridge, 2015). Although the production of certain environmental services, such as water production by evapotranspiration would be more democratic, depending on local climate conditions, tree cover in some of the largest cities in the world may not be able to provide the environmental services necessary to adapt urban areas to the effects of global warming.

Authors contribution statement UL and MB wrote the paper.

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