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SPECIAL SECTION

THE URBAN FOREST AND ECOSYSTEM SERVICES

The Urban Forest and Ecosystem Services: Impacts on Urban Water, Heat, and Pollution Cycles at the Tree, Street, and City Scale

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Abstract

Many environmental challenges are exacerbated within the urban landscape, such as stormwater runoff and flood risk, chemical and particulate pollution of urban air, soil and water, the urban heat island, and summer heat waves. Urban trees, and the urban forest as a whole, can be managed to have an impact on the urban water, heat, carbon and pollution cycles. However, there is an increasing need for empirical evidence as to the magnitude of the impacts, both beneficial and adverse, that urban trees can provide and the role that climatic region and built landscape circumstance play in modifying those impacts. This special section presents new research that advances our knowledge of the ecological and environmental services provided by the urban forest. The 14 studies included provide a global perspective on the role of trees in towns and cities from five continents. Some studies provide evidence for the cooling benefit of the local microclimate in urban green space with and without trees. Other studies focus solely on the cooling benefit of urban tree transpiration at a mesoscale or on cooling from canopy shade at a street and pedestrian scale. Other studies are concerned with tree species differences in canopy interception of rainfall, water uptake from biofilter systems, and water quality improvements through nutrient uptake from stormwater runoff. Research reported here also considers both the positive and the negative impacts of trees on air quality, through the role of trees in removing air pollutants such as ozone as well as in releasing potentially harmful volatile organic compounds and allergenic particulates. A transdisciplinary framework to support future urban forest research is proposed to better understand and communicate the role of urban trees in urban biogeochemical cycles that are highly disturbed, highly managed, and of paramount importance to human health and well-being.

Core Ideas

- The urban forest can be managed to impact the urban water, heat, carbon, and pollution cycles.
- An evidence base is needed for the ecosystem service benefit urban trees can provide.
- This special section presents 14 studies from five continents on the ecosystem service impact of urban trees.

Over recent decades, research has shown that urban trees are integral to the environmental quality of cities and towns around the world (Bolund and Hunhammar, 1999; Dwyer et al., 1991). Our understanding of the relationships between urban forest structure and function has developed and led to a more complete picture of how these complex systems operate (McPherson et al., 1997). As such, urban forest managers are better equipped to argue their case and promote the roles of trees and green spaces for addressing the problems that confront our urban centers. Contributing to this is a growing awareness of the intrinsic and monetary value of the ecosystem services that the urban forest can provide, such as energy conservation, carbon storage, reduced stormwater runoff, improved air quality, and enhanced human health and well-being (Brack, 2002; Escobedo et al., 2011; Escobedo and Nowak, 2009; Livesley et al., 2014; McPherson et al., 2011). This special section presents new empirical evidence that will assist in selecting, planning and managing our urban forests for target ecosystem services, whilst minimizing any associated disservices.

Urban Policy Makers, Planners, and Managers Need an Urban Forest "Evidence Base"

Many environmental or "biogeochemical" challenges exist within the urban landscape. Some key challenges revolve around the management of:

- urban catchment hydrology and stormwater runoff,
- chemical and particulate pollution of urban air, soil and water,
- carbon sequestration, and
- the urban heat island and enhanced summer heat waves.

These environmental challenges can adversely affect human health and well-being and can be costly to mitigate. The arduous growing conditions that face urban forests can in some ways be seen as analogous to those facing urban dwellers in the midst of global climate change (Calfapietra et al., 2015). As such,

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Abbreviations: BVOC, biogenic volatile organic compound; WSUD, water sensitive urban design.

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understanding the role of vegetation, the physiological response of urban vegetation to these environmental conditions, and especially the management of the urban forest in addressing these challenges can be highly informative.

Urban stormwater runoff and flash flooding occur when impervious surface cover increases with continued urbanization (Walsh et al., 2012) and may be a growing problem as the frequency of extreme rainfall events increases with climate change (Wissmar et al., 2004). Increasing the capacity of urban stormwater discharge systems is difficult because of scale, disturbance, and cost. This presents a challenge to conventional urban water resource management and requires new ways of thinking about retaining, retarding, and using stormwater within the urban landscape—water sensitive urban design (WSUD). Urban trees in pervious spaces, or engineered WSUD systems, have a role to play in rethinking how we manage urban catchment hydrology (Fig. 1).

Urbanized catchments can also experience greater nitrate, phosphate, sulfate, carbon, and heavy metal pollution in waterways as compared to undeveloped catchments (Bernhardt et al., 2008; Kaushal and Belt, 2012). Urban tree and soil systems could play a significant role in reducing nutrient pollution concentrations in urban catchment run-off. Similarly, urban areas are often hot spots for atmospheric pollution from mobile and stationary sources (Garty et al., 1996; Johnson et al., 1982; Sawidis et al., 2011). Trees have long been recognized as one

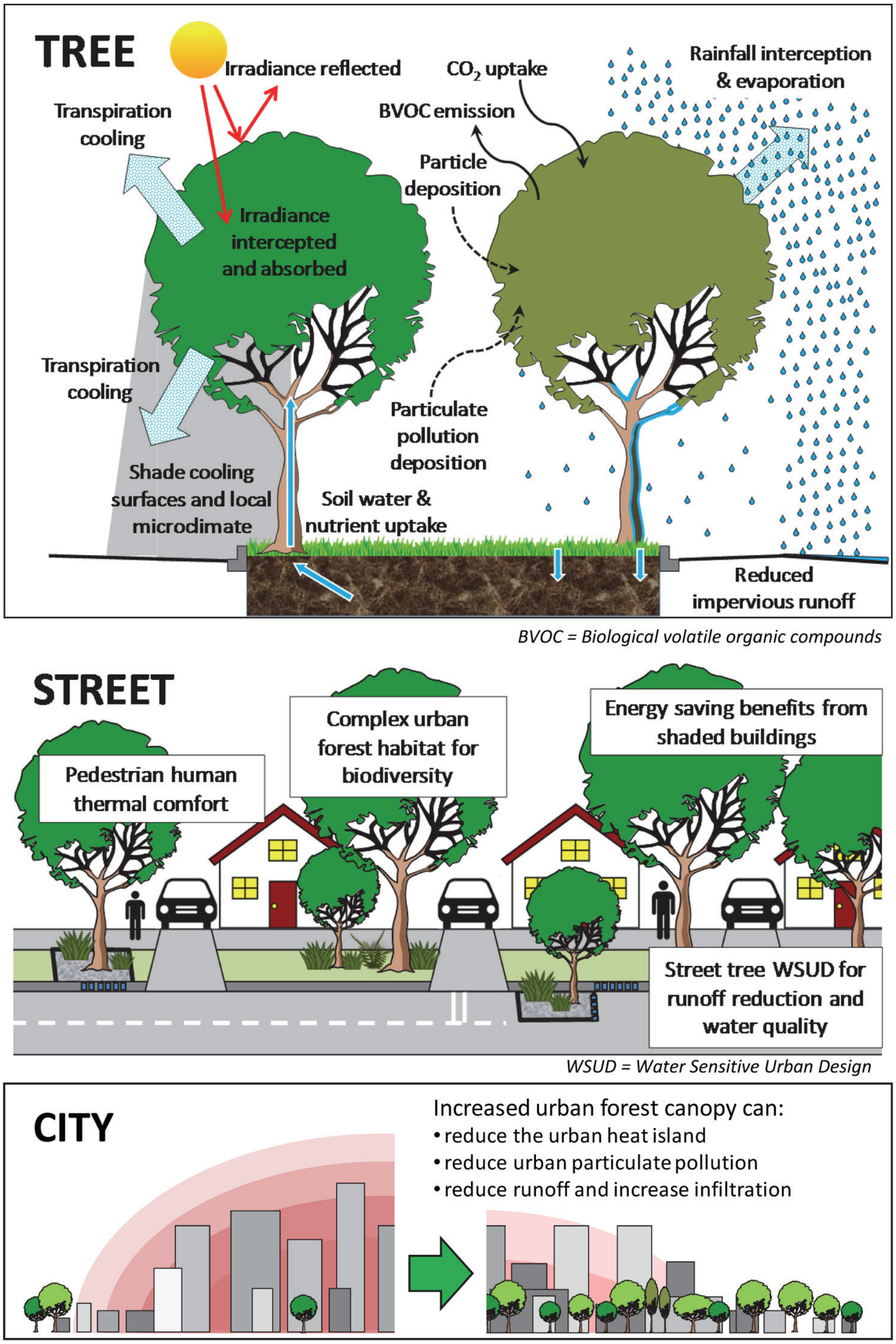

Fig. 1. Urban forest ecosystem service and function: at the tree, street, and city scale.

way to reduce concentrations of gaseous and particulate pollutants (Dochinger, 1980; Nowak et al., 2006) (Fig. 1). At the same time, the role of certain species of trees that emit volatile organic compounds on ozone formation remains a research focus, particularly in urban areas (Calfapietra et al., 2013; Chameides et al., 1992; Nowak et al., 2006). Besides the role in air pollutant uptake, urban green infrastructure and particularly the tree component can highly influence the carbon sequestration capacity in the urban areas (Edmondson et al., 2012; Pataki et al., 2006). Numerous large-scale tree planting programs exist, particularly in developed countries, that demonstrate the importance of urban forests as cities strive to implement carbon neutral policies.

Another serious environmental and human health challenge facing our urban centers is the nexus between the urban heat island, summer heat waves, and a gradually warming global climate (Hamin and Gurran, 2009; McGeehin and Mirabelli, 2001). Green infrastructure, defined as vegetation systems intentionally designed to promote environmental quality, can reduce the intensity of heat islands by providing shade and evapotranspirational cooling. Urban trees are perhaps the most effective and least costly approach to urban heat island mitigation and adaptation (Norton et al., 2015; Solecki et al., 2005) (Fig. 1).

As awareness of the potential benefits that urban forests deliver grows, there is increasing need for empirical evidence to answer the questions of "how beneficial" and "under what circumstances." Stricter financial standards demand that the services delivered by urban forestry projects are real and quantifiable. To support decision making, research is needed that describes and quantifies the many biogeochemical processes and functions that urban forests provide. This special section presents new research that advances our knowledge on the ecological and environmental services provided by the urban forest. The studies presented herein explain how urban trees can be planned and managed to maximize these ecosystem services in towns and cities. A real strength of this special section is the truly global evidence base provided by these 14 studies from four continents (North America, Europe, Asia, and Australia) (Fig. 2). It should be recognized that urban trees will not be valued for the same ecosystem services in all towns and cities, as each urban center presents its own topographical, climatic, cultural, and industrial context. However, judiciously planned and managed urban forests can improve urban ecosystem function in all climates, sociocultural circumstances, and biogeographical locations. This special section contains new knowledge that will help those trying to plan and manage the "right" urban forest, in the "right" way, to obtain the desired ecosystem services while minimizing disservices.

The Urban Forest, Green Spaces, and the Urban Heat Island

The urban heat island is very real phenomenon that confronts people living in towns and cities with increased exposure to heat stress and potential heat stroke, as well as increased energy use for building space cooling. Sugawara et al. (2016) describe the cooling benefit of a large park in the hot urban environment of Tokyo, Japan. Under calm wind conditions, the cooling benefit of a large park generally extended 200 m downwind into surrounding residential areas, and provided a cooling benefit equivalent to 39 W m^{-2}. Jaganmohan et al. (2016) demonstrate that the cooling benefit of an urban green space is significantly greater when forested than if managed as more open parkland. Furthermore, the cooling effect is influenced more by the size of the forested area than its shape. As such, Jaganmohan et al. (2016) suggest that urban planning for heat island mitigation may not work along the same lines as urban planning for environmental justice, where equal access and proximity are desired. Many small treed urban green spaces will not provide the same magnitude of cooling as fewer, but larger, treed urban green spaces.

Fig. 2. Global urban forest studies presented in this special section.

Knowledge of the effects of tree shade on urban surface heat (radiation) exchange is fundamental to understanding the effectiveness of urban forest strategies aimed at the urban heat island mitigation (Oke, 1988). Napoli et al. (2016) measured surface temperature reductions in the shade of 10 different tree species and in sunny conditions. They measured both asphalt and grass surfaces under a range of climatic conditions to test the performance of a one-dimensional heat transfer model. On asphalt, surface temperature in shade was negatively related to the leaf area index of trees (ranging from 13.8 to 22.8°C), whereas on turfgrass, the relationship was weaker (ranging from 6.9 to 9.4°C) probably because of the confounding effect of evapotranspiration from grass.

Understanding the role of evapotranspiration from trees on the urban heat balance is also central to understanding the potential of urban forest strategies to mitigate heat island effects. Through the development of a sophisticated climatic and physiological model, Ballinas and Barradas (2016) reveal that individual trees can provide profound cooling benefits from daily evapotranspiration. The four species studied ranged in average optimal water use from 3.64 to 4.35 L d^{-1}. Their model predicts that evapotranspiration can reduce urban air temperature by 1°C in Mexico City. However, the number of trees needed to achieve a 1°C reduction in daytime air temperature depends on the tree species, as 63 mature *Eucalyptus camaldulensis* trees per hectare are required to produce the same effect as 24 *Liquidambar styraciflua* trees. Although establishing a mature urban forest stand with such a high tree stem density may be difficult in dense urban areas, this study does show that attention must be given to species selection and water supply when urban heat island mitigation is a primary ecosystem service desired from an urban forest.

The Role of Urban Trees in Human Thermal Comfort

Sanusi et al. (2016) present evidence as to the likely microclimate cooling and human thermal comfort benefits that can be expected from well-developed street tree canopies. Many urban forest strategies target an increase in tree canopy cover over time and state that this will lead to an expected decrease in overall urban air temperature, based on climate models (Solecki et al., 2005) and not direct empirical evidence. Sanusi et al. (2016) compare similar residential streets in Melbourne, Australia, that have very low (<20%) and very high (up to 80%) canopy cover from *Platanus acerifolia* (London planetree). On the warmest summer days, there was an air temperature reduction of 2.1°C in east-west oriented streets and 0.9°C in north-south oriented streets. Sjöman et al. (2016) investigated the urban microclimate (temperature and wind) impacts of deciduous trees when they are "out-of-leaf" in winter. Branch area index was significantly different among species, ranging between 0.27 (*Gingko biloba*) and 2.09 (*Pinus strobus*). The ENVI-met 3.1 climate model was used to simulate the microclimate impacts of these bare trees in complex urban settings. Wind speed and mean radiant temperature decreases were reported on the tree leeward side of bare trees. Sheltering effects were more pronounced as tree branch area index increased. These findings are of interest to planners trying to improve summer and winter human thermal comfort in densely built up urban environments where tree planting space is restricted.

The Role of Trees in Urban Catchment Hydrology

Tree crowns and the urban forest as a whole have important roles throughout the hydrological cycle. Tree crowns intercept rain and reduce the amount of water reaching the pervious or impervious surfaces below. Xiao and McPherson (2016) provide a comparative study of one aspect of tree crowns that influence interception, surface water storage capacity. The depth of this film of rainwater stored on crown surfaces was measured for 20 different tree species using a novel rainfall simulator and load-cell balance system. A threefold variation among tree species was found: from 0.6 mm on *Lagerstroemia indica* to 1.8 mm for the needle leaf evergreen *Picea pungens*. Simulation modeling over 40 yr indicates that for most rainfall intensities, an event duration exceeding 30 min invariably exceeded the storage capacity of even large trees—valuable new information on the role of an urban forest in stormwater runoff reduction.

Once rainfall reaches an impervious surface and becomes runoff, some of it can be directed into WSUD systems to reduce, retard, and retain stormwater from entering the drainage system and urban waterways. Including trees in WSUD systems can increase the return of runoff to the atmosphere through transpiration, providing associated air cooling benefits. Scharenbroch et al. (2016) provide evidence that trees in bioswales can be responsible for between 46 and 72% of total water use by these systems, thereby greatly reducing runoff and discharge from impervious urban catchments. They point out, however, that not all tree species are equally suited to growth and performance in WSUD systems. Tree species with high stomatal conductance and the capacity to grow well under fluctuating saturated and dry conditions are likely to perform best.

The Role of Trees in Urban Soil and Water Pollution

Urban runoff, streams, and waterways frequently experience pollution. The capacity of urban trees to remove nutrient pollutants and some heavy metals from stormwater can be better exploited to provide water quality and pollution reduction benefits. Denman et al. (2016) provide evidence for this in an elegant WSUD mesocosm study with four common urban tree species. Trees were able to reduce oxidized nitrogen and reactive phosphorus in comparison to unplanted controls. There were no significant differences among the four tree species in their ability to reduce stormwater nutrient pollution, but Denman et al. (2016) suggest that future research should target the most promising tree species based on their traits.

Turfed green spaces within towns and cities often receive large inputs of inorganic and organic fertilizers. In fact, urban turfgrass is the largest irrigated and fertilized crop in North America (Milesi et al., 2005). As such, there is potential for excess nutrients to pass through the soil and into urban waterways or groundwater resources. Livesley et al. (2016) present evidence that areas of urban green space planted with trees and understory can develop relatively high soil C/N ratios that can improve nutrient buffering capacity. Given this finding, a simple pollution prevention strategy involves establishing urban woodland or forest areas that border waterways or "higher-risk" areas and that receive inorganic nutrient fertilizers.

The Urban Forest and Air Pollution

Atmospheric pollution is a concern from an environmental and human health perspective. The urban forest can provide pollution reduction benefits, but certain urban tree species can also contribute to the problem. Some species emit biogenic volatile organic compounds (BVOCs) that can act as a precursor to smog or ozone formation, particularly when NO_x is present and climatic conditions are conducive (Chameides et al., 1992; Calfapietra et al., 2013). Ozone represents a harmful pollutant in the urban atmosphere, promoted by warm climates and precursor pollutants from anthropogenic and natural sources. The urban forest often contains some tree species that are a source of ozone precursors (Dunn-Johnston et al., 2016), but at the same time it can also contribute to the ozone removal from the atmosphere (Calfapietra et al., 2016). Laboratory experiments, field measures, and modeling all have roles in better understanding, predicting, and managing the ozone reduction potential of the urban forest (Calfapietra et al., 2016). Dunn-Johnston et al. (2016) examined isoprene emissions from tree species in a subtropical city. They note that some species are high emitters of BVOCs, often defined as major "disservices" to the urban landscape (Pataki et al., 2011). However, some commonly accepted isoprene emission factors for urban tree species are overestimated. This new knowledge will help managers select tree species or genotypes that provide the greatest air quality benefits and demonstrates the need to determine species-specific BVOC emission factors for locally important urban tree species.

Another ecosystem disservice that certain urban trees may provide is the release of allergenic pollen, which can have an adverse impact on the health of people who are most susceptible (Cariñanos et al., 2016). An increasing proportion of the urban population is susceptible and allergic to tree-derived pollen.

Therefore, identifying tree species that are most responsible for allergic reactions is important. Cariñanos et al. (2016) present a practical allergenic index based on factors such as the period of pollen emission and allergenic intensity. Application of this index can help urban forest managers improve human health and well-being by making good choices when selecting and removing different tree species. This paper reminds us that research regarding ecosystem services and disservices provided by the urban forest needs to be translated into robust and practical tools for changes in policy, planning, and management.

The impact of trees on urban air quality is not all bad. Park and Schade (2016) demonstrate that tree photosynthesis in urban green space was able to offset a fraction of the CO_2 emitted from traffic combustion engines, and ecosystem respiration in Houston, TX. This study provides evidence of a strong correlation between the urban CO_2 emission rates in spring and summer as measured by eddy covariance and the photosynthetically active radiation on the same days.

A Transdisciplinary Framework for Future Urban Forest Research

The studies presented in this special section contribute to a growing evidence base that supports the need for better urban forest management, recognition, and valuation. However, it is apparent from many of the studies that to do this comprehensively so as to make a real change in urban planning and policy, it is necessary to take a more transdisciplinary approach to urban forest research. For example, there is a clear nexus between managing our urban forest for improved ecosystem service while at the same time managing the urban landscape for improved catchment hydrology. This is reinforced by many of the studies presented herein. To this end, future urban ecosystem research should strive for, and facilitate, greater integration and collaboration between relevant disciplines such as water infrastructure engineering, urban forest science, and urban planning. Whether a city is in a high rainfall, flood risk climate or in a low rainfall, hot, arid landscape, the nexus between the urban forest, green space and catchment hydrology remains central to planning, designing, and managing an urban landscape for future challenges. In a similar vein, for urban forest science to help address public health issues such as heat exposure, allergens, air pollution, and respiratory health, there is the need for collaboration between epidemiology, environmental monitoring agencies, urban climatology, urban forest science, water engineering, and urban planning.

The urban forest can play a significant role in making our towns and cities more livable and better adapted to the rigors we expect from a changing climate. But to do this, and to make it a policy, planning, and pubic reality, urban forest research needs to embrace transdisciplinary approaches and find ways to better communicate the scientific evidence to a nonscientific audience.

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