Urban Forests: Biophysical Features and Benefits

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Abstract

Urban forests are all the trees, forests, associated vegetation growing in or very near the cities, towns, and communities where people live, work, and play. What makes urban forests different from forests outside urban areas is their existence in dense areas of human settlement—cities, towns, suburbs, etc. What qualifies as urban from the standpoint of urban forestry includes a range of population sizes or densities (parallel to the Ellis et al. (2010) mapping of anthropogenic biomes, or anthromes, to human population densities): There is no minimum threshold for how many people must live in a community for it to have an urban forest, and the term urban forestry is applied to the management of populations of trees in communities of all sizes. This article discusses the definitions of urban, urban forests, and urban forestry, describes the biophysical characteristics of urban forests and what makes urban forests different from non-urban forests, and details the ecosystem services and disservices provided by urban forests.

Urban Forests and Urban Forestry

Urban forests are all the trees, forests, and associated vegetation and ecosystem components growing in or very near the cities, towns, and communities where people live, work, and play. These "dense settlements"—inclusive of large urban areas and their suburbs, but also towns, etc.—are one of the levels of anthropogenic biomes, or "anthromes," that has the highest human population density and intensity of impact (Ellis et al., 2010), and urban forests can help mitigate negative impacts. Urban forests can include trees planted in many different types of growing spaces: in the parkways (i.e., boulevards, tree lawns) along streets and next to sidewalks in cities (called "*street trees*"); in public parks or cemeteries; trees in front or back yards (i.e., private gardens) on residential property; on institutional properties such as school or hospital campuses or business or industrial parks; along highways; growing spontaneously in vacant lots and along alleys; trees in remnant natural areas or planted woodlands; and more (Fig. 1). Because they are co-located in places inhabited by people, urban forests include not only the trees and soil and other abiotic and biotic features in the surrounding growing environment, but also the people living in cities who impact the urban forest.

The science and practice of planting, maintaining, monitoring, and managing the populations of trees in urban areas in order to ensure the provision of the benefits these trees and forest produce for people is called "*urban forestry*." Urban forestry—sometimes also called "urban forest management"—consists of a suite of activities, including but not limited to planting, maintaining (pruning, watering, mulching, staking, etc.), and removing trees, but also tree inventory, pest monitoring and plant health care, tree risk assessment, planning for future tree planting and management, and even educating the general public on the benefits and care of trees and advocating on behalf of the urban forest. Performed under ideal circumstances—that is, when experienced urban forest managers have access to complete data on their urban forest, as well as adequate time, labor, and sufficient monetary and quality material resources—urban forest management ensures the net benefits provided by the entire urban forest are maximized (see the section below on "The Benefits and Values of Urban Forests"). Urban forestry is closely connected to the field of *arboriculture*, or the "practice and study of the care of trees and other woody plants in the landscape" (ISA, 2019). Whereas urban forestry deals with entire populations of trees in cities, arboriculture is more often concerned with the care and maintenance of single trees.

In the sections that follow, I describe the biophysical aspects of urban forests, what makes urban forest different from non-urban forests, and the ecosystem services and disservices provided by urban forests.

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Fig. 1 The many types of trees in the urban forest. All photos taken by the author.

Biophysical Aspects of Urban Forests

What Is "Urban"?

What makes urban forests distinctly different from forests outside urban areas is their existence in areas of human settlement. In the anthromes terminology, this includes "dense settlements" (urban and mixed settlements) and populated "seminatural lands" such as residential woodlands and populated woodlands (Ellis et al., 2010). In order to understand urban forests as a central component of these anthromes, it is crucial to understand what "urban" means in this context. What is considered urban for the sake of urban forests varies around the world and even from community to community within a single country, but generally means the communities where people live. Sometimes, the term "urban" is defined by the number of people living in a community or population center, sometimes also with respect to the density of people living in an area. For instance, the US Census Bureau defines the term "urbanized areas" as those having 50,000 or more people, while "urban clusters" have between 2500 and 50,000 people; "rural," then, is a term inclusive of all areas that do not qualify as urban (US Census Bureau, 2018). This definition of urban is not consistent across the entire world, or even all of North America: Statistics Canada, responsible for the Canadian census, for instance, defines urban as all population centers of greater than 1000 people with a density of greater 400 people per square kilometer (1036 people per square mile) (Statistics Canada, 2017). And in Africa, for example, urban definitions range considerably—containing more than 2000 inhabitants (Ethiopia, Kenya), more than 5000 inhabitants (Zambia), or more than 10,000 inhabitants (Senegal)—or, in Algeria, are defined instead by the number of "constructions" (100+, spaced 200 m or less apart; United Nations Statistics Division, 2011, as summarized in Francis and Chadwick, 2013).

What qualifies as urban from the standpoint of urban forestry can actually include a range of population sizes or densities. Generally, there is no minimum threshold for how many people must live in a community for the it to have an urban forest, and the term urban forestry is applied to the management of populations of trees in communities of all sizes. Because of this, sometimes the term "community forestry" is preferred by smaller towns for which the term "urban" may not resonate. The US Forest Service, for instance, uses the phrase "urban and community forestry" to refer to the program within the Forest Service that administers to urban forests. However, "community forestry" and "urban forestry" are not interchangeable in all parts of the world. In Canada for instance, "community forestry" refers to communities that have a significant economic dependency on forest resources and the forestry industry (i.e., forest-dependent communities; Duinker et al., 1994). In Europe also, the term "community forestry" was also initially linked not to modern concepts of "urban forestry" but instead to heritage woodlands in smaller towns or more rural areas that are managed by the local community (Konijnendijk et al., 2006).

Urban Forest Characteristics

Most readers will be more familiar with the idea of a "forest" than with an "urban forest," despite the fact that more than 50% of the global population lives in some type of city or town, and 29% live in so-called urban anthromes (Ellis et al., 2010). City dwellers may experience the urban forest on a more regular basis than "natural" forests outside cities. Urban forests differ from non-urban forests in several essential ways. First, the image of a "forest" may conjure expansive stands of trees, shrubs, and other vegetation with a closed canopy of leaves overhead letting little light through to the forest floor, which may be dense with leaf litter and ground vegetation. Some parts of the urban forest may look similar to non-urban forests, for instance, if there are remnant patches of native forest that have been enclosed by urban development and set aside as parks, nature preserves, or backyard woodlands. There may also be areas of planted (non-remnant) forest within a city that share this more traditional forested character. Whether planted or remnant, these areas are sometimes called urban forest natural areas, naturalized areas, forest patches, urban woodlands or woodlots, or forested parks. These areas likely include more than just trees, but also shrubs and herbs as ground cover, and depending on quality, may contain habitat for urban wildlife including small mammals, insects, and birds. Urban forest natural areas may abut bodies of water that are near or within urban areas, such as streams, rivers, ponds, lakes, or canals. The growing conditions for trees in these types of areas are more likely to mimic those for trees in natural areas outside of cities, and the soils, hydrology, nutrient flows, microclimate, and ecology may be more similar to natural areas.

However, urban forests also include trees growing outside of more natural or naturalized areas within cities—in parks, the front or back yards of residential properties, along streets, etc. These types of growing conditions are much different from the semi-natural conditions of urban forest natural areas. Both above and belowground growing space may be more constrained, especially for trees highly constructed spaces. For instance, trees growing in a tree pit are especially constrained: tree pits are small growing spaces with perhaps only a couple square meters of growing substrate (soil, sometimes mixed with gravel or other medium), often found along streets, in plazas, parking lots. The base of a tree in a tree pit is likely surrounded on all four sides by concrete paving impervious to water, and the area immediately adjacent to the tree trunk may be covered with a metal grate that, if not properly sized, may interfere with the root flare and healthy trunk growth. Belowground, tree roots must compete with urban infrastructure such as buried power and cable lines, storm and sanitary sewer pipes, gas lines, building and road foundations, etc., not to mention cope with high levels of soil compaction, soil nutrient imbalance, and inadequate soil drainage (or conversely, poor water retention). Aboveground, these trees may be heavily pruned so that they do not interfere with urban infrastructure such as buildings, fences, signage, street lights, above ground power and cable lines, etc., or may have limited exposure to light due to shading by tall urban buildings. Because of this suite of constraints, trees in constrained urban areas may be in poor condition, of small size and sub-optimal form, and experience high mortality rates and short life spans.

Yet other trees in some urban spaces may experience more favorable growing conditions. For instance, trees in high-quality urban parks may have relatively unlimited growing space, be well-cared for (through regular pruning and watering, pest management, etc.), and even may have access to additional nutrients (either through direct fertilizing of the tree, or as a byproduct of fertilizing the nearby turf grass). They may be growing in a wide-open area free of competition with other trees or other urban infrastructure. These high-quality growing conditions may lead to long-lived trees that grow large and provide significant benefits.

The Benefits and Values of Urban Forests—Ecosystem Services

Urban forests are important for cities because trees provide benefits that have substantial value for the people who live in those cities. This section will discuss how urban forests produce benefits, how these benefits are valued, and how this value is calculated.

Structure, Function, Benefits, and Value

The mechanism through which urban trees and forests provide value to people can be conceptualized as the structure-function-benefits relationship (Fig. 2). The structural characteristics of urban trees—such as tree size, species, etc.—and urban forests—such as the extent of urban tree canopy cover across all or a portion of an urban area—contribute to the ecosystem functions provided by those trees and forests. Trees and forests, whether in urban or non-urban areas, perform a variety of ecosystem functions, including regulating functions such as climate management through shading and evapotranspiration; biodiversity functions such as providing nesting habitat for urban wildlife; production functions such as producing edible fruits and nuts; and "information functions" (c.f., de Groot et al., 2002) such as the aesthetic and scientific opportunities afforded by the existence of urban trees (Table 1). These ecosystem functions, when viewed through an anthropocentric lens, translate into benefits and value for people, often termed ecosystem services. (In urban forestry, "benefits" is often used synonymously with "ecosystem services". In the broader ecosystem services literature, *ecosystem services* are "the benefits humans obtain from ecosystems" (Millennium Ecosystem Assessment, 2005, p. v). However, urban forest discourses more frequently use the more general "benefits" term in both the scholarly literature as well as in communications with the general public.) For instance, the water regulating functions of trees benefit people when trees are used as part of green infrastructure-based solutions for managing stormwater in urban areas.

Urban forest structure and function are biocentric ways of conceptualizing the importance of the urban forest. *Biocentric*, in this context, refers to the intrinsic value of trees and forests—that is, nature for nature's sake; the urban forest will have these functions regardless of what if any value humans place on them. All of the functions listed in Table 1 (with the exception of information functions) can be considered biocentric. Urban forest benefits and value, on the other hand, are anthropocentric concepts. *Anthropocentric* refers to the value of trees and forests explicitly for human benefit and use; that is, the functions of urban forests would have no benefits or value without that which humans place on them. Urban forestry and urban forest management are mostly anthropocentric, which makes sense given the explicit consideration of urban forests as trees located in the places where people live and work.

The structure-function-benefits relationship has implications for how people think about and manage urban forests. Urban forests may be managed according to goals that align with the biocentric, intrinsic value that structure and function has. For instance, managers may have goals for species composition (e.g., a single species can account for no greater than 10% of all public trees) or size distribution (e.g., have more small, young trees than large, mature trees in the urban forest) of their urban forest. These types of biocentric goals often imply a rationale related to urban forest function (e.g., a diverse species composition decreases vulnerability of the urban forest to taxa-specific pest or disease outbreak). On the other hand, anthropocentric urban forest management goals related to the benefits and values of trees might consider management of the urban forest in order to provide a specific level of benefits (e.g., gallons of stormwater diverted from runoff in order to prevent the city from needing to issue capital improvement funds to allow the public works department to install larger pipes when updating stormwater infrastructure).

The list of particular benefits provided by urban forests is extensive, and the benefits of trees is one of the more well-researched areas of urban forestry as a scholarly discipline. Urban forest benefits can generally be thought of as falling into three categories: environmental benefits, including those related to urban environmental quality issues such as air quality, water quality, and microclimate, as well as biodiversity and conservation benefits such as wildlife habitat; social benefits such as human quality of life,

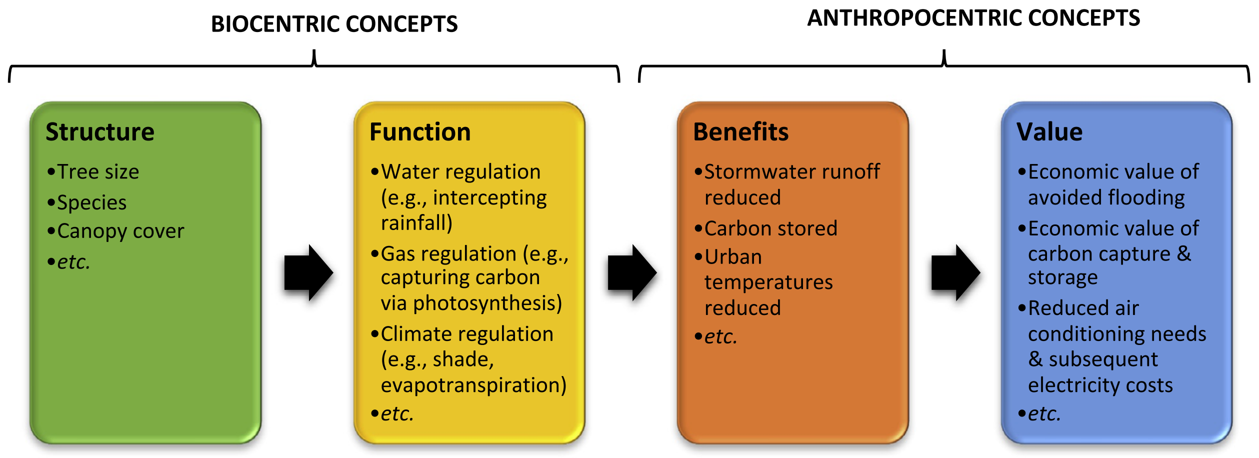

Fig. 2 Urban forest structure such as tree size and species impact how urban trees and forests perform key ecosystem functions such as climate regulation (through shading and evapotranspiration), which in turn impacts the production of benefits such as reducing urban temperatures. Since these benefits often have real value to people living in urban areas, they are often translated to economic terms, such as the decreased electricity costs resulting from reduced need for air conditioning. Note that urban forest structure and function are "biocentric" concepts while benefits and value are "anthropocentric" concepts. See main text for a more detailed discussion of structure, function, benefits, and value in the context of biocentric and anthropocentric ideas of the urban forest.

Table 1 Select ecosystem functions performed by trees and forests in cities.[a]

Function	*Explanation*
Regulation functions	*The "maintenance of essential ecological processes and life support systems"* (de Groot et al., 2002, p. 396)
Gas regulation	Trees photosynthesize, taking in carbon dioxide and releasing oxygen.
Climate regulation	Through shading and evapotranspiration trees have a cooling effect on the local microclimate, while larger groups of trees or forested areas such as parks contribute to the urban breeze cycle, whereby as the hot air over paved areas and buildings rises, drawing in the cooler air from adjacent vegetated areas.
Water regulation	Tree canopy and roots slow the infiltration of stormwater and help manage runoff in urban areas, as well as filter, retain, and store fresh water (e.g., in retention ponds or local bodies of freshwater).
Soil retention	Tree roots make sure that soil is not eroded, particularly along steep slopes (e.g., next to highways).
Waste treatment	The leaf surface area provided by tree canopies filters the air of particulate matter and pollutants.
Biological control	A diverse species composition within the urban forest helps reduce vulnerability to infestation by a taxa-specific pest or disease.
Habitat functions	*The function urban trees of urban forests have of providing habitat for plant and animal species.*
Refuge	Trees and forests provide living spaces and foraging resources for wildlife.
Nursery	Trees and forests provide habitat for wildlife to use to reproduce (e.g., nesting locations for birds, squirrels).
Production functions	*Trees and urban forest can, in certain cases, provide natural resources for human use.*
Food	Trees produce edible fruits, nuts, and seeds.
Raw materials	As they grow and mature, trees have increased wood volume, which can be used for human purposes at the end of their urban life.
*Information resources**	*Trees and urban forests can "provide opportunities for cognitive development"* (de Groot et al., 2002, p. 396)
Aesthetic*	Trees and urban forests produce greenery and flowers that have aesthetic appeal for humans in urban areas.
Recreation*	Trees and urban forests in cities are physical spaces for—as well as encourage individuals to—exercise and recreate outside in cities.
Scientific and education*	Trees and urban forests can provide opportunities for scientists and the general public alike to study and learn about nature.

Ecosystem functions list borrowed in part from de Groot et al. (2002) typology of ecosystem functions. An * indicates an ecosystem function that is dependent on the presence and values of humans in order to be a function (anthropocentric).

[a]Some readers may be familiar with the Millennium Ecosystem Assessment (2005) categories for ecosystem services (provisioning, regulating, cultural, and supporting). The above table does not use these categories here because the table presents a list of ecosystem functions, which are slightly different from services: ecosystem functions are about what an ecosystem does as a system of biotic and abiotic components, while ecosystem services are about what an ecosystem provides to people. Ecosystem functions can be translated into ecosystem services by applying an anthropocentric filter to examine how the functions of an ecosystem benefit humans. See main text for a more detailed description of the translation of urban forest structure and function into benefits and values for people.

human health, and community social capital; and economic benefits such as those related to property values, utilities expenditures and investments such as electricity and water and associated infrastructure, and economic development. Table 2 provides a semi-comprehensive but non-exhaustive list of the benefits of urban forests, since researchers are constantly investigating new benefits. In particular, significant new research on the social and human health benefits of urban forests is emerging through the work of several dedicated communities of scholars.

Calculating Urban Forest Economic Value

Urban forest benefits are sometimes translated into dollars or monetary terms to express the value that urban forests have in economic terms. Using methods from the field of ecological economics, urban forest researchers have monetized benefits such as stormwater management, air pollution, reduced energy costs, aesthetic benefits manifesting as property value increases, and even improvements in physical and mental aspects of human health. Table 3 describes select studies that have used scientific research to empirically examine the connection between urban forest structure, function, benefits, and, for select studies, economic value.

i-Tree: A case study of calculating urban forest value

One of the most dedicated and long-term efforts to translate urban forest structure and into benefits and economic value for people is the effort by researchers with the US Forest Service and Davey Resource Group to develop i-Tree (www.itreetools.org). i-Tree is a suite of online software tools into which an urban forest researcher or manager can enter data about the structure of a tree population (either by uploading a spreadsheet of a tree inventory or by accessing existing tree canopy cover data, where available) and get back data about some of the most commonly-valued benefits (stormwater, aesthetics/property value, energy, air quality, and carbon dioxide) produced annually by a tree population as well as the dollar value of these benefits. (Note that because the i-Tree software automatically quantifies both the benefits (e.g., kilowatt hours of electricity conserved due to the cooling benefits of trees) as well as the economic value of this benefit (e.g., dollars saved on electricity), the term "benefits" when used by i-Tree means both benefits and value.) A simple version of i-Tree built for entering data for just a single tree can be found at the National Tree Benefits Calculator (http://www.treebenefits.com/calculator/). Fig. 3 shows the results from the National Tree Benefits Calculator for the benefits provided by a 12-in. (30 cm) diameter red maple (*Acer rubrum*)—a common urban street tree planted across the world—growing on a single-family residential property in Chicago, Illinois.

Table 2 A semi-comprehensive list of the benefits of urban trees.

Environmental	*Social*	*Economic*
Air quality	*Urban quality of life*	*Property value*
Produce oxygen	Enhance urban quality of life	Increase property, land value
Filter air	Provide outdoor recreation/leisure opportunities	Increase neighboring property value
Remove ozone	Provide nature in the city	Reduce time to sale for property sales
Remove carbon monoxide	Reduce noise and apparent loudness	Increase rental price for properties
Remove nitrogen dioxide	Decreased incidences of some types of crime	Increase property taxes
Remove particulate matter	*Human health*	*Utility benefits*
Remove smog	Create relaxed psychological states	Reduce expenditures on stormwater infrastructure
Stormwater	Averted premature death (e.g., decrease mortality from cardiovascular disease and upper respiratory illness)	Avoid investments in new power infrastructure
Reduce rate and volume of stormwater runoff	Decreased length of hospital stays following surgery	Provide potential for future carbon offsets
Reduce flooding damage	Improve mental health (e.g., decrease ADHD symptoms, reduce stress)	Save on annual heating/cooling costs
Reduce water quality problems	Improve physical health (e.g., decrease asthma rates, cardiovascular disease, and low birth weight)	Save on electricity costs
Recharge groundwater	*Community/social capital*	Save on fuel expenditures
Carbon related	Build a sense of community (stronger neighborhood ties)	*Economic development*
Reduce carbon dioxide emissions	Enhance a community's social identity and self esteem	Increased tourism revenue
Store/sequester carbon	Provide a sense of place	Increased business activity
Energy related	Provide settings for significant emotional and spiritual experiences	Contribute to the economic vitality of the community
Reduce annual energy use	*Individual human capital*	Provide returns on municipal investments
Reduce summer time energy use	Provide opportunities for inner city children to experience nature	*Pollution abatement*
Reduce seasonal cooling energy	Build skills associated with green trades	Reduce expenditures on air pollution removal
Reduce carbon dioxide emissions from power plants	Promote individual environmental responsibility	
Microclimate	*Aesthetic benefits*	
Provide shade	More pleasant urban environments	
Reduce solar radiation	Improve scenic quality	
Modify microclimate	Provide privacy	
Reduce relative humidity	Create seasonal interest and highlighting seasonal changes	
Reduce air temperature		
Reduce urban heat island effect		
Reduce glare/reflection		
Control wind		
Biodiversity and conservation		
Provide wildlife habitat		
Enhance biodiversity		
Provide stability to urban ecosystems		

Re-classified from a list presented by Roy et al. (2012) in their literature review of 115 studies, with additions from more recent literature as necessary.

Table 3 Examples of scientific studies that have provided evidence for select environmental, economic and social benefits of urban trees and forests.

Benefit	*Description of scientific study*	*Source*
Environmental		
Oxygen production	Used data on tree biomass from field plots in 16 cities across the continental US to extrapolate oxygen production by trees in US urban forests to be 61 million metric tons, but because of the large amount of oxygen already in the atmosphere, notes that the value of oxygen production by urban forests to society is negligible.	Nowak et al. (2007)
Air pollution removal*	Used data from field plots in 10 US cities to model particulate matter ($PM_{2.5}$) removal by urban forests and observed average air quality improvements in each city ranging from 0.05% to 0.24%, with an annual value to society ranging from $1.1 million to $60.1 million (2012 USD).	Nowak et al. (2013)
Cooling/temperature regulation	Used bicycle-sensed microclimate and weather data in combination with tree canopy cover data from Madison, Wisconsin, and observed that daytime air temperatures were inversely linearly correlated with tree canopy cover, and that temperatures were substantially lower for neighborhood blocks with canopy cover greater than 40%, and that the air temperature increases caused by high amounts of impervious surface cover can be offset by the cooling effects of trees.	Ziter et al. (2019)

Table 3 (Continued)

Benefit	*Description of scientific study*	*Source*
Stormwater management	Compared structure of street tree populations in 9 communities around Cincinnati, Ohio, and used i-Tree software to model stormwater benefits and observed greater stormwater benefits for those communities with greater tree canopy cover, and for those communities meeting the urban forest management standards of the Tree City USA program.	Berland and Hopton (2014)
Social		
Increased opportunities for recreation	Conducted surveys of park visitors and gathered data about urban forest structure in public parks in Berlin, Germany, and Salzburg, Austria, and found that visitors engaged in both active and passive forms of recreation and rated shaded (treed) areas as most important to passive relaxation activities.	Voigt et al. (2014)
Decreased mortality	Compared county-level mortality rates from 1990 to 2007 across 15 states impacted by emerald ash borer (EAB), and observed a decrease in cardiovascular- and lower-respiratory-tract illness-related mortality rates in counties not invested with EAB compared to counties with EAB infestations (which had thus experienced a significant loss of tree canopy in a short period of time).	Donovan et al. (2013)
Stronger community ties	Compared “greener” and “less green” areas of public housing complexes in Chicago in a number of studies conducted in the late 1990s, and observed greater social interaction among residents in greener areas, greater incidence of adult-child interactions, stronger social ties among neighbors, and a reported stronger feeling of belonging for residents in greener areas.	Kuo (2003)
Economic		
Increased business district retail sales*	Conducted surveys of residents in small and large towns and observed that for both size communities, shopping area streetscapes with trees were not only perceived as more pleasant and desirable by patrons but that patrons were willing to pay more for goods purchased in treed shopping areas compared to those without trees.	Wolf (2005)
Increased residential property value*	Compared 600 recently-sold single-family residential properties across six communities around Cincinnati, Ohio, and observed higher property sales prices for properties with higher urban tree canopy cover in the amount of $780 (2012 USD) per every 1% increase in tree cover.	Dimke et al. (2013)

An * next to the benefit indicates that the study measured the economic value of the benefit.

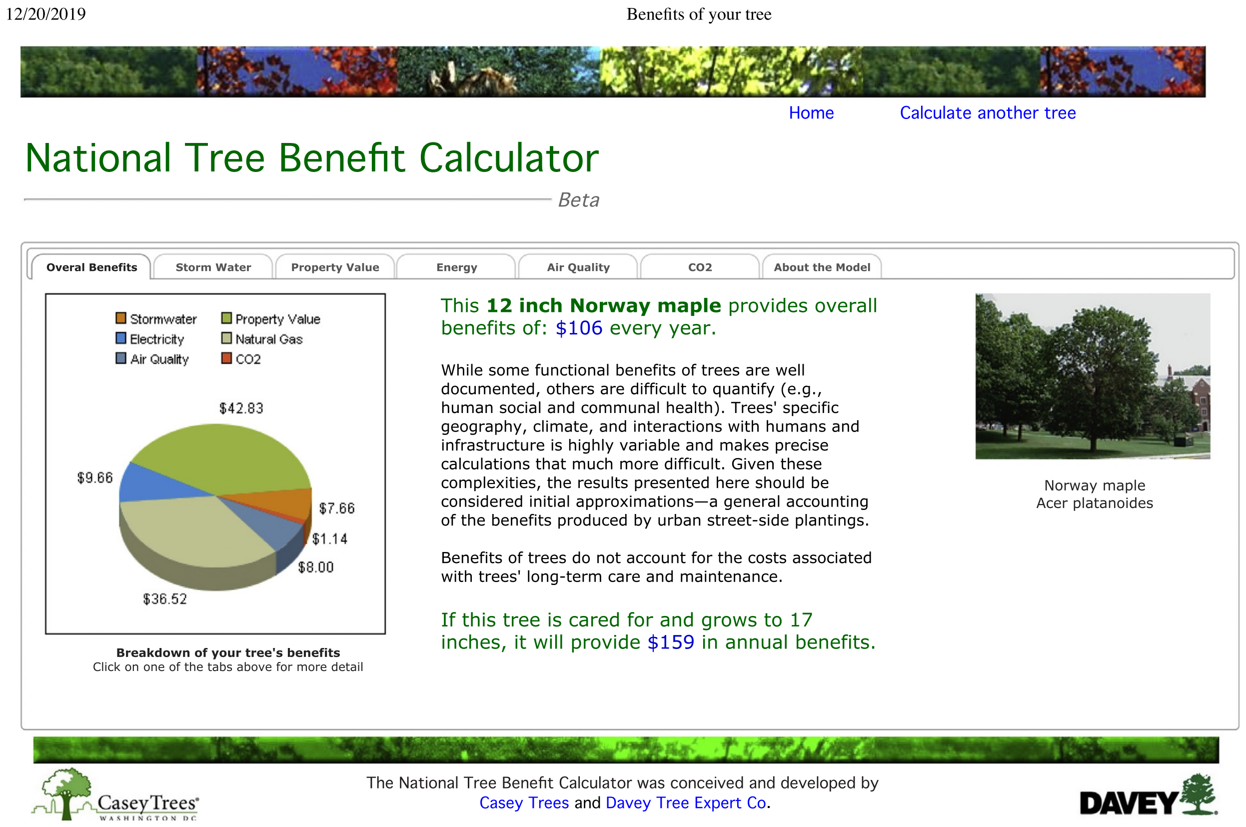

Fig. 3 The results of translating the structure of a 12″ Norway maple (*Acer platanoides*) growing in a single-family residential land use area in Chicago, Illinois into urban forest benefits and value. Using the National Tree Benefits Calculator (http://www.treebenefits.com/calculator/).

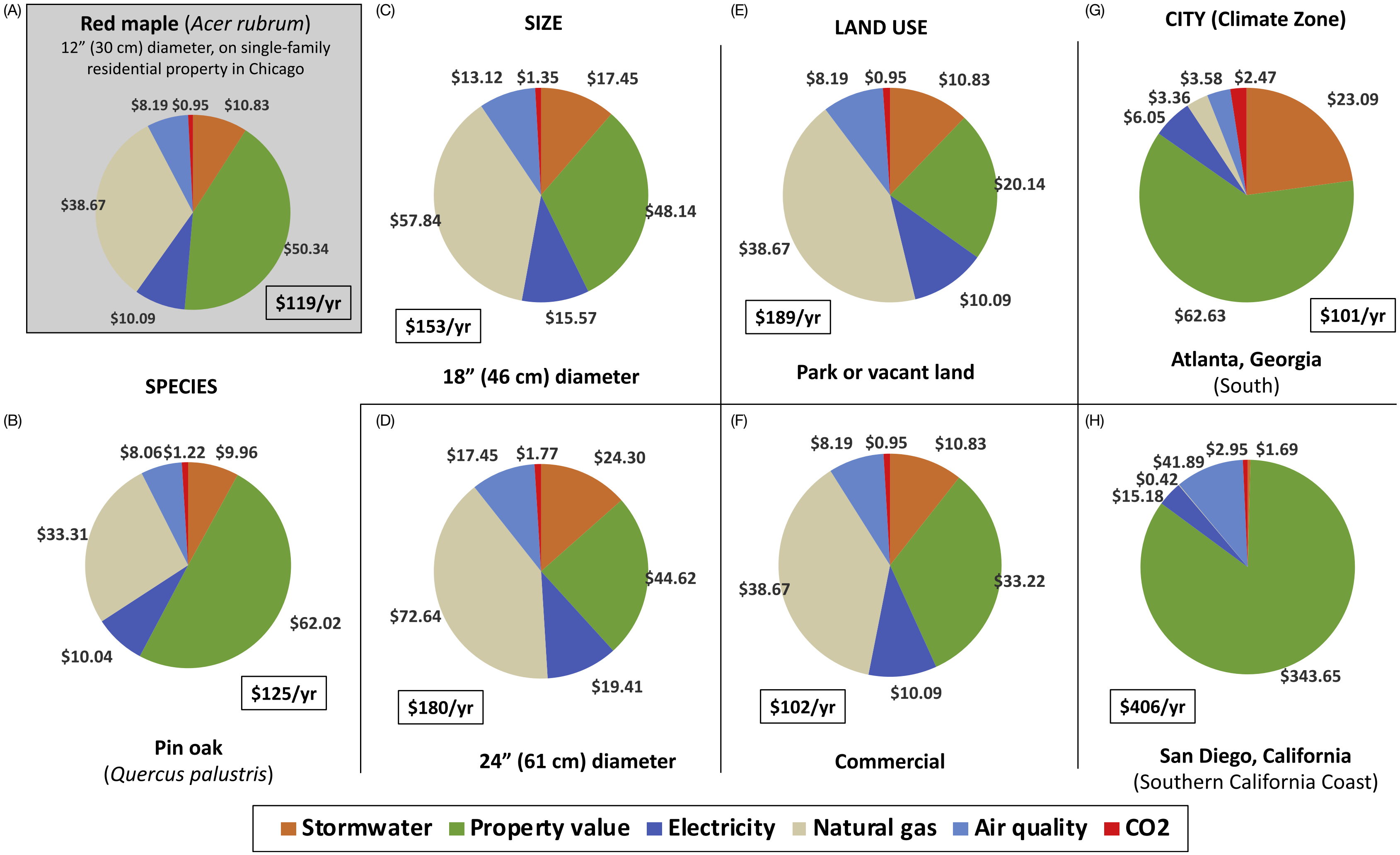

Fig. 4 Comparing urban tree benefits for a 12-in. (30 cm) diameter red maple (*Acer rubrum*, a) grown on single-family residential land use in Chicago, Illinois, to a similarly grown pin oak (*Quercus palustris*, b), 18- and 24-in. (46- and 61-cm) red maples (c and d), the same 12-in. red maple grown on park or commercial land (e and f), or on single-family residential property in Atlanta or San Diego (g and h). Based on results from the National Tree Benefits Calculator (http://www.treebenefits.com/calculator/). Specifications used in the calculator are as follows: (a) Red maple (*Acer rubrum*), 12″ diameter, Single-family residential, Chicago, Illinois (Northeast climate zone). (b) *Pin oak* (*Quercus palustris*), 12″ diameter, Single-family residential, Chicago, Illinois (Northeast climate zone). (c) Red maple (*Acer rubrum*), 18″ diameter, Single-family residential, Chicago, Illinois (Northeast climate zone). (d) Red maple (*Acer rubrum*), 24″ diameter, Single-family residential, Chicago, Illinois (Northeast climate zone). (e) Red maple (*Acer rubrum*), 12″ diameter, Park or other vacant land, Chicago, Illinois (Northeast climate zone). (f) Red maple (*Acer rubrum*), 12″ diameter, Small commercial business, Chicago, Illinois (Northeast climate zone). (g) Red maple (*Acer rubrum*), 12″ diameter, Single-family residential, Atlanta, Georgia (Southern climate zone). (h) Red maple (*Acer rubrum*), 12″ diameter, Single-family residential, San Diego, California (Southern California Coastal climate zone).

The structure, function, benefits, and value provided by a tree are impacted by countless factors related to the tree itself, where it is growing, maintenance performed, and any number of additional variables in the surrounding community that might impact a tree's structure. The key factors considered by i-Tree calculations include species, size, land-use type, and the climate in which the tree is growing. Comparing the value of benefits for similar trees that vary only on one of these dimensions can be instructive towards understanding the connection between tree structure and benefits (Fig. 4). For instance, climate impacts not only how a tree grows but also the value of benefits such as heating and cooling energy savings. Of the major benefits valued by i-Tree (and the National Tree Benefits Calculator), for a 12-in. red maple tree growing in Chicago, Illinois, located in i-Tree's Northeast climate zone, the largest portion of a tree's value comes from property value benefits, followed by energy savings due to decreased consumption of natural gas. However, for the same 12-in. red maple tree growing in warmer climates, such as Atlanta, Georgia (located in the Southern climate zone) or San Diego, California (in the Southern California Coastal climate zone), while property values are still important (especially for San Diego where the housing market is highly competitive and residential real estate prices are high), natural gas energy savings from reduced heating needs are negligible (compare panels a, g, and h of Fig. 4).

The five major benefits (stormwater, property value, energy, air quality, and carbon dioxide) considered in i-Tree-based analyses are not the only benefits of urban trees (as illustrated by the extensive list in Table 2), nor are they the only benefits researchers have translated to economic values. Thus, the calculation of tree value provided by i-Tree and applications like the National Tree Benefits Calculator is a conservative estimate of the true value of an urban tree or forest. Researchers with the i-Tree team are currently working to expand the ability of this software tool—widely used by urban forest managers—to integrate value calculations for a larger list of tree benefits, including human health. For instance, a recent study considered four major human health-related benefits (birth weight, attention deficit hyperactivity disorder [ADHD], cardiovascular disease, and Alzheimer's disease) plus two additional urban quality-of-life benefits (school performance, crime), and found that the potential total annual value of urban trees and forests in the United States is between $2.7 and $6.8 billion (2012 USD) (Wolf et al., 2015). Incorporating this new research into tree benefits calculations will improve researchers' and managers' abilities to communicate the benefits of urban trees and forests to the general public and, importantly, urban policy makers. Additionally, researchers are working to expand the ability of i-Tree for use in a greater variety of locations around the world (currently i-Tree is most accurate in calculating benefits and values for urban trees and forests in the United States).

Externalities of Urban Forests—Ecosystem Disservices

The functions of urban trees and forest produce not only benefits or ecosystem services for people, but also "*ecosystem disservices*," or negative consequences for people from nature (c.f., Lyytimäki and Sipilä, 2009). These "*externalities*" are public costs—that is, not captured in the private cost of a good or service. Externality-related costs are not paid for by any particular individual as part of the costs of the urban forest. Urban trees produce many types of ecosystem disservices that can be classified as either environmental or social (Table 4). Ecosystem disservices that might be classified as economic are better conceptualized as direct costs, though it

Table 4 Environmental and social ecosystem disservices produced by urban trees and forests.

Environmental	*Social*
Water-related problems	*Health problems*
Increased water consumption (especially in drought-plagued regions)	Allergies due to release of plant pollen
Drainage problems from tree root-sewer conflict	Attacks by insects/animals associated with urban forests (e.g., mosquito habitat)
Debris/waste issues	Increase of insects/animals acting as vectors for disease
Disposal of green waste generated during tree pruning/removal	*Safety concerns*
Disposal of debris/clutter from leaves and nuts/fruits/seeds	Obscured views/decreased traffic visibility
Disposal of debris during infrastructure repair due to tree conflicts	Risk to human safety from falling limbs
Air pollution-related	Actual increases in crime
Release of biogenic volatile organic compounds (BVOCs; air pollution)	*Aesthetic concerns*
Release of carbon dioxide during maintenance due to use of fossil-fuel powered equipment	Darkness
Release of carbon dioxide during decomposition of tree or tree debris	Debris/clutter of leaves and nuts/fruits/seeds
Ecosystem integrity	Sap dripping on parked cars
Displacing native species/escape of invasive species from urban forests	Improper maintenance leads to displeasing form (e.g., topped trees, weed-filled vacant lots, excessive sprouting)
Energy-related	*Negative perceptions of trees/forests*
Increased energy consumption due to improperly placed trees	Fear of crime
Increased energy consumption due to tree maintenance	Fear of disease
Loss of solar panel capacity due to shading by trees	Fear of insects or other animals
	Fears of forests and trees

Re-classified from a list presented by Roy et al. (2012) in their literature review of 115 studies, with additions from literature focused explicitly on ecosystem disservices (Lyytimäki and Sipilä, 2009; Dobbs et al., 2011; Lyytimäki, 2014). (Note that ecosystem disservices of trees in Roy et al. (2012) that might be considered economic costs are better conceptualized as either direct costs (cost of planting and irrigation, trees falling across power lines, etc.) rather than externalities or ecosystem disservices.)

should be noted that many of the disservices listed in Table 4 may be translated into economic value the same way the benefits listed in Table 2 may be translated into economic value. However, these values most of the time are not explicitly paid for by any particular actor associated with the urban forest, and thus are external (i.e., "externalities") to the decision-making of individuals or groups with respect to urban forest management.

Conclusion

This article has described urban forests as all the trees, forests, and associated vegetation and ecosystem components growing in or very near the cities, towns, and communities where people live, work, and play. This includes trees planted along streets and boulevards, in parks, on private property, in vacant lots, and even those trees that spring up in unmanaged alleys or along transportation corridors. Urban forests produce significant benefits, or ecosystem services, for urban residents, but also have externalities, or ecosystem disservices. While this article has focused on the biophysical, or ecological, elements, there are also significant human influences on urban trees and forests.

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