# Urban Forests as Social-Ecological Systems

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### Abstract

Urban forests are all the trees, forests, associated vegetation growing in anthromes with higher levels of population density (e.g., dense settlements and populated woodlands). This chapter describes the important human elements of urban forest ecosystems, including actors, ownership regimes, and management, the distribution of urban forest benefits, the direct costs of urban forests, and current conceptions of urban forest sustainability. The chapter concludes by presenting a comprehensive framework for understanding the many factors that shape urban forests as social-ecological systems of inseparable natural and human components.

Urban forests are by their very nature systems of both natural components (i.e., trees, etc.) and human components (i.e., people living in urban areas) found in anthromes (cf., Ellis et al., 2010) ranging from dense settlements to populated woodlands. Thus, in addition to considering the biophysical characteristics of the trees and forested areas that make up urban forests, it is also necessary to consider the human elements of the urban forest.

This article examines how the human elements of urban forests produce observed outcomes, in particular, urban forest benefits and costs. These human elements include the actors (people and groups) who interact with the urban forest, patterns of urban land ownership (e.g., whether urban forests are located on public or private property), and the management undertaken by these actors on different property types. Actors, ownership, and management impact the distribution of the benefits of urban forests as well as the direct costs of urban forests. The article concludes by presenting a comprehensive framework, synthesized from the literature, for understanding and studying urban forests as social-ecological systems.

## Actors in the Urban Forest

The biophysical and ecological character of forests and trees in urban areas are extensively influenced by human actions. There are a number of different actors—individuals and groups—interacting in various capacities. The list of actors influencing the urban forest includes municipalities; privately-owned tree care companies; power companies managing utility rights-of-way; nonprofit organizations with missions connected to urban greening; residents' or neighborhood associations; business associations; stormwater management districts; real estate developers and builders; property management companies; large institutional landowners (e.g., colleges and universities, hospitals, schools); homeowners, landowners, and other urban residents; and more. Each of these actors has a different jurisdiction and area of influence, as well as goals and capacities related to the urban forest. For instance, real estate developers looking to develop or redevelop single properties or large parcels of land may or may not value the urban forest as an important part of residential or commercial building projects, and they may or may not possess the skill, knowledge, or interest to design developments with infrastructure that promotes a healthy urban forest (e.g., by protecting large trees, preserving patches of existing forest, or designing adequate spaces for planting new trees). Utility companies manage trees along a utility corridor in which electricity infrastructure (power lines, etc.) is located; as such, utility foresters are concerned with maintaining the necessary clearance around power lines to as to avoid electrical service disruptions caused by trees.

Even within a single actor type, involvement with and capacity for urban forest management may vary across cities. For municipalities, resources (expertise, budget, etc.) available for urban forest management at the municipal level also impact the

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urban forest. In some cities, authority for urban forest and tree management is designated to the department of public works, while in others this authority may be held by parks and recreation, or in rare cases, a stand-alone urban forestry department. Some municipalities have certified arborists on staff—highly skilled, certified professionals trained in the care of trees—while other cities contract out tree work to private companies, or rely on untrained city staff to perform tree care (though the latter is not advisable). Additionally, the budget for municipal management of the urban forest can vary significantly from city to city, and some cities may even lack a dedicated urban forestry budget entirely, relegating urban forest management to crisis-response only (e.g., removal of hazardous trees, cleaning up debris from storms).

Actors may interact with one another on urban forest management. For instance, municipalities may be legally obligated to maintain the trees located along streets in the public right-of-way, but may contract the planting, maintenance, and/or removal of street trees to a private tree care company staffed by certified arborists or even to a local nonprofit organization that may in turn engage neighborhood residents as un-trained or semi-trained volunteer tree stewards in simple tree care tasks (e.g., watering recently-planted trees). Or, a local urban forestry nonprofit organization may collaborate with residents' associations and homeowners to plant trees in a new housing development with low canopy cover. Or stormwater management districts may collaborate with the local municipality on a tree giveaway program to encourage more planting of trees on private property.

## Ownership: Public Versus Private Urban Trees

As alluded to above, different actors may be responsible—formally (legally) or informally—for taking care of different parts of the urban forest. The urban forest in cities is frequently described in terms of existing on either public property or private property (The concepts of ownership and property discussed in this section are biased towards Western European (colonial) ideas of private property. For better or worse, this is consistent with the majority of the urban forest discourses *writ large*. While the study of urban forestry in developing and non-Western countries is growing, future discourse and scholarship would benefit from being more inclusive of other land management regimes). *Public property* includes land owned or managed by a public entity, such as a municipality (village, town, city, or county government), public utility or other public authority (such as a state or national highway department), or the *public right-of-way* (area extending from the edge of a public street a certain distance onto adjacent private property, to which one or more public authorities have limited rights of access and use and sometimes also maintenance responsibilities over). Public trees include park trees and any additional trees on public land (a golf course, town square, publicly-managed cemetery, etc.), but also all trees in the public right-of-way (street trees, trees along a publicly-owned and managed trail, etc.).

Across an entire city, the public urban forest accounts for only a small percentage of the urban forest (though it should be noted that in some parts of a city, e.g., a city center business district, all of the urban forest may exist on public land or in the public right-of-way such as boulevards, parks, and public plazas). Private trees are the remainder of the urban forest not on public property, accounting for as much as an estimated 90% of "*urban tree canopy cover*" (the geographic extent of tree canopy covering an urban area, as measured through use of aerial or remote sensing imagery) (e.g., for Baltimore, MD, USA: Troy et al., 2007). This means that the vast majority of urban trees exist outside of direct public control or management, despite the fact that the benefits produced by the urban forest are largely benefits to the general public. And though a large scholarly discourse and practitioner community exist centered on municipal urban forest management (including even a specific certification for "Municipal Specialist" that supplements the International Society of Arboriculture [ISA] Certified Arborist credential; ISA, 2019), the portion of the urban forest existing on public land is minimal. Thus, collaboration among actors responsible for the public urban forest (i.e., municipal—staff and contracted—foresters and arborists) and those responsible for the private urban forest (e.g., individual homeowners, businesses, institutions with large tracts of land such as colleges, hospitals, etc.), is necessary for the urban forest as a whole to produce optimal benefits to all.

## The Complexity of Urban Forest Management

All of these different actors all influencing urban forest outcomes in different ways creates a complicated and "polycentric" urban forest management situation. *Polycentric* refers to the many overlapping yet independent centers of decision making that exist in urban areas (Ostrom et al., 1961: p. 831). Also called urban forest "governance" (e.g., Lawrence et al., 2013; Krajter Ostoić and Konijnendink van den Bosch, 2015), this polycentric situation contributes to the sustainability and resilience of urban forests by creating redundancies in the management of urban forests: if one of these actors is unable to act on behalf of the urban forest (e.g., a recession causes municipal budget cuts that eliminate an entire urban forestry program or department), the others may be able to pick up the slack (e.g., adjacent homeowners may be able to pay for tree planting and maintenance in the public right-of-way).

Given this polycentric urban forest management, the specific level (or intensity) of management for a group of trees within the urban forest is connected to a number of factors, including whether the trees are planted or grew up spontaneously, what type of land use or property ownership the tree is growing on, and the party (or parties) responsible for or engaging in the management of the trees. The configuration of factors that impact urban forest management creates a gradient of management levels (Fig. 1), ranging from the completely unmanaged trees (e.g., such as those that have spontaneously grown up in vacant lots that are completely neglected by humans) to the most highly managed trees (e.g., street trees in narrow boulevards or tree pits adjacent high

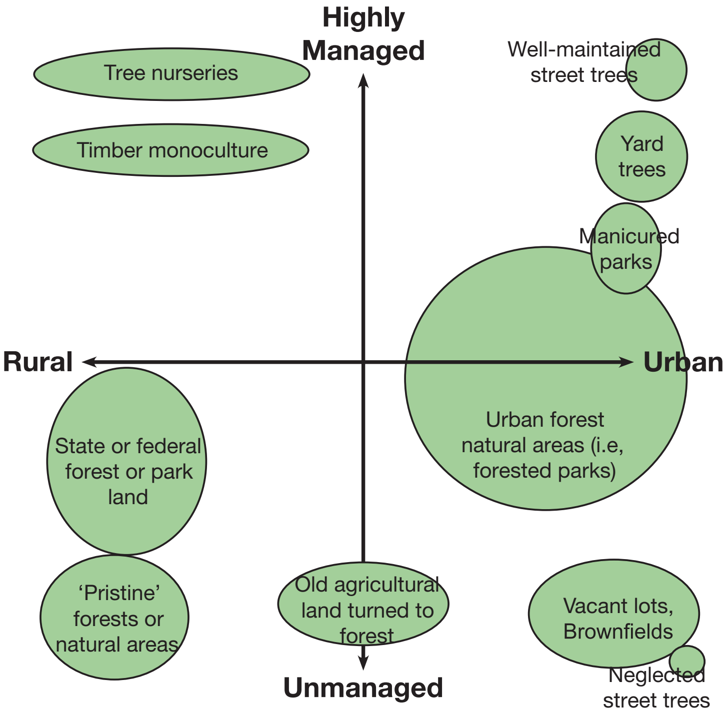


**Fig. 1** Examples of the types of trees and forests in and around urban areas, presented by where they likely exist along an urbanization and management gradient.

traffic streets, or in plazas in urban centers, where they need to be regularly watered, pruned, and monitored for pest/disease damage in order to maintain the appropriate and safe tree form). Fig. 1 shows how this gradient intersects with the urbanization (i.e., urban-to-rural) gradient for different types of forests.

## The Distribution of Urban Forest Benefits across Urban Areas

The complexities of urban forest management in combination with the social and ecological heterogeneity of urban landscapes result in an unevenness of urban forest structure, which in turn creates disparities in who benefits from urban forests. Additionally, the people and groups who receive benefits from the urban forest may have different experiences of what those benefits are depending on how they interact with the urban forest and what their personal values, preferences, and experiences with nature are. This section describes these two issues and demonstrates that discussions of the benefits of trees are more complicated than just listing the many benefits and calculating an economic value.

Research has demonstrated that the urban forest is distributed unequally across urban areas. This results in environmental justice and equity issues since people are also not distributed equally across urban areas. Two recent meta-analyses (systematic, quantitative analyses of existing literature) have examined the relationship between urban tree canopy cover and income (Gerrish and Watkins, 2018) or race (Watkins and Gerrish, 2018), finding evidence for inequitable distribution of tree canopy by both demographic variables. Gerrish and Watkins (2018) synthesized 61 studies that researched the relationship between urban forests and income in urban areas and discovered that urban forests are inequitably distributed across income groups, with tree canopy cover (on both public and private lands) disproportionately lower in low-income areas. Watkins and Gerrish (2018) find a similar pattern for race: in their synthesis of 40 studies, they observe lower urban forest cover in areas of high minority populations (Watkins and Gerrish (2018) note that since low income and minority populations are often co-located in urban areas, the relationship between race and tree canopy cover is tightly connected to income, and thus recommend that any policies to address systemic inequities should consider both race- and income-based inequalities). They observe especially lower forest cover on public land in non-humid climates for African American residents (Watkins and Gerrish 2018). These findings have important implications for urban forest practice, particularly for efforts to address urban forest inequities. The actors engaged in urban forest management—including municipalities, nonprofit groups, professional urban foresters and arborists, and urban residents—have different responsibilities, capacities, and goals. For instance, research conducted in the Toronto, Canada, area by Conway et al. (2011) examined the urban forestry activities (e.g., conducting a tree inventory, planting or maintaining vegetation, stated importance of vegetation-related issues) of business improvement associations and neighborhood residents' associations. Their findings suggest that residents' associations in particular engage in uneven levels of urban forest activities, leading to inequities in urban forest structure across neighborhoods that differ by racial, ethic, and income characteristics (Conway et al., 2011).

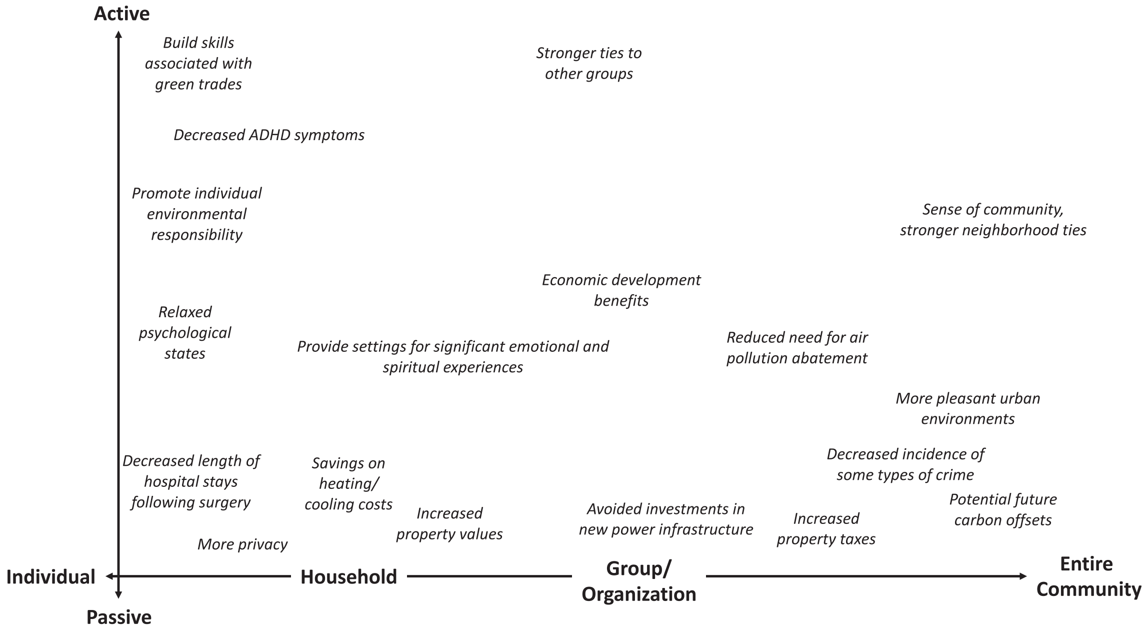


**Fig. 2** The social and economic benefits of urban forests can be mapped along two dimensions: passive vs. active engagement with the urban forest; and, whether the benefit accrues on the level of a single individual to an entire community. Dimensions of social benefits of urban greening after Westphal, L. M. (2003). Social aspects of urban forestry: Urban greening and social benefits: A study of empowerment outcomes. *Journal of Arboriculture* **29**(3), 137–147.

Furthermore, urban forest benefits are experienced differentially by different people and groups within urban areas. Westphal (2003) developed a typology of understanding urban forest benefits—particularly social and economic benefits—that considers, on one dimension, whether benefits are accrued through passive experience of versus active involvement the urban forest and, on a second dimension, to whom the urban forest benefits accrue (on a scale of single individuals to an entire community). Westphal (2003) defines "passive experience" of the urban forest as simply being in the presence of urban trees, forests, and greenspace, while "active involvement" is defined as participation in an activity to green the urban environment such as planting trees or gardening. Fig. 2 maps select social and economic benefits of urban forests along these two dimensions. Both dimensions help answer the question of how urban forest benefits accrue to people. Some types of benefits are only experienced by those who actively engage with the urban forest. For instance, individuals who actively participate in tree planting, care, and management—either as professionals or as volunteer stewards of the urban forest—build skills associated with green trades. The benefit of skill building is only experienced by individuals engaged in active greening activities but not to the community at large. Another benefit that only results through active engagement is the stronger ties to other groups that organizations may experience as a byproduct of participation in collaborative urban forest management (e.g., city-wide tree planting initiatives). On the other hand, some benefits accrue to all people regardless of their level of engagement with the urban forest, simply due to the presence of trees. Individuals engaged in either active or passive forms of engagement with the urban forest may experience relaxed psychological states. The entire community benefits from a more pleasant urban environment due to the presence of trees.

A final issue in determining who benefits from the urban forest stems from the fact that the values of trees often calculated in tree benefits analyses (e.g., i-Tree or Tree Benefits Calculator, which produce a monetary figure for the economic benefit of the urban forest or single urban tree, respectively) are overly simplified. Valuations of the urban forest by necessity homogenize the preferences and values of people and groups in urban areas with respect to trees. In reality, the values of trees are heterogeneous not only across the spatial dimensions an urban landscape, but also across human communities. Different types of people, groups, and communities may value trees for different benefits. People's landscape preferences vary (e.g., a manicured lawn versus xeriscaped yard; trees and forests versus wide open spaces). The objectives of groups and organizations differ (e.g., a tree planting organization interested in planting large shade trees in a park that would produce lots of urban forest benefits versus an urban gardening group interested in planting only small fruit bearing trees and leaving sunny open spaces for gardening). Another example is the stormwater management benefits of trees and green infrastructure, which may be a primary concern for the municipal authority and stormwater utility coping with combined sewer overflows in a particular neighborhood; however, individual homeowners who do not experiencing flooding on their property may place a much higher value the shade and property value benefits of trees, or may even dislike trees due to needing to clean-up their leaves or because trees shade and reduce the efficacy of rooftop solar panels (see Opportunity costs in the section "The Costs of Urban Forests" below). Ultimately, the heterogeneity and complexity of urban environments and people complicate assessments of the benefits and value of urban trees and forests to human communities.

## The Costs of Urban Forests

Another factor that complicates discussions of how urban forest management impacts urban forest benefits to people is that urban forests do not only have benefits; they also have substantial costs—both to individuals and groups, as well as to the public and the environment as a whole.

In order to understand how costs impact urban forest management and decision-making (and vice versa), it is helpful to review how urban forest professionals conceptualize tree benefits and costs in practice. Urban foresters often speak of trees and forests as one of the few types of physical infrastructure in urban areas that appreciate in value after installation, in contrast to the gray infrastructure such as streets, sidewalks, sewers, and other hardscape that begin depreciating the day they are completed. It is true that because trees grow after being planted in urban areas, a tree should theoretically provide an increasing level of benefits throughout its lifetime until being removed (Fig. 3). However, urban trees only appreciate if they are healthy and able to survive and grow to a large size where they provide substantial benefits. Research has found that if a cohort of trees (group of trees planted at the same time) do not survive at sufficiently high rates, the benefits produced by the cohort of trees does not increase over time—that is, the appreciation of benefits resulting from the growth of surviving trees does not outweigh the loss of benefits resulting from high tree mortality (Widney et al., 2016). Thus, for the benefits of the urban forest to increase over time, planted trees must survive. For planted urban trees, the establishment period—or the first 1–3 years after being transplanted, sometimes into a potentially harsh growing environment—can be a particularly vulnerable time where mortality rates are high. In order to survive and grow, planted trees must be cared for by people and, in particular, watered during the establishment period. Thus, though surviving trees do appreciate and provide benefits to people, they also require significant investment from people.

Investment, or maintenance costs incurred during a tree's early life, may be quite high (Fig. 3). Early costs include the costs of planting (purchasing high-quality tree stock from a nursery, plus labor and materials to put the tree in the ground, including tree workers, shovels for small trees or heavier equipment for large trees, any soil amendments used, mulch, water, etc.) as well as the costs of early essential maintenance for recently planted trees (watering during the first 2–3 growing seasons after planting, formative pruning to create appropriate tree form for urban areas, etc.). If a tree is optimally maintained early in life, the maintenance costs during the mature phase then go way down and are limited to occasional pruning, pest monitoring, and other types of routine mature tree maintenance.

For the urban forest as whole, there are two major categories of costs: "private costs" and "public costs" (Table 1; modified from a typology presented in Vogt et al., 2015b). *Private costs* are costs borne by a particular actor (group or individual) as part of expenditures on or because of the urban forest. Private costs include the direct costs incurred during management of the urban forest and costs resulting from tree conflicts (infrastructure repair and liability costs). *Public costs* are costs incurred because of the urban forest but not paid for by any particular actor and instead borne by society at large. Public costs include externality-related costs (also called ecosystem disservices) and opportunity costs. Direct costs, costs from tree conflicts, liability costs, and opportunity costs are discussed in greater detail below.

### Direct Costs—Management and Maintenance

Direct costs incurred during the provisioning and maintaining of trees and the urban forest are private costs. These costs—i.e., management costs—include expenditures on labor and materials required to plant trees (the trees, tools, mulch, soil amendments, water and water equipment, etc.). Direct costs are paid by actors performing specific actions in order to manage the urban forests, for instance, municipal budget outlays for the pruning of street trees. In order to better understand the magnitude of the direct costs of

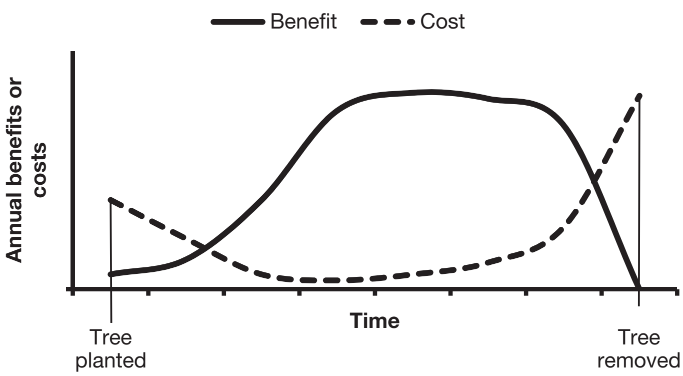


**Fig. 3** Generalized (hypothetical) profile of the annual benefits provided by and costs incurred from over the entire lifetime of a single tree from planting to removal. The net benefits provided over the entire tree's life can be conceptualized as the area in between the benefits (*solid line*) and costs (*dashed line*). Modified from Vogt, J. M., and Fischer, B. C. (2014). A protocol for citizen science monitoring of recently-planted urban trees. *Cities and the Environment* **7**(2), art. 4. Available at: http://digitalcommons.lmu.edu/cate/vol7/iss2/4 and Vogt, J., Hauer, R. J., and Fischer, B. C. (2015b). The costs of maintaining and not maintaining the urban forest: A review of the urban forestry and arboriculture literature. *Arboriculture & Urban Forestry* **41**(6), 293–323.

**Table 1** Types of costs associated with urban forests.

| | *Type of cost* | *Explanation/examples* |
|---|---|---|
| Private costs | Direct costs (i.e., maintenance and management costs) | Dollars expended to purchase labor and materials involved in the planting, pruning, watering, and other types of maintenance of trees in the urban forest |
| | Infrastructure interference costs (i.e., repair costs) | Pavement and sewer repair costs; removal of tree limbs or debris blocking signage, power lines, storm drains, etc.; costs from tree-initiated power outages; or other costs incurred when trees damage or interfere with infrastructure |
| | Liability costs | Damages paid from a lawsuit or settlement awarded when trees or parts of trees cause injury to persons or property, such as an improperly cared for tree falling on a house, vehicle, or person |
| Public costs | Externality-related costs (aka, "ecosystem disservices") | Emissions of biogenic volatile organic compounds (VOCs) by trees; allergies due to tree pollen; release of carbon dioxide during decomposition of trees or tree debris or by maintenance equipment (gas-powered chain saws, lift trucks used to access tree canopy during maintenance, etc.); leaf/debris clean-up |
| | Opportunity costs | Space where trees are planted cannot be allocated to other competing uses, such as parking, bike lanes, sidewalk cafés, etc.; shade from trees may preclude use of sunny areas for installation of solar panels or for gardening |

Modified from Vogt, J., Hauer, R.J., and Fischer, B.C. (2015b). The costs of maintaining and not maintaining the urban forest: A review of the urban forestry and arboriculture literature. *Arboriculture & Urban Forestry* **41**(6), 293–323.

urban forests, it is helpful to understand the types of maintenance required by urban trees and forests, and how maintenance and management impact urban forest outcomes.

A note on terminology: The terms "maintenance" and "management" are often used interchangeably with respect to the urban forest, though they mean slightly different things. For the purposes of the following discussion, *maintenance* will refer to activities undertaken with the intent of caring for individual trees, while *management* will refer to activities to care for urban trees in the aggregate (so, maintenance of trees, but management of the urban forest).

There are a number of activities commonly undertaken to maintain urban trees, including transplanting, various types of pruning (e.g., formative pruning of young trees and structural pruning of mature trees to create appropriate form for urban spaces, pruning to remove dead or broken branches after storms); watering (during establishment after transplanting, or during periods of drought); mulching (ideally, seasonally, to hold in soil moisture and minimize competition between tree roots and grass, weeds, and other plants); amending soils (if needed, through fertilization or inoculation with mycorrhizae), inspecting and treating for pests and diseases (also called "plant health care"), installing tree support or lightning protection systems (generally only for old, mature, or particularly significant trees), and, finally, removing trees and tree stumps (either due to conflict with other infrastructure, during construction, as a result of natural or pest/disease-related mortality, etc.).

The cost of the labor and materials necessary to performing these maintenance tasks may be paid for by one or more actors in the urban forest: municipal urban forestry programs; individual homeowners, business-owners, or institutional landowners maintaining trees on private property; nonprofit urban forestry organizations; or any other party taking fiscal responsibility for the maintenance of public or private trees. The data that exists on the relative costs of different types of tree maintenance activities is limited (Vogt et al., 2015b), but a recently conducted census of municipal tree care activities in the United States revealed that tree pruning and tree removal are the costliest tree care expenditures as a percent of total municipal urban forestry budget (Hauer and Peterson, 2016). Fig. 4 shows the relative costs of other specific maintenance and management activities included in municipal tree care (from Hauer and Peterson, 2016).

One of the ways trees are maintained is by being planted in cities in the first place. However, researchers have estimated that only approximately one-third of trees in North American cities are planted (Nowak, 2012), leaving a substantial number of trees within urban areas that emerge spontaneously. This spontaneous tree generation has led to a significant invasive species problem for some cities. For instance, in Chicago area, it has been estimated that over one-quarter (28.2%) of the trees in the region (by count) are the invasive European buckthorn (Nowak et al., 2013). Since buckthorn is a small-stature species that does not provide a large number of benefits, this can yield substantial pressure on urban forest managers to remove this and other invasive species in the urban forest, particularly in the more naturalized, less highly managed areas of the urban forest where buckthorn may compromise the quality and integrity of urban forest ecosystems.

In examining how maintenance impact urban forest outcomes, the language of ecologists when discussing the impact of ecological disturbances (cf., Walker and Willig, 1999) is useful. Urban forest structure is influenced not only by the type of maintenance, but also the party performing the maintenance as well as intensity (how much maintenance is performed), frequency (how often maintenance is performed), duration (for how long maintenance is performed), and extent (on what part of a tree, or which trees within the urban forest). Just like when considered for ecological disturbances are called a "disturbance regime" (e.g., Hobbs and Huenneke, 1992), these factors together make up a "maintenance regime," which impacts the structure of each urban tree individually as well as the urban forest in the aggregate.

In addition to the maintenance performed on urban trees, additional urban forest management activities are also part of the direct costs of urban forests. Management activities consider the entire urban forest—or a significant aggregation of trees such as those in a park or park system, all the trees in a neighborhood or along a corridor, etc.—and generally involve higher-level planning,

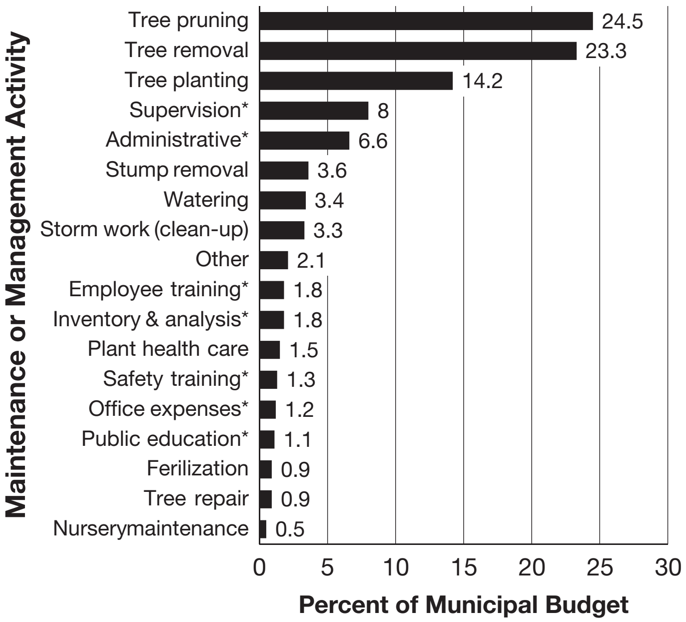


**Fig. 4** The average percent of municipal urban forestry program budgets spent on particular tree maintenance and management activities, based on a 2014 survey of municipal urban forestry programs in the United States. An * indicates an activity that is management, while other activities are maintenance. Data used with permission from Hauer, R., and Peterson, W. (2016). Municipal Tree Care and Management in the United States: A 2014 Urban & Community Forestry Census of Tree Activities. 16–1. Stevens Point, WI. Available at: https://www.uwsp.edu/cnr/Pages/Forestry—MTCUS.aspx.

advocacy, and even policy-making activities. This includes urban tree inventory and analysis, generating master and strategic plans for the urban forest, engaging in public education, outreach, and awareness building, lobbying for or creating tree policy at the municipal or even state or national level, plus the generic administrative and office expenses of running any type of program. These costs are more likely paid for by groups engaging in stewardship of the urban forest for a city such as municipal urban forestry programs or urban greening nonprofits, rather than by particular individuals such as homeowners. However, large private or institutional landholders such as colleges and universities, or neighborhood/residents' associations or business associations may also engage in management activities that have costs.

### Costs Resulting from Tree Conflicts—Infrastructure Repair and Liability Costs

In addition to the direct costs of urban forest maintenance and management, there are also private costs that result from tree conflicts in the urban environment including infrastructure interference and liability costs. Infrastructure repair costs are incurred due to above- and belowground conflicts. Above ground conflicts include tree branches growing into fences, signage, or—most commonly—above ground power and cable lines. In particular and most costly, when trees sufficiently conflict with power lines such as during or after a storm or high-wind event, they can cause power outages that result in costly tree debris cleanup and power infrastructure repair, as well as loss of revenue to the power company for the duration of the service outages. Belowground conflicts result when tree roots grow into storm sewer drains or water supply pipes or underneath sidewalks or curbs causing buckling of the concrete. The cost of repairing damaged infrastructure are generally paid by the actor responsible for management of the infrastructure needing repair (electric utility companies, water management authorities, or public works departments managing streets and sidewalks).

In almost all cases, conflict between trees and infrastructure results from improperly planted and/or maintained trees, not from inherent or unavoidable tendency for trees to cause damage. For instance, it is a common misconception that tree roots will always interfere with a storm sewer or water supply pipe if the two share the same underground space. However, in reality existing small cracks or inadequately sealed joints in aging pipes leak moisture or nutrients that attract small tree roots, which then expand small cracks into large cracks or roots grow into the pipes contributing to clogs. Similarly, a tree with a large mature size planted under a power line will become an interference, while a tree with a small mature size planted in the same place will cause no problems with above ground power infrastructure. This is why there is a popular maxim among urban foresters: "right tree, right place, right time," meaning that when planting trees, urban foresters must consider the proper tree (species, size at maturity, etc.) for the proper place (planting area type, soil and environmental quality, etc.) and plant the tree at the right time (at the right time of year for seasonal climate, or after a major construction project not before, etc.).

In the worst cases, improperly planted and maintained trees can cause serious damage to property or injury to people. If the person whose property or person is injured decides to pursue legal remedy, a lawsuit can result in the assigning of liability for the tree causing injury and paying of monetary damages to the victim. Thus, liability costs are incurred and paid as legal settlements by the actor taking responsibility for (or deemed responsible in a court of law) the tree that caused the damage. In the case of trees on private property, this is usually the property owner, but for trees in the public right-of-way, assigning legal responsibility for the damage caused by the tree can get more complicated. For instance, the physical land in the right-of-way is owned by the adjacent property owner but the city generally has access rights for certain purposes such as maintaining the sidewalk or accessing buried sewer pipes. Responsibility for mowing the grass or maintaining any non-tree vegetation in the right-of-way boulevard between the street and the sidewalk may fall to the adjacent homeowner, yet legal responsibility for planting, maintaining, and removing any trees in the right-of-way may be either held by the city or may also be the duty of the adjacent homeowner. If legal responsibility over a tree is unclear due to the lack of clear delegation of responsibility of tree care and maintenance or lack of clear ownership of the property on which the tree itself is located, who has liability for the tree in the event of partial or entire tree failure is murky and will need to be determined in a court of law. Whoever is liable for the tree will then be responsible for paying any monetary damages awarded to the victim. Municipalities that take responsibility over the trees in the public right-of-way may even budget for paying liability claims (in or out of court), although it is obviously preferable for any party in charge of part of the urban forest to monitor and maintain trees in order to proactively assess tree risk and avoid any tree failures that cause injury to persons or property.

### Opportunity Costs—A Public Cost of Urban Forests

The private costs described above—maintenance and costs resulting from tree conflicts—are paid for by someone. The public costs of urban trees and forests, on the other hand, are those costs borne by no particular individual or group but instead by urban residents as a whole. These include ecosystem disservices and "opportunity costs." Ecosystem disservices are the negative externalities produced by urban trees and forests, such as pollen that causes allergies. *Opportunity costs* are the costs of undertaking one particular action or decision and foregoing another. In the context of urban trees and forests, opportunity costs refer to the activities or land uses that cannot be engaged in if urban trees and forests are planted, managed, etc. For instance, there is limited space in the public right-of-way and many competing possible uses for this space such as parking, bicycle lanes, sidewalks, a grassy boulevard, bench, bike racks, waste receptacle, sidewalk café, raised flower bed, trees, etc. Since not all of these uses can happen simultaneously, whenever one particular use is chosen for a given space, the cost of forgoing the other types of uses for the space is considered the opportunity cost of a particular use. If trees are planted in the public right-of-way, the space cannot be used for a sidewalk café by an adjacent restaurant. On other types of public land such as parks or public squares, opportunity costs are similar: for instance, if there is a forested area in a portion of a park, this area cannot be used for a parking lot, picnic area, public pool, or other use. The opportunity costs of trees are not just relevant on public lands. Private landowners can face opportunity costs as well. Trees that cast too much shade may preclude installation of solar panels on the roof or use of a yard space for gardening of vegetables that require sunlight.

## Urban Forest Sustainability

Whatever the configuration of individual trees and patches of forest and actors managing the urban forest, in the end, when the costs of urban forests are subtracted from the benefits—either as a formal, mathematical calculation, or an informal comparison of the benefits and costs—ideally, net benefits are positive. And in the optimal scenario, the net benefits of the urban forest are not just positive at a given point in time, but they are sustained (or increase) over time.

### What Does "Sustainability" Mean for Urban Forests?

There are two different angles from which scientists and practitioners have conceptualized sustainability as related to the urban forest. The first and most common way of conceptualizing urban forest sustainability considers primarily the persistence of the urban forest resource itself—that is, the trees—over time, and thus, by proxy, the net benefits provided by the urban forest in the aggregate. A "sustainable urban forest" in this context refers to maintaining an approximately consistent level (or increasing level) of a particular structural parameter such as canopy cover, stocking level or number of trees (Fig. 5A), or of the urban forest benefits provided

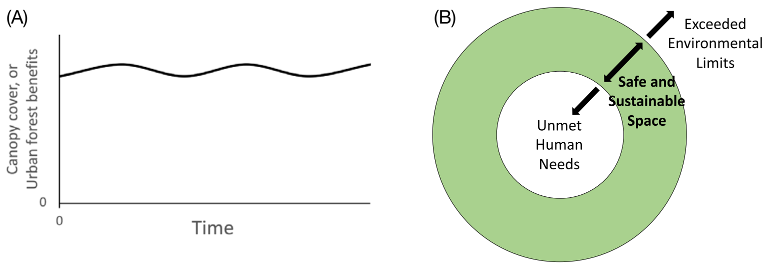


**Fig. 5** Two different ways of conceptualizing urban forest sustainability: (A) As an approximately sustained level of a particular urban forest structural parameter such as canopy cover (or level of net benefits) over time; or, (B) As part of meeting human needs while making sure that Earth's environmental limits are not exceeded. (B) After Raworth, K. (2017). *Doughnut economics: 7 ways to think like a 21st century economist.* White River Junction, Vermont: Chelsea Green Publishing, as adapted for urban forests by Vogt, J., and Hauer, R. (2017). Sustainability science for urban foresters and arborists. *Arborist News* **26**(4), 28–34.

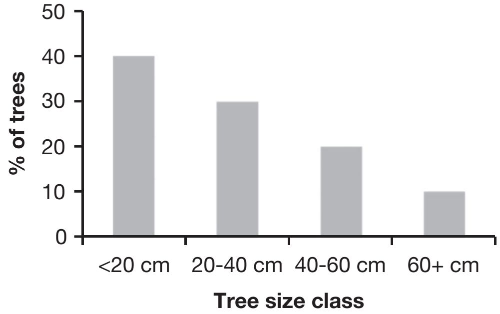


**Fig. 6** Size class distribution of trees in an urban forest that sustains a constant level of net benefits over time. Figure created from a text description of the appropriate "age distribution"—where tree size is a proxy for age—for a "stable" urban forest, as described in Richards, N. A. (1983). Diversity and stability in a street tree population. *Urban Ecology* **7**(2), 159–171.

(cf. Clark et al., 1997; Dwyer et al., 2003). Because of the way tree structure is connected to function and benefits, the largest trees in the urban forest provide the most benefits and since tree mortality is highest for planted trees during the establishment period just after transplanting, sustaining an optimized level of urban forest benefits through time involves maintaining a diverse species assemblage and appropriate distribution of trees of different sizes and ages (Fig. 6; after Richards, 1983).

The second way to conceptualize urban forest sustainability involves a more holistic assessment of how urban forests might fit into larger efforts for community or urban sustainability (or even global sustainability). In this context, sustainability is defined as meeting human needs (food, housing, energy needs, etc.) while making sure that the environmental limits of the Earth (for processes such as climate change, freshwater use, land system change, etc.) are not exceeded (cf., the definition of sustainability used by Steffen et al. (2015) and Raworth (2017)) (Fig. 5B). So the quest for the sustainable urban forest then is how can urban forests contribute to meeting human needs without exceeding Earth's environmental limits (cf., Vogt and Hauer, 2017)? For instance, in hot dry climates, properly placed drought-tolerant trees can provide shade and decrease urban temperatures help mitigate the impacts of climate change without requiring excessive amounts of freshwater for irrigation. Another example is the planting of fruit trees, which provide fresh food in urban food deserts and contribute to meeting human needs.

These two conceptualizations of urban forest sustainability are not necessarily incompatible. The former (Fig. 5A) is a much more specific idea of what sustainability of the urban forest is and to be satisfied requires only that the urban forest (i.e., the trees as a natural resource) be maintained. The latter (Fig. 5B) requires consideration of multiple urban forest benefits and costs in the context of the trade-offs between environmental- and human-related sustainability goals, which can contribute to the maintenance of the urban forest (that is, the persistence of urban forest structure over time, as in Fig. 5A). Depending on the existing urban forest situation (structure, actors, etc.), one or the other means of operationalizing sustainability may be more desirable.

### Criteria for Evaluating Urban Forest Sustainability

Within the field of urban forestry one of the first to consider urban forest sustainability was Clark et al. (1997), who presented an approach for evaluating urban forest sustainability. They consider the characteristics of the urban forest and urban forestry activity within a single municipality that are crucial to sustaining the urban forest resource over time. For these authors, a "sustainable urban forest" refers to an urban forest system that persists "over time in a way that provides maximum benefits from the functioning of that forest" (Clark et al., 1997: p. 17). To this end, they describe the three core components of a sustainable urban forest—a healthy vegetative resource, comprehensive management, and a supportive community—as well as a set of criteria that if achieved should yield a sustainable level of urban forest benefits over time (Clark et al., 1997; Table 2). The framework was updated and clarified by Kenney et al. (2011), who added detailed performance indicators to each of the criteria in the Clark et al. (1997) three core components, in order that managers or others might actually measure the sustainability of a particular urban forest according to the framework by assessing the level of performance for each of the sustainability criteria.

## What Shapes Urban Forest as Social-Ecological Systems?

As illustrated in this chapter, a confluence of complex factors shape the trees and forests in urban areas. Observed characteristics of urban forests—such as urban forest structure, benefits, ecosystem disservices, and sustainability—are ultimately shaped by both human and biophysical factors. Because of this urban forest ecosystems can be best understood as "social-ecological systems." A *system* is a group of components interacting in a self-organizing capacity to generate some type of outcome or function that would not be intuitive based on the sum of the components. More simply, systems are "a set of things . . . interconnected in such a way that

**Table 2** Components and criteria of a sustainable urban forest. Optimal performance levels, as well as the key objective that performance level is designated to achieve as defined by Kenney et al. (2011) are shown. Performance levels for each criteria can be found in the Appendix of Kenney et al. (2011).

| *Component* | *Criteria* |
|---|---|
| Vegetative resource | Relative canopy cover |
| | Age distribution of trees in the community |
| | Species suitability |
| | Species distribution |
| | Condition of publicly owned trees |
| | Publicly owned natural areas |
| | Native vegetation |
| Community support | Public agency cooperation |
| | Involvement of large private and institutional land holders |
| | Green industry cooperation |
| | Neighborhood action |
| | Citizen-municipality-business interaction |
| | General awareness of trees as a community resources |
| | Regional cooperation |
| Resource management | Tree inventory |
| | Canopy cover inventory |
| | Citywide management plan |
| | Municipality-wide funding |
| | City staffing |
| | Tree establishment planning and implementation |
| | Tree habitat suitability |
| | Maintenance of publicly owned, intensively managed trees |
| | Tree risk management |
| | Tree protection policy development and enforcement |
| | Publicly owned natural areas management planning and implementation |

Components and criteria listed from: Clark, J. R., Matheny, N. P., Cross, G., and Wake, V. (1997). A model of urban forest sustainability. *Journal of Arboriculture* **23**(1), 17–30.

they produce their own pattern of behavior over time" (Meadows, 2008). *Social-ecological systems*—sometimes also called "socio-environmental systems" or "coupled human-natural systems"—are systems of both human and natural subsystems, where the inter-workings of each subsystem are inseparable from one another and the entire system cannot be fully understood without looking at the system as a whole (c.f., Ostrom, 2009; Epstein et al., 2013; Vogt et al., 2015a). Urban forests—with their interlinked systems of trees and the people and groups who interact with those trees to produce the character of the urban forest—are social-ecological systems (Vogt and Fischer, 2014; Vogt et al., 2015c).

In seeking to understand how any system functions, it is often of interest to examine the sets of components within the system and the relationships between components, in order to elucidate how interactions lead to observed outcomes. A framework is useful to this end. A framework contains general sets of variables that may be related to one another in order to "[provide] a metatheoretical language to enable scholars to discuss any particular theory or to compare theories" (Ostrom, 2010). Frameworks can be particularly useful for fields such as urban forestry that are *transdisciplinary*—that is, that combine knowledge and methods from multiple academic disciplines and from research and practice and integrate both researchers as well as non-researcher stakeholders from across multiple sectors—and can help provide a common language for communicating.

For urban forests, a comprehensive framework for understanding and examining urban forests as social-ecological systems is presented in Fig. 7 (based on an unpublished manuscript-in-progress by the author; synthesized from existing urban forestry frameworks by Clark et al. (1997), Mincey et al. (2013), Vogt and Fischer (2014), Vogt et al. (2015b,c), Steenberg et al. (2016), Roman et al. (2018), and Hilbert et al. (2019); and the social-ecological systems framework by Ostrom (2009); as updated by Epstein et al. (2013) and Vogt et al. (2015a)). In the framework, the factors that shape urban forest outcomes are numerous, but can be broadly grouped into four core sets of variables: the characteristics of the tree; the surrounding growing environment; *institutions* (the rules and strategies governing interactions between humans and between humans and the environment, in this case, the maintenance and management of the urban forest); and the characteristics of the human community. These core sets of variables interact with one another, but are also influenced by broader ecosystem dynamics, as well as the larger social, economic, and political systems within which urban forests exist. All of these factors must be considered in order understand the complex outcomes observed in urban forest ecosystems and in efforts to study urban forest dynamics.

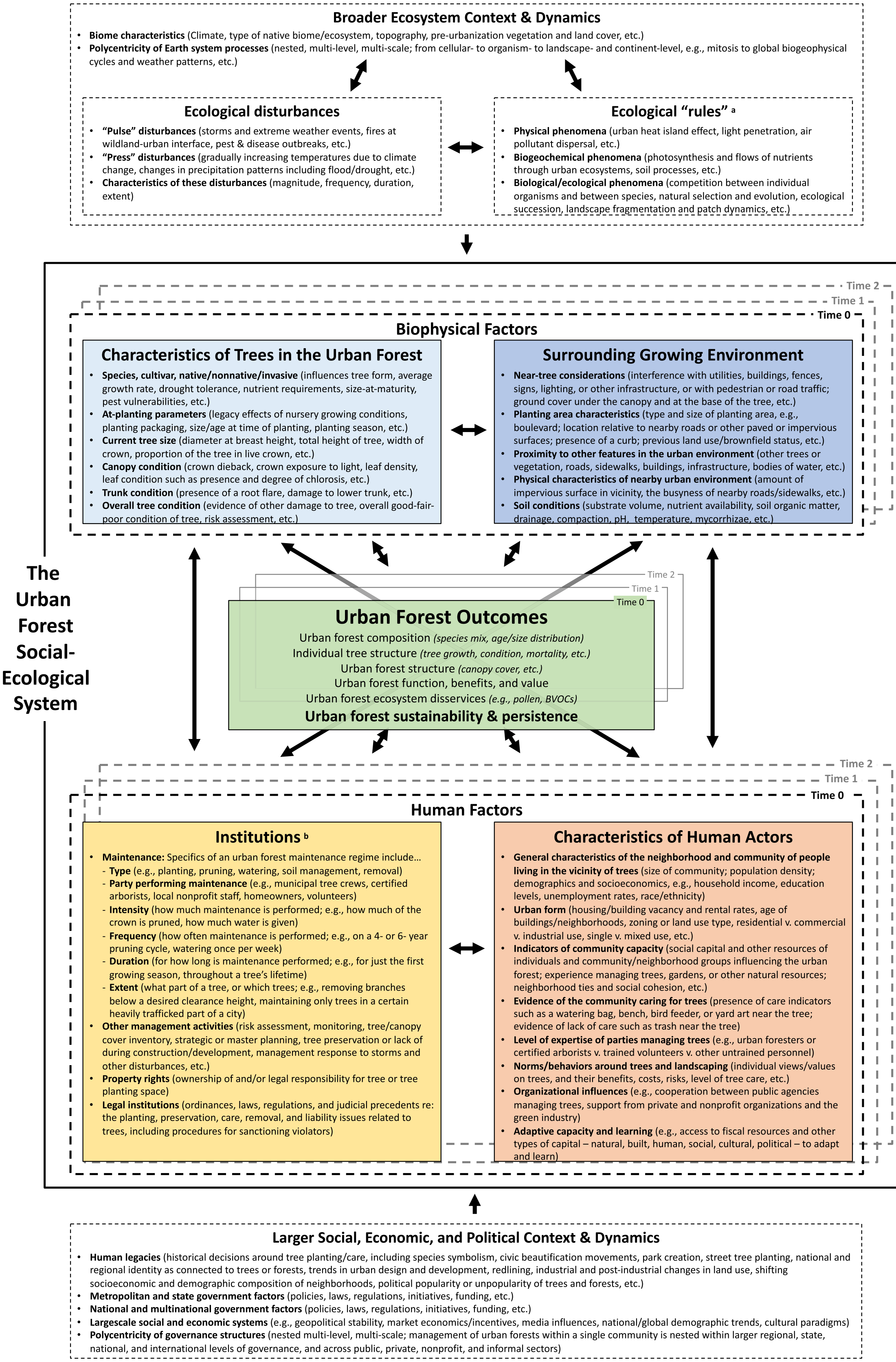
Broader Ecosystem Context & Dynamics
• Biome characteristics (Climate, type of native biome/ecosystem, topography, pre-urbanization vegetation and land cover, etc.)
• Polycentricity of Earth system processes (nested, multi-level, multi-scale; from cellular- to organism- to landscape- and continent-level, e.g., mitosis to global biogeophysical cycles and weather patterns, etc.)
Ecological disturbances
• “Pulse” disturbances (storms and extreme weather events, fires at wildland-urban interface, pest & disease outbreaks, etc.)
• “Press” disturbances (gradually increasing temperatures due to climate change, changes in precipitation patterns including flood/drought, etc.)
• Characteristics of these disturbances (magnitude, frequency, duration, extent)
Ecological “rules” a
• Physical phenomena (urban heat island effect, light penetration, air pollutant dispersal, etc.)
• Biogeochemical phenomena (photosynthesis and flows of nutrients through urban ecosystems, soil processes, etc.)
• Biological/ecological phenomena (competition between individual organisms and between species, natural selection and evolution, ecological succession, landscape fragmentation and patch dynamics, etc.)
The Urban Forest Social-Ecological System
Time 2
Time 1
Time 0
Biophysical Factors
Characteristics of Trees in the Urban Forest
• Species, cultivar, native/nonnative/invasive (influences tree form, average growth rate, drought tolerance, nutrient requirements, size-at-maturity, pest vulnerabilities, etc.)
• At-planting parameters (legacy effects of nursery growing conditions, planting packaging, size/age at time of planting, planting season, etc.)
• Current tree size (diameter at breast height, total height of tree, width of crown, proportion of the tree in live crown, etc.)
• Canopy condition (crown dieback, crown exposure to light, leaf density, leaf condition such as presence and degree of chlorosis, etc.)
• Trunk condition (presence of a root flare, damage to lower trunk, etc.)
• Overall tree condition (evidence of other damage to tree, overall good-fair-poor condition of tree, risk assessment, etc.)
Surrounding Growing Environment
• Near-tree considerations (interference with utilities, buildings, fences, signs, lighting, or other infrastructure, or with pedestrian or road traffic; ground cover under the canopy and at the base of the tree, etc.)
• Planting area characteristics (type and size of planting area, e.g., boulevard; location relative to nearby roads or other paved or impervious surfaces; presence of a curb; previous land use/brownfield status, etc.)
• Proximity to other features in the urban environment (other trees or vegetation, roads, sidewalks, buildings, infrastructure, bodies of water, etc.)
• Physical characteristics of nearby urban environment (amount of impervious surface in vicinity, the busyness of nearby roads/sidewalks, etc.)
• Soil conditions (substrate volume, nutrient availability, soil organic matter, drainage, compaction, pH, temperature, mycorrhizae, etc.)
Time 2
Time 1
Time 0
Urban Forest Outcomes
Urban forest composition (species mix, age/size distribution)
Individual tree structure (tree growth, condition, mortality, etc.)
Urban forest structure (canopy cover, etc.)
Urban forest function, benefits, and value
Urban forest ecosystem disservices (e.g., pollen, BVOCs)
Urban forest sustainability & persistence
Time 2
Time 1
Time 0
Human Factors
Institutions b
• Maintenance: Specifics of an urban forest maintenance regime include…
- Type (e.g., planting, pruning, watering, soil management, removal)
- Party performing maintenance (e.g., municipal tree crews, certified arborists, local nonprofit staff, homeowners, volunteers)
- Intensity (how much maintenance is performed; e.g., how much of the crown is pruned, how much water is given)
- Frequency (how often maintenance is performed; e.g., on a 4- or 6- year pruning cycle, watering once per week)
- Duration (for how long is maintenance performed; e.g., for just the first growing season, throughout a tree’s lifetime)
- Extent (what part of a tree, or which trees; e.g., removing branches below a desired clearance height, maintaining only trees in a certain heavily trafficked part of a city)
• Other management activities (risk assessment, monitoring, tree/canopy cover inventory, strategic or master planning, tree preservation or lack of during construction/development, management response to storms and other disturbances, etc.)
• Property rights (ownership of and/or legal responsibility for tree or tree planting space)
• Legal institutions (ordinances, laws, regulations, and judicial precedents re: the planting, preservation, care, removal, and liability issues related to trees, including procedures for sanctioning violators)
Characteristics of Human Actors
• General characteristics of the neighborhood and community of people living in the vicinity of trees (size of community; population density; demographics and socioeconomics, e.g., household income, education levels, unemployment rates, race/ethnicity)
• Urban form (housing/building vacancy and rental rates, age of buildings/neighborhoods, zoning or land use type, residential v. commercial v. industrial use, single v. mixed use, etc.)
• Indicators of community capacity (social capital and other resources of individuals and community/neighborhood groups influencing the urban forest; experience managing trees, gardens, or other natural resources; neighborhood ties and social cohesion, etc.)
• Evidence of the community caring for trees (presence of care indicators such as a watering bag, bench, bird feeder, or yard art near the tree; evidence of lack of care such as trash near the tree)
• Level of expertise of parties managing trees (e.g., urban foresters or certified arborists v. trained volunteers v. other untrained personnel)
• Norms/behaviors around trees and landscaping (individual views/values on trees, and their benefits, costs, risks, level of tree care, etc.)
• Organizational influences (e.g., cooperation between public agencies managing trees, support from private and nonprofit organizations and the green industry)
• Adaptive capacity and learning (e.g., access to fiscal resources and other types of capital – natural, built, human, social, cultural, political – to adapt and learn)
Larger Social, Economic, and Political Context & Dynamics
• Human legacies (historical decisions around tree planting/care, including species symbolism, civic beautification movements, park creation, street tree planting, national and regional identity as connected to trees or forests, trends in urban design and development, redlining, industrial and post-industrial changes in land use, shifting socioeconomic and demographic composition of neighborhoods, political popularity or unpopularity of trees and forests, etc.)
• Metropolitan and state government factors (policies, laws, regulations, initiatives, funding, etc.)
• National and multinational government factors (policies, laws, regulations, initiatives, funding, etc.)
• Largescale social and economic systems (e.g., geopolitical stability, market economics/incentives, media influences, national/global demographic trends, cultural paradigms)
• Polycentricity of governance structures (nested multi-level, multi-scale; management of urban forests within a single community is nested within larger regional, state, national, and international levels of governance, and across public, private, nonprofit, and informal sectors)

**Fig. 7** A comprehensive framework for understanding and examining observed outcomes in urban forests as social-ecological systems. There are four core sets of endogenous variables relating to characteristics of the tree, the surrounding growing environment, institutions, and the characteristics of the human community, which interact to produce observed urban forest outcomes. Core sets of variables, interactions, and observed outcomes are dynamic and may change over time. Additionally, core sets of variables are influenced by the context and dynamics of the broader ecosystem and social, economic, and political systems within which urban forest exist. [a]"Ecological rules" language after Epstein et al. (2013) and Vogt et al. (2015a). [b]"Institutions" refers to the formal and informal rules and strategies that structure interactions between people and between people and the environment, after Ostrom (2005). Unpublished manuscript-in-progress by the author. Synthesized from the many existing frameworks for understanding urban forests outcomes (Clark, J. R., Matheny, N. P., Cross, G., and Wake, V. (1997). A model of urban forest sustainability. *Journal of Arboriculture* **23**(1), 17–30; Mincey, S. K., Hutten, M., Fischer, B. C., Evans, T. P., Stewart, S. I., and Vogt, J. M. (2013). Structuring institutional analysis for urban ecosystems: A key to sustainable urban forest management. *Urban Ecosystem* **16**(3), 553–571. https://doi.org/10.1007/s11252-013-0286-3; Vogt, J. M. and Fischer, B. C. (2014). A protocol for citizen science monitoring of recently-planted urban trees. *Cities and the Environment* **7**(2), art. 4. Available at: http://digitalcommons.lmu.edu/cate/vol7/iss2/4; Vogt, J.M., Watkins, S. L., Mincey, S. K., Patterson, M. S., and Fischer, B. C. (2015c). Explaining planted-tree survival and growth in urban neighborhoods: A social–ecological approach to studying recently-planted trees in Indianapolis. *Landscape and Urban Planning* **136**, 130–143. https://doi.org/10.1016/j.landurbplan.2014.11.021; Vogt, J., Hauer, R. J., and Fischer, B. C. (2015b). The costs of maintaining and not maintaining the urban forest: A review of the urban forestry and arboriculture literature. *Arboriculture & Urban Forestry* **41**(6), 293–323; Steenberg, J. W. N., Millward, A. A., Nowak, D. J., and Robinson, P.J. (2016). A conceptual framework of urban forest ecosystem vulnerability. *Environmental Reviews* 1–12. https://doi.org/10.1139/er-2016-0022; Roman, L. A., Pearsall, H., Eisenman, T. S., Conway, T. M., Fahey, R. T., Landry, S., Vogt, J. M., van Doorn, N. S., Grove, J. M., Locke, D. H., Bardekjian, A. C., Battles, J. J., Cadenasso, M. L., Konijnendijk van den Bosch, C. C., Avolio, M., Berland, A., Jenerette, G. D., Mincey, S. K., Pataki, D. E., and Staudhammer, C. (2018). Human and biophysical legacies shape contemporary urban forests: A literature synthesis. *Urban Forestry & Urban Greening* **31**, 157–168. https://doi.org/10.1016/j.ufug.2018.03.004; Hilbert, D. R., Roman, L. A., Koeser, A. K., Vogt, J., and van Doorn, N.S. (2019). Urban tree mortality: A literature review. *Arboriculture & Urban Forestry* **45**(5), 167–200) and the social-ecological systems framework (Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science* **325**(5939), 419–422. https://doi.org/10.1126/science.1172133; Epstein, G., Vogt, J. M., Mincey, S. K., Cox, M., and Fischer, B. (2013). Missing ecology: Integrating ecological perspectives with the social-ecological system framework. *International Journal of the Commons* **7** (2), 432–453. Retrieved from http://www.thecommonsjournal.org/index.php/ijc/article/view/371/331; Vogt, J.M., Epstein, G. B., Mincey, S. K., Fischer, B.C., McCord, P. (2015) Putting the "E" in SES: Unpacking the ecology in the Ostrom social- ecological system framework. *Ecology and Society* 20(1), art. 55. Available at: http://www.ecologyandsociety.org/vol20/iss1/art55/).

## Conclusion

Urban forests are all the trees and vegetation existing in close concert with humans in some of the most densely settled places on the planet. As such, in order to understand the biophysical and ecological character of urban forests, we must examine how the various actors, from professional urban foresters to homeowners to urban greening nonprofits, maintain and manage the urban forest on both public and private property. This management (or, sometimes, such as on vacant lots, lack thereof ) results in urban forest benefits or ecosystem services (such as aesthetic beauty, shade, and stormwater management). But trees, forests, and the management they require also has costs, including direct, private costs for maintenance (such as pruning, watering) or to deal with tree conflict with infrastructure (e.g., heaving up sidewalks), as well as public costs in the form of ecosystem disservices (e.g., tree pollen producing allergies) and opportunity costs (space for trees in the public right-of-way cannot also be used for a bike lane). Because of these interactions between humans and the vegetation in cities, the urban forest can be best understood as a social-ecological system.

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