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MEASURING AND MONITORING URBAN TREES AND URBAN FORESTS

Justin Morgenroth and Johan Östberg

The urban forest and its components

The urban forest includes diverse floristic and physiognomic plant communities, including trees, shrubs, herbaceous plants, and mosses. This chapter focuses solely on measuring and monitoring urban trees, rather than all plant communities within the urban forest. Urban trees can be classified into numerous groups including street trees, residential trees, park trees, and woodland trees. They may have been recently planted or they may be old-growth remnant forests on public or privately owned land.

Measuring and monitoring urban trees has been conducted for over a century (e.g. Solotaroff, 1912), certainly prior to the establishment of urban forestry as a discipline in the late 1960s and early 1970s (Jorgensen, 1986). As knowledge about ecosystem services has developed, and as government responsibility for urban forest management has increased, the need for standardised monitoring has increased. Without detailed data on the location, structure, and condition of city trees, it is not possible to manage them effectively, nor to estimate ecosystem service provision or urban forest value, nor to develop informed policy or strategy.

In this chapter, we will introduce the reader to the topic of urban forest assessment. The chapter begins with a description of some variables measured during urban forest assessment and the tools and approaches used for this task. This is followed by a discussion of the different stakeholders who engage in urban forest assessment, including citizen volunteers, researchers, and governments.

Measuring and monitoring the urban forest

Forest mensuration is among the most fundamental disciplines in forestry and related sciences, including urban forestry. It focuses on the technical aspects of tree and forest measurement and monitoring. The terms ‘measuring’ and ‘monitoring’ are often used synonymously, but should not be confused with one another. In an urban forestry context:
• **measuring** refers to determining the number of trees, their structure, their condition, and other quantitative or qualitative characteristics; this yields data for a single point in time.

• **monitoring** involves repeatedly measuring over time to observe and describe changes in the urban forest.

While measuring is useful, monitoring the urban forest allows for better informed policy and decision making with respect to urban forest management. For example, if a city had measured their urban forest species composition ten years ago, they would have known that, at that time, the most abundant species comprised 15 per cent of all planted trees. If the same city had measured their urban forest species composition every ten years between 1950 and 2010, they would know how species diversity changed over that time period. They could correlate these changes with pest and disease outbreaks or climate change to understand how species diversity responded to these, among other factors. The city could develop informed policies and management strategies to achieve desirable future tree species diversity goals and – importantly – the city could monitor how urban forest diversity responds to those policies or management strategies.

### Common urban forest variables for measurement

The question of what to measure in an urban forest has many answers depending on the context or purpose of measurement. Miller et al. (2015b) suggest that data collection should aim to provide a minimal level of data to allow intelligent decisions. Measuring the urban forest to inform policy may only require determining tree canopy cover. But this variable fails to differentiate between individual trees and does not describe the health and condition, nor the three-dimensional structure, nor the diversity of the urban forest. A more comprehensive set of variables is required to improve urban forest management. These data may include the location of each tree, its species, and basic structural variables like height and diameter at breast height (DBH). To estimate ecosystem services, more detailed structural variables may be required, including estimation of tree volume and leaf area (Nowak et al., 2008a). To minimise risk in the urban forest, a city may regularly update tree condition and keep records of all maintenance activities conducted on publicly owned trees. An inventory of veteran or notable trees may include planting date as well as details about who planted the tree and why it was planted (e.g. to commemorate an event or person).

The hypothetical examples presented above suggest that the set of potential variables to measure for urban trees and forests will depend on the desired end use of the data. It follows that many different potential end uses will require numerous structural variables to be measured and/or derived. Generally, the measured variables can fall under the categories of location (e.g. latitude, longitude), 1D structure (e.g. DBH, height, crown spread; Figure 3.1), 2D structure (e.g. crown area), 3D structure (e.g. volume), form (e.g. crown shape, lean), condition (e.g. defoliation, leaf chlorosis), and risk (e.g. cracks, weak attachments). While it’s impractical to compile all potential urban tree variables, we can examine existing examples of urban forest inventory variables and discuss how they achieve their purpose (Table 3.1 below).

### Urban forest variables for estimating ecosystem services

The United States Department of Agriculture (USDA) Forest Service software i-Tree recommends collecting a set of variables that are critical for estimating environmental and...
Measuring and monitoring urban trees and urban forests

Figure 3.1 Common variables that are measured to describe a tree’s structure
Source: Allan McInnes

economic ecosystem services (i-Tree, 2015). These include the tree variables of species, DBH, total tree height, height to live top, height to crown base, crown width, percent missing crown, percent crown dieback, and crown light exposure, as well as the site variable of land use. The tree and crown structural variables are necessary for estimating tree leaf area and biomass and subsequently modelling rainfall interception, carbon sequestration and storage, and energy savings, among other ecosystem services.

Urban forest variables for long-term monitoring

For long-term monitoring of urban trees, the Urban Tree Growth and Longevity working group recommend collecting project variables including measurement date and training level of the field crew, site variables including site type and land use, and tree variables including GPS coordinates, species, mortality status, tree condition, DBH, and the height at which DBH was measured (UTGL, 2014). The GPS coordinates, in conjunction with the species and size data, allow the same tree to be observed over time. The data about field crew training level allows for any spurious data over a time series to be validated or discounted based on the skill level of the field measurement crew.

Urban forest variables for management

The city of Christchurch, New Zealand, collects urban forest inventory for three main reasons:

1 to identify and mitigate risk;
2 to plan future renewal programmes including budgeting; and
3 to inform future strategic directions and planning (e.g. setting species diversity goals).
To meet these goals, the city collects the GPS location of each tree, species, height, crown width, DBH, structural condition, health condition, overall condition, planting date, type of protection, damage, cause of damage, maintenance record, and cost of maintenance activity.

The three previous examples highlight that:

1. the possible variables to measure in an urban forest are varied;
2. there are core variables common to many data collection undertakings (e.g. species, DBH), and optional variables used to meet specific desired outcomes (e.g. percentage crown dieback, cost of tree maintenance activity); and
3. the choice of variables to include must be determined by stakeholders to meet a given outcome – and so the purpose of measurement must be clearly defined before the variables can be agreed upon.

Table 3.1 A comparison of the plot and tree variables collected by three different inventory systems, each with a different purpose

<table>
<thead>
<tr>
<th></th>
<th>i-Tre</th>
<th>UTGL</th>
<th>Christchurch City Council</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Purpose of data collection</strong></td>
<td>• Ecosystem service modelling</td>
<td>• Long-term monitoring</td>
<td>• Risk mitigation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Budgeting</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Strategic planning</td>
</tr>
<tr>
<td><strong>Location variables</strong></td>
<td>• N/A</td>
<td>• GPS coordinates</td>
<td>• GPS coordinates</td>
</tr>
<tr>
<td><strong>Structural variables</strong></td>
<td>• DBH</td>
<td>• DBH</td>
<td>• Total tree height</td>
</tr>
<tr>
<td></td>
<td>• Total tree height</td>
<td>• Height at which DBH was measured</td>
<td>• Crown width</td>
</tr>
<tr>
<td></td>
<td>• Crown width</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Height to live top</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Height to crown base</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Condition variables</strong></td>
<td>• Percent missing crown</td>
<td>• Crown dieback</td>
<td>• Health condition</td>
</tr>
<tr>
<td></td>
<td>• Percent crown dieback</td>
<td>• Crown transparency</td>
<td>• Overall condition</td>
</tr>
<tr>
<td><strong>Risk variables</strong></td>
<td>• N/A</td>
<td>• Wood condition</td>
<td>• Structural condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Damage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Cause of damage</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>• Maintenance record</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Cost of maintenance activity</td>
</tr>
<tr>
<td><strong>Other variables</strong></td>
<td>• Species</td>
<td>• Species</td>
<td>• Species</td>
</tr>
<tr>
<td></td>
<td>• Crown light exposure</td>
<td>• Tree record</td>
<td>• Planting date</td>
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<tr>
<td></td>
<td>• Actual land use</td>
<td>• Identification code</td>
<td>• Type of protection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Mortality status</td>
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<tr>
<td></td>
<td></td>
<td>• Site type</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>• Land use</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Date of measurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Training level of the field crew</td>
<td></td>
</tr>
</tbody>
</table>
Table 3.1 highlights these three points by showing that i-Tree data collection focuses on measuring tree structure, UTGL data collection focuses on ensuring the same tree can be identified and measured consistently over time, while the Christchurch City Council data collection focuses primarily on risk and condition variables.

**The importance of standardisation**

Management, planning, and strategic directives for urban forests can be informed by comparing variables like canopy cover, structural distribution, or species diversity across different cities or with data previously collected for the same city. This spatial and temporal comparison is most useful if the data collected is available in a common form. While standards for urban forest measurement are widely recommended in the scientific literature (Roman et al., 2013; Nielsen et al., 2014), different approaches to urban forest inventorying are commonly used and different variables are collected. Methods vary widely and efforts to collect data across cities remain uncoordinated (Roman et al., 2013). This is not only true globally, but also locally – cities adjacent to one another are likely to have different standards for data collection and also reporting.

Fortunately, standardised approaches to data collection and reporting are becoming more common in urban forestry. The USDA i-Tree Eco software is arguably the most widely adopted standard globally. Dozens of cities have undertaken such inventories and assessments; while most have been conducted in the USA and Canada, cities in Australia, China, England, Hungary, Portugal, Scotland, Spain, and Switzerland have also used i-Tree Eco to develop knowledge about their urban forests. As of 2015, the US Forest Service began monitoring urban areas as part of their national forest inventory, using i-Tree as the analysis tool. One of the keys to i-Tree’s success is that it is in the public domain and is freely available. Not only does i-Tree provide data collection standards, but also reporting is standardised and generally publicly available.

Numerous countries or cities have alternative approaches to data collection and reporting (e.g. the Swedish Tree Portal). But because i-Tree has been used by numerous communities, it is allowing for some of the spatial and temporal comparisons that are best made with standardised data. For example, the cost-benefit ratio of urban trees was calculated for five different cities in the USA using the STRATUM (a precursor to i-Tree Streets) standardised approach to data collection (McPherson et al., 2005). Urban forest functional diversity was compared across seven cities in the Northeastern United States whose inventory data had been collected using the i-Tree Eco plot sampling standard (Nock et al., 2013). Species diversity in 38 cities globally was compared using data collected by the UFORE (a precursor to i-Tree Eco) standardised approach to plot sampling and data collection (Yang et al., 2015). The standardised approach provided by i-Tree has made it possible to find answers to questions that would otherwise be difficult (if not impossible) to solve.

**Methods for measuring the urban forest**

Once a set of variables has been decided upon, the next step is to undertake the measurements – but how? The detailed methods used to measure trees and forests are described in numerous excellent publications (e.g. Miller et al., 2015b), so this section will not endeavour to provide the reader with another such description. Instead, this section will firstly introduce the reader to common tools and technological advances to measure some common urban forest variables. Secondly a description of general approaches to urban forest inventory will be provided, and thirdly the difference between sample, partial, and complete inventories will be discussed.
Common tools for urban forest measurement

Many of the tools used to measure urban trees were originally used in mensuration of natural and plantation forests. Some of them have been used for decades or even centuries, but new technologies are beginning to replace some of these traditional tools. In particular, remote sensing technologies like satellite imagery and LiDAR are being used more frequently to accurately measure various attributes of urban trees and forests. While remote sensing technologies are being employed more frequently, traditional techniques remain most common for urban forest inventories, due to their simplicity, ease of use, and track record of adequacy. The different tools described in this section have differing accuracy (nearness of the measurement to the actual value), precision (variation when the same measurement is repeated), cost, reliability, and ease of use.

STEM DIAMETER MEASUREMENTS

A nearly ubiquitous tool for forest and urban forest measurement is the diameter tape, used to measure diameter at breast height. The diameter tape generally has a linear scale on one side which can be used to measure the circumference of the tree. On the other side of the tape is a diameter scale, whereby the diameter scale divides the linear scale by pi ($\pi \approx 3.14$). When the tape is placed around the circumference of the tree, the tape measures the circumference and estimates the diameter of the tree for any given circumference value, assuming that the tree stem is circular. Another common tool for measuring tree stem diameter, particularly for small trees, is the calliper. Callipers can be used on any sized tree, but in urban forestry they are typically used on small trees in the nursery before planting out into the landscape.

Both the diameter tape and calliper are considered contact dendrometers, a category of diameter measurement tool that also includes the permanent diameter tape, the Finnish parabolic calliper, and the electronic tree measuring fork. Contact dendrometers come into physical contact with the tree stem. In contrast, optical dendrometers remotely estimate the diameter of trees; these include Wheeler’s pentaprism, McClure’s pentaprism, and the Barr and Stroud optical dendrometer. Hybrid optical/contact dendrometers also exist, including the Biltmore stick, Bitterlich’s sector fork, and the Samoan diameter stick. Clark et al. (2000a) comprehensively review many of these tools, describing them in detail and summarising their benefits and drawbacks. They conclude that the diameter tape and calliper provide the greatest accuracy for the lowest cost and that the two tools do not differ in their accuracy.

TREE HEIGHT AND CROWN MEASUREMENTS

Accurately measuring tree height and crown variables (e.g. height to base of live crown, height to live top, crown spread) is relatively challenging, with errors exceeding 30 per cent having been documented (Bragg, 2008). The large size of trees makes direct measurement difficult, though not impossible. Telescopic height rods are useful for directly measuring small trees, but are limited as tree height increases beyond the height of the extended pole. For large trees, direct measurement is much more difficult, but is possible by dropping a fabric tape from the highest point of a tree to the ground; this method is practically limited to those with adequate climbing training (Bragg, 2008). Indirect methods are generally better suited for estimating, rather than measuring, the height of large trees. Hypsometers estimate tree height using trigonometric (e.g. Suunto, Blume-Leiss, Haga, Abney level; see Figure 3.2) or geometric (e.g. Christen, Merritt, Vorkampff-Laue, Chapman) principles.
Though the term hypsometer is commonly used, some literature refers to hypsometers as clinometers or altimeters.

More recently, multi-purpose instruments using laser or ultrasonic technologies have been developed. Laser dendrometers combine laser range finding and angle measurement for estimating tree structure, while the Vertex (Haglöf Sweden AB, Långsele, Sweden) uses ultrasonic sensing and angle measurement to estimate height or other vertical linear variables. A benefit of these instruments is that height is calculated automatically by the instrument and displayed to the user. In contrast, manual hypsometers require the user to record distances and angles from which height can subsequently be calculated (Figure 3.2).

**Technological advance in urban forest measurement**

Technological advances have yielded the possibility of measuring tree structure using remote sensing approaches. Though photography has been used to measure tree structure for decades (e.g. Crosby et al., 1983), it suffers from several limitations. Photographic techniques only estimate one-dimensional tree structure variables (e.g. DBH, height) and thus, fail to provide measurements of three-dimensional variables like total tree volume. Moreover, they require fastidious attention to calibration and procedure to ensure accurate estimates. Perhaps for these reasons, photographic techniques have generally only been used in research settings (e.g. Clark et al., 2000b), while contact dendrometers and hypsometers have remained the preferred tools for users outside the research community.

More recently, advances in sensor technology and computer vision approaches have resulted in the potential to remotely measure the structure of urban trees. LiDAR (light detection and ranging) sensors can estimate one-dimensional, two-dimensional and three-dimensional tree variables in natural and planted forests, including urban forests. LiDAR sensors generate three-dimensional point clouds of trees (Figure 3.3), from which any number of structural variables can be estimated. LiDAR sensors can be attached to an aerial platform (e.g. fixed-wing aircraft), a terrestrial platform (tripod), or a mobile platform (e.g. car) for flexibility of use.

![Figure 3.2 How to estimate tree height using trigonometric methods, the sine method (left) and the tangent method (right)](image)
In urban settings, mobile and terrestrial LiDAR sensors have been used to estimate a variety of structural tree variables, though this has generally been limited to research settings. Mobile LiDAR scanners have been used to detect street trees and estimate their height, crown diameter, and DBH with a comparable accuracy to field-based measurements (Wu et al., 2013). Terrestrial LiDAR data has also been used to estimate tree height, stem diameter, total volume, and tree location (Holopainen et al., 2013). In contrast to terrestrial and mobile LiDAR acquisition, aerial LiDAR data cannot accurately measure DBH due to its aerial perspective (Figure 3.3). Instead, aerial LiDAR’s main uses in urban forestry are for estimating canopy cover, tree numbers, tree height, crown depth, and crown spread. Of the three platforms, aerial LiDAR is most likely to be used operationally for urban forest inventory, because it can be undertaken over large areas. Moreover, the fact that it does not directly measure DBH can be overcome by using height (which is directly measured) to estimate DBH (Saarinen et al., 2014). When combined with hyperspectral imagery, it is possible to identify individual trees, determine their species, and measure common structural variables (Alonzo et al., 2014).

Though LiDAR technology has demonstrated utility for forest assessment, its use for urban forestry inventory is less common. Zhang et al. (2015) suggest three reasons for this, namely the ‘complexity of urban areas, the spatial heterogeneity of urban forests, and the diverse structure and shape of urban trees’. We add to that list by suggesting that the high cost of data acquisition, as well as the technically challenging and computationally intensive data analysis, are contributors to the slow uptake of LiDAR-based urban forest inventories.

An alternative to LiDAR is structure-from-motion with multi-view stereo-photogrammetry (SfM-MVS) – an approach that combines stereo-photogrammetry with computer vision. Like LiDAR, SfM-MVS produces spatially accurate three-dimensional models using sets of overlapping two-dimensional digital images. SfM-MVS has not been used in urban forestry outside of specialised research applications (Miller et al., 2015a; Morgenroth and Gomez, 2014) and it is unlikely to be of use over large scales. However, for measuring the size, structure, and form of individual trees using SfM-MVS is intriguing due to its high degree of accuracy and low cost.

Figure 3.3 Point cloud of a *Fraxinus* spp. tree created with a terrestrial laser scanner (left) and aerial laser scanner (right)

Only basic tree structural data can be measured from aerial laser scanning (e.g. height, crown depth, average crown spread), while terrestrial laser scanning can measure DBH and even crown or woody volume with a high degree of accuracy.
General approaches to undertaking urban forest measurement

Presently, the vast majority of urban forest measurement and monitoring is conducted by ground-based field surveys (Nielsen et al., 2014), but other approaches exist including windshield surveys and remote sensing methods. The approach to data collection must be considered in the context of the desired outcomes, as not all approaches can accurately describe all tree and urban forest variables (Table 3.2). Even when an approach to measurement has been demonstrated to accurately measure or estimate a variable, it is important to recognise that the approach may not succeed in all scenarios. For example, a terrestrial LiDAR approach may be useful for describing the structure of an individual street tree, but will fail to do so for trees in an urban woodland due to occlusion effects. Likewise, a ground-based survey of species diversity will be appropriate for a public park, but perhaps not for trees on private property where access restrictions may limit visually assessing trees. Even if an approach is possible, it may not be practical. For example, measuring tree volume by ground-based measurements is possible through laborious destructive methods, but impractical for a large number of trees or trees that cannot be destroyed. However, it is possible to estimate volume reasonably well from ground-based measurements (Nowak et al., 2008a). Alternatively, modern LiDAR and photogrammetric techniques are non-destructive and can be used to efficiently estimate tree volume with a high degree of accuracy (Hackenberg et al., 2014).

Sample, partial, and complete inventories

Two important considerations during urban forest assessment are:

1. how many trees to measure; and
2. which trees to measure.

Depending on the answers to these questions, there are three options to choose from, each with their own benefits and drawbacks: sample inventory, partial inventory, and complete inventory. Sample and partial inventories measure a subset of the whole urban forest, in contrast to a complete inventory in which all trees are measured. Sample inventories rely on selecting a subset of trees from the entire population, whereas a partial inventory measures all trees meeting a particular condition. This could include all street trees or all trees in a park/neighborhood. Meanwhile a complete inventory measures all trees in the urban forest population and thus requires a high degree of resourcing relative to sample or partial inventories. Practically, complete inventories are often limited to trees on public lands (Miller et al., 2015b), though improvements in remotely sensed data (e.g. satellite imagery, LiDAR) and associated analysis methods allow for complete inventories to incorporate trees on private property (albeit with relatively limited information; see Table 3.2).

The quality of data obtained from sample, partial, and complete inventories can differ markedly. Complete inventories are the most accurate (Nowak et al., 2008b) given they directly measure the attributes of all trees in the urban forest. Partial inventories provide the same level of accuracy, but only for the specific subset they have measured. For example, the city of Milwaukee used a partial inventory (only street trees) to map ash trees (*Fraxinus* spp.) in preparation for an invasion of emerald ash borer. Numerous partial inventories can be strategically implemented over time to yield a complete inventory that is as old as the oldest partial inventory.

Sample inventories use mean and summary data from sampled data to estimate attributes for the whole urban forest (Nowak et al., 2008a). Because not all trees are measured, the
Table 3.2 Different approaches to measuring the urban forest are required depending on the desired outcomes. A ✓ suggests that the approach to measurement is likely to be able to measure or estimate the metric with a high degree of accuracy. A ✗ suggests that the approach to measurement is unlikely to be able to measure or estimate the metric with a high degree of accuracy. The ✓ and ✗ symbols are only a guide; specific examples that contradict the symbols may exist.

<table>
<thead>
<tr>
<th>Ability to accurately measure or estimate</th>
<th>Low and medium resolution satellite imagery †</th>
<th>High resolution satellite imagery †</th>
<th>Aerial photography †</th>
<th>Terrestrial photography ‡</th>
<th>Aerial LiDAR †</th>
<th>Terrestrial LiDAR ‡</th>
<th>Windshield survey ‡</th>
<th>Ground-based measurement ‡</th>
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<tbody>
<tr>
<td>Tree species</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>DBH</td>
<td>x</td>
<td>x</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>x</td>
<td>✓</td>
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</tr>
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<td>Crown depth</td>
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<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
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</tr>
<tr>
<td>Crown spread/area</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Tree/crown volume</td>
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<td>x</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
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<td>x</td>
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<td>x</td>
<td>x</td>
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<tr>
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<td>✓</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Canopy cover</td>
<td>✓</td>
<td>✓</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>x</td>
<td>x</td>
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</tbody>
</table>

† denotes an approach capable of being employed for trees on public and private land without seeking land owner permission, while ‡ denotes an approach that may require seeking land owner permission.
estimates yielded by sampling approaches have inherent variation (Nowak et al., 2015). But the variation can be minimised by increasing the number of samples (Miller et al., 2015b). Different strategies have been developed to obtain more precise estimates from sampled data that are representative of the urban forest as a whole. These include random, systematic, cluster, and stratified sampling. These strategies are generally applicable to any statistical sampling, but all have been used in urban forest inventory (Miller et al., 2015b).

Who measures urban forests?
A variety of stakeholders engage in urban forest assessment, including researchers, governments, and citizen volunteers. This section presents examples of the ways that different stakeholders measure and monitor urban forests.

Urban forest measurement by researchers
Researchers measure and monitor urban forests to quantify the ecosystem services they provide, including provisioning services (e.g. fuel and food), regulating services (e.g. air quality improvement, stormwater management), cultural services (recreation, aesthetics), and supporting services (e.g. primary production, nutrient cycling). By measuring the structure of trees, researchers can quantify the urban forest’s impact on micro-climate (Bowler et al., 2010), carbon sequestration (Nowak et al., 2013), atmospheric and particulate air pollution (Escobedo et al., 2011), and stormwater runoff (Kirnbauer et al., 2013). Qualitatively, a description of the urban forest can be correlated with human well-being (Dallimer et al., 2012), resilience during times of war (Lacan and McBride, 2009) or natural disasters (Morgenroth and Armstrong, 2012), food provision (McLain et al., 2012), property values (Dimke et al., 2013), and energy savings (McPherson and Simpson, 2003).

Quantification of ecosystem services, derived from measurements of urban forest structure, allows for economic valuation of the urban forest resource. For example, Nowak et al. (2002) estimated the total compensatory value for the urban forests of the 48 contiguous states in the United States to be 2.4 trillion USD. While measurement allows for ecosystem service quantification and economic valuation of urban forests, monitoring temporal dynamics allows researchers to describe change in urban forest structure or composition and relate this to anthropogenic, environmental, or climatic factors.

Urban forest measurement by government
Global forest monitoring is reported by the Food and Agriculture Organization of the United Nations in their Global Forest Resources Assessments reports. However, urban areas – and hence urban forests – are excluded from these reports. As such, efforts to measure and monitor urban forests at larger scales (e.g. region, country) are rare, though some exist (e.g. Nowak et al., 2001). Instead, monitoring is generally left to local governments. Local government tree inventories are motivated by factors including budgeting, maintaining the urban tree stock, identifying and mitigating high risk trees, and creating informed management plans which can include species distribution and canopy cover goals, or pruning frequencies. To highlight different motivations and different approaches to urban forest inventory by local governments, two case studies are presented, on the Swedish city of Malmö and the metropolitan city of New York, USA.
Malmö, Sweden

Malmö’s work with tree inventory and digitisation of its maps began in 1995 when houses, roads, and trees (in parks and streets) were digitised using computer-aided design (CAD). As part of the digitisation, a tree inventory was conducted. The tree inventory was fully undertaken when Dutch elm disease (DED) was found to have reached the city. The inventory data were used to efficiently identify susceptible trees and remove those infected by DED. This reduced the spread and impact of the disease, making it possible for Malmö to focus efforts and resources on replanting trees. The inventory helped Malmö recognise its over-reliance on elms (*Ulmus* spp.), which consequently resulted in the city’s decision to replant with a large diversity of species. That decision has resulted in Malmö having greater tree species diversity than many other Scandinavian cities (Sjöman et al., 2012).

The initial inventory (1995–1996) was continually updated with new plantings and removals, however, there was no full re-inventory until 2008. The re-inventory was a consequence of a tree falling and nearly hitting a person sitting on a park bench under the tree. This incident made Malmö realise that they needed to implement a new inventory, including a risk assessment for all trees. The new variables included in the 2008 inventory were: risk classification, damage (root/stem base, trunk, crown), presence of fruiting bodies, DBH, and recommended management action.

Malmö faces several monitoring challenges, including extracting the most value from their inventory data and data accessibility. The tree inventory database’s initial use was for paying contractors, whereby contractors are paid a fixed amount annually for regular maintenance and oversight of each tree in the database. To extract further value from the database, it is also used for strategic planning, risk management, as well as planning establishment and maintenance activities like planting, pruning, and removals. Data accessibility was also a problem for city arborists in Malmö. Though new tree variables were collected in 2008, the data were not available to city arborists until 2014 due to a poorly executed software upgrade. By the time city arborists could view the data, much of it was out of date. Further to this accessibility issue, Malmö’s tree inventory is not linked to the city’s other infrastructure databases. With better linkages, the city would have a better understanding of the spatial overlap between trees and below-ground infrastructure, which could reduce the risk of pipe root intrusion and allow planning for open stormwater systems.

New York City, USA

New York has conducted three street tree inventories (1995, 2005, and 2015). As part of the 2005 tree census, all the parameters necessary to conduct an i-Tree Eco assessment were collected. This provided an overview of the whole urban tree population, but also allowed for estimation of the economic value of the urban tree population, thereby allowing for a cost-benefit analysis to be undertaken. These calculations led to the city’s MillionTreesNYC programme, which aimed to plant one million trees around New York (the millionth tree was planted in 2015). This result demonstrates the importance of using an inventory to understand the current resource as well as plan strategically for the future of the urban forest.

The number of variables collected during the inventory was reduced significantly between 2005 and 2015. In 2005, approximately 50 different variables were collected, some of which provided little or no value to urban forest managers. For the 2015 census, the number of collected variables was optimised to include only those with a targeted end use. For example,
obvious signs of tree stewardship, like flowers planted beneath street trees (Figure 3.4) were noted, because this was evidence of a community group who took an active interest in the urban forest. NYC used this data to catalyse new tree stewardship programmes with community groups. The lesson learned between the 2005 and 2015 inventories was to select inventory variables only after the purpose of the inventory was well defined.

**Urban forest measurement by citizens**

Volunteer involvement in measuring and monitoring urban forests is a paradigm shift from traditional approaches conducted by trained government staff and professional contractors. But there are numerous potential benefits. Involving citizen scientists directly links a community to its urban forest, thereby increasing public consciousness of the benefits provided by the urban forest, and enhancing support for its stewardship. Cities are not the only beneficiaries of volunteer involvement in urban forest monitoring. Citizens become
empowered by partaking in the betterment of their own community and develop an enhanced appreciation of the urban forest (Van Herzele et al., 2005).

Cities are increasingly soliciting volunteers for help with urban forest monitoring – a top-down approach to involving citizens in urban forest measurement and monitoring. The 2015 TreesCount! inventory in New York City involved over 8,000 volunteers who signed up for online training, participated in inventories and became independent mappers. New York achieved their goal of updating their street tree inventory while at the same time engendering a sense of stewardship among the citizen volunteers. London, England, undertook an i-Tree Eco assessment using over 200 volunteers to measure all trees in 476 plots of 0.4 hectares. Volunteers were trained prior to surveying, but also there was a professional arborist or forester in each volunteer surveying team. Ecosystem services and urban forest values were quantified using the measured urban forest structural data as model inputs. The city of Melbourne, Australia, trains volunteers in data collection methods such that they can become citizen urban foresters, helping with street and park tree vegetation mapping, among other activities.

Despite the numerous benefits of using a citizen-science approach to urban forest monitoring, it remains important to consider data quality, cost, and citizen uptake. Training is essential to ensure data quality and the potential for newly collected data to be integrated seamlessly with existing inventory data. A study of an inventory of qualitative characteristics (e.g. species, condition) of street trees in Massachusetts, USA, found that the accuracy of data collected by trained volunteers compared favourably with that collected by certified arborists (Bloniarz and Ryan III, 1996). A previous study in Quercus garryana and Pinus ponderosa forests in Oregon, USA, showed that student volunteers measured quantitative characteristics (e.g. count, diameter at breast height) as accurately as professionals, but estimates of qualitative characteristics (e.g. crown shape) differed significantly from professional estimates (Galloway et al., 2006). An issue directly related to data quality is the availability of simple standards that are designed for citizen scientists rather than an academic or professional audience (Roman et al., 2013). Another consideration for citizen- or volunteer-led efforts for urban forest measurement is the cost. While volunteers donate their time, costs exist for recruitment, training, mobilisation, and supervision. Twenty years ago, in a study in Massachusetts, USA, these costs were in line with the costs of an urban forest inventory conducted by professional tree care companies (Bloniarz and Ryan III, 1996); it is unclear whether that remains true today.

**Perspectives and conclusion**

The importance of measuring and monitoring urban forests is being increasingly recognised by a variety of stakeholders, including communities, researchers, and governments. Their motivations range from a desire to quantify the ecosystem services provided by urban forests, to assessing the risks posed by unhealthy or damaged trees, to monitoring long-term urban forest dynamics. Sample, partial, and complete inventories should be undertaken with recognised, standardised approaches, with the provision that these may be modified to meet the specific objectives of any given mensurational undertaking. Though ground-based surveys remain the most common means to measure urban forests, windshield surveys and remote sensing approaches are also undertaken during monitoring. These approaches can be used independently or combined; the key point is to ensure that selected approach is appropriate for measuring the desired urban forest variables, recognising that approaches vary in their accuracy, precision, applicability, and practicality.
References


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