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Review of Urban Tree Inventory Methods Used to Collect Data at Single-Tree Level

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Abstract. With a growing number of urban tree inventory methods and diversifying use of tree inventory data by city authorities and researchers, there is a need to evaluate, review, and critically assess the inventory methods available. This study reviewed studies using urban tree inventories at single-tree level as their data source. Based on this, a bibliographic overview was established and a typology of contemporary urban tree inventory methods was created and used as a framework for evaluation and discussion of the measurement type and accuracy achievable with different methods. The authors found that data from urban tree inventories are currently being employed in research with an increasing number of focuses across a geographical scope that spans all continents except Africa. Four main types of urban tree inventories were distinguished: satellite-supported methods, airplane-supported methods, on-the-ground scanning or digital photography, and field surveys. Compiling results across studies and evaluating the parameters collected by these inventory methods and their accuracy of measurement revealed that the technology itself and current data processing methods limit the reliability of the data obtained from all methods except field surveys. The study authors recommend further technological development and scientific testing before these methods can replace field surveys.

Key Words. Airborne; Field Survey; Ground Scanning; Inventory; Satellite; Street Tree; Tree Assessment; Urban Forestry.

In recent decades there has been increased interest in urban tree inventories, resulting from growing problems with pest and disease attack on the urban tree stock (e.g., Raupp et al. 2006) and growing awareness among decision-makers of the multiple ecosystem services trees provide in the cityscape (Hubacek and Kronenberg 2013). The surge of interest in urban tree inventories has been supported by rapid methodological and technological developments (e.g., i-Tree 2012). City authorities, especially in North America and Europe, have increasingly started to perform tree inventories (e.g., Keller and Konijnendijk 2012; Sjöman 2012). Parallel to this, inventories have become valuable data sources for researchers studying the environmental, social, and economic services provided by urban trees. Scientific uses of data from urban tree inventories include studies of storm-damaged trees and identification of species and dimensions most affected (Jim and Liu 1997); risk assessments (Mattheck and Breloer 1994; Lonsdale 1999); identification of species composition and diversity (Raupp et al. 2006; Sjöman et al. 2012); modeling of local climate (Nowak et al. 2001; Yokohari et al 2001; Dimoudi and Nikolopoulou 2003; Nowak et al. 2006a); impacts on air pollution, urban heat island effects, and stormwater runoff (McPherson et al. 1997); assessment of the economic benefit of urban trees (Maco and McPherson 2003; i-Tree 2012); and monetary evaluation of individual trees (CTLA 2000; Cullen 2002; Randrup 2005).

While the urban forest is widely regarded as encompassing all woody vegetation in a city (Randrup et al. 2005), urban tree inventories have mostly focused on information at the single-tree level rather than stands or groups of trees in places such as woodlands or parks (Sjöman 2012; Östberg et al. 2013). The focus on information at single-tree level reflects the motives and goals of city authorities regarding urban forestry programs, where hazard management, traffic safety, arboricultural management, species choice, replanting decisions, and monitoring changes in the urban forest have been found to dominate (Keller and Konijnendijk 2012). However, scientific studies with different objectives and different traditions of urban tree management and planning each have their own specific information needs (Schipperijn et al. 2005). Smiley and Baker (1988) argue therefore that before deciding on what type of data to collect from each tree, the 'why' needs to be answered. The present does not only include the "why", but also the 'how' (i.e., how the tree inventory was performed and what technical aids were used to support data collection).

In response to the growing and diversifying use of data on single-tree level from urban tree inventories, the variety of inventory methods has expanded rapidly (Smiley and Baker 1988; McBride and Nowak 1989; Schipperijn et al. 2005). While field surveys offered the starting point, rapid technological development has meant that data at the single-tree level can now also be obtained from different types of ground scanning and digital photography (e.g. Buhyoff et al. 1984; Patterson et al. 2011; West et al. 2012), as well as a variety of satellite- and airplane-supported technical aids (e.g., Jutras et al. 2009; Ardila et al. 2012). Aerial methods have a range of applications for land-use and vegetation inventories at coarser scales (e.g., Mausel et al. 1992; Holopainen et al. 2006; Jutras et al. 2009). However different, all methods have their limitations regarding the data parameters that can be collected at single-tree level and their measurement accuracy, a fact that needs to be taken into account (Abd-Elrahman et al. 2010; Ardila et al. 2012). Therefore, Keller and Konijnendijk (2012) call for more research on the status of urban tree inventories and the accuracy and validity of data that can be obtained from different types of inventories. Against this background, the objectives of the present study were to:

1. Provide a bibliographic review of previous studies in which urban tree inventories at single-tree level are used as the primary data source.
2. Establish a typology of contemporary urban tree inventory methods and identify the type of data and the accuracy of measurements collected at single-tree level using different methods.
3. Evaluate the suitability of different urban tree inventory methods for data collection at single-tree level.

METHOD

Search Strategy

The study was conducted as a review restricted to peer-reviewed scientific literature.

Two widely recognized databases were used, Web of Science and Scopus. Aiming for high sensitivity, as recommended by Pullin and Stewart (2006), the search was restricted to a single search string with few search terms, namely: *tree* invent* urban**. The search terms were considered among the categories 'Title, abstract, keywords' (Scopus) and 'Topic' (Web of Science).

The search generated 154 hits. After the initial search, two rounds of selection were undertaken. First, articles were included or excluded based on their title and abstract. The remaining papers were reviewed and evaluated for their relevance. A total of 57 studies met the inclusion criteria, which were:

- urban tree inventories used as the main data source
- specification of the inventory method and the technical aids applied and the type of parameters collected at single-tree level
- published prior to December 31, 2012
- published in English

Among the articles that did not meet the inclusion criteria, those specifically studying the accuracy of measurements obtained from one or more inventory methods (but not applying the inventory data in further studies) were identified (n = 9) and used to support the accuracy assessment, which will be explained later. The authors understand that limiting the search to peer-reviewed scientific papers published in English may also have excluded a number of interesting studies published as national reports and papers, but these publications were excluded to assure a systematic search and high data quality.

Data Extraction and Analysis

A standardized data extraction spreadsheet was used to ensure controlled data retrieval. In the case of doubts and queries about whether data from an article or the entire article should be included, a discussion was held among the authors and a consensus decision was reached.

Bibliographic information was extracted on: a) year of publication, b) publishing journal, and c) geographical region in which the study was conducted. The main focus in information extraction was: d) information about the subject-specific focus of the study (henceforth, 'study focus'), e) the inventory method and type of technical aids applied, and f) the data parameters collected from each tree (e.g., diameter at breast height, tree height, species).

In total, 152 parameters were identified across the 57 studies. However, many were redundant, like variations on the same type of measurement (e.g. crown width, canopy width, canopy drip line width, crown diameter, crown spread, width of crown). After correcting for redundancies, a total of 59 parameters were grouped into 15 types of tree information parameters and three types of data-based parameters [e.g., various items of information on planting site in one group and various abiotic and biotic damage in another group (Appendix)]. Similarly, the inventory methods used to collect the data were clustered into overall typologies, reflecting differences with respect to terrestrial versus aerial methods, mode of transportation, and type of technical aid used to collect the data parameters from each tree.

A comparative analysis was then made of the relationship between study focus, inventory method, and the 15 types of tree parameters collected. The data-based parameters were excluded from the analysis. Finally, the accuracy of the measurements obtained from each inventory method was evaluated for the 15 parameter groups. For each inventory method, the accuracy evaluation was restricted to the parameter groups collected by use of the method and/or tested by studies addressing the accuracy of the measurements. In the evaluation, the findings of studies specifically assessing the accuracy of measurements obtained by different inventory methods was the starting point. Due to the inclusion of both qualitative parameters (e.g., maintenance need) and measurable parameters (e.g., DBH and crown diameter), and the heterogeneity in studies in terms of methodology and reporting of data (some studies reporting deviation from field survey data (e.g., Park et al. 2010) and others omitting this information (e.g., Rutzinger et al. 2011), quantitative criteria for evaluation of accuracy levels were not deemed suitable. Thus the evaluation of accuracy comprised an interpretation of findings across the studies addressing the individual inventory methods, with the accuracy divided into a qualitative scale with four levels: 0 = not possible or with very low precision; 1 = low precision; 2 = intermediate precision; and 3 = high precision, meaning the accuracy corresponded to that obtained from direct measurements on site (field surveys).

RESULTS

Bibliographic Overview

More than half the studies that met the inclusion criteria were conducted in North America (58%, n = 33), while articles originating from Asia accounted for 18% (n = 10), Europe 16% (n = 9), Australia 5% (n = 3), and South America 4% (n = 2). The search did not identify any publications from Africa.

The studies were published in as many as 36 different journals. *Arboriculture & Urban Forestry* (named *Journal of Arboriculture* until 2006) was the journal with the most publications, with 26% of the articles (n = 15), followed by *Landscape and Urban Planning* (n = 4), *Urban Forestry & Urban Greening* (n = 3), and *Remote Sensing* (n = 3). The remaining 32 journals were represented with one article each.

Articles were published from 1984 onwards, and two breakpoints in the flow of publications could be distinguished. Up until the mid-1990s, the publications were few and scattered, but from then on, publication stabilized with 1–2 articles per year, nearly all of which originated from North America (Figure 1). A second breakpoint occurred in the late 2000s, where the annual publication rate increased to 3–15 articles. This increase coincided with a noticeable rise in the number of articles reporting research from South America, Australia, Europe, and Asia (Figure 1).

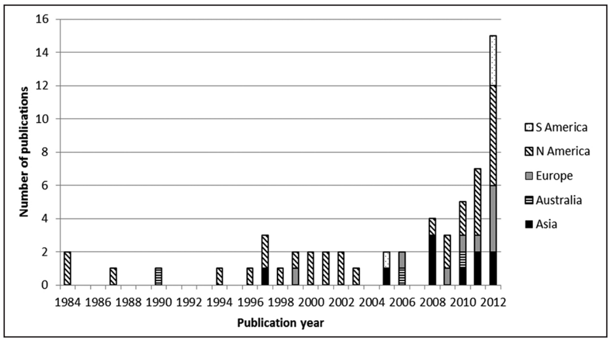

Figure 1. Number of publications on urban tree inventories per year and their geographical origin.

Table 1. Number of articles on urban tree inventories grouped according to study focus and year of publication.

Subject-specific focus	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	SUM
Biodiversity aspects																													3	3
Digitalization of tree shape																											1	2		3
Effect on urban climate, greenhouse gas and CO_2 storage																											2		1	3
Comparisons of models																						1	1							2
Cost-benefit analysis of urban trees																				1								2	1	4
Urban tree canopy cover																			1										1	2
Tree vitality																1		1	1						1				1	5
Land-use and land-use change														1								1								2
Species distribution and diversity													1				1						1		1	1	1	1		7
Comparison of trees in different types of urban green space											1																			1
Test of tree inventory methods							1							1												2	1	1	7	13
Arboricultural management				1										1		1												1	1	5
Transmission of volatile organic compound (VOC)	1														1		1	1							1					5
Tree architecture and amenity values	1																								1					2

Over the years, the number of different aspects examined in studies increased steadily, to a total of 14 (Table 1). Nearly all studies focusing on the economic benefits of urban trees (grouped under 'Cost-benefit analysis') and environmental aspects (grouped under 'Biodiversity', 'Canopy cover', and 'Climate/greenhouse/CO_2 storage') were published after 2001. However, studies addressing transmission of volatile organic compounds (VOCs) by urban trees were an exception from the temporal pattern in studies on the environmental aspects of urban trees. The growing number of publications from 2008 onwards is largely due to an increase in the number of methodological studies focusing on 'test of tree inventory methods' and 'digitalization of tree shape', and is also due to the emergence of studies in which urban tree inventory data on single-tree level are applied to assess 'Biodiversity aspects' (n = 3) (Table 1).

Typology of Urban Tree Inventory Methods

Four types of inventories for data collection at single-tree level with distinct characteristics were distinguished: 1) Satellite-supported methods, 2) airplane-supported methods, 3) on-the-ground scanning or digital photography, and 4) field surveys with direct manual measurements and/or visual inspection. As shown in Table 2, each of these types is supported by different means of technical aid.

Satellite-supported methods can collect information from very large areas (Cook and Iverson 1991; Small and Lu 2006). Very High Resolution (VHR) images, as well as Panchromatic and multispectral images taken by equipment on satellites (e.g., the QuickBird satellite), can be used to extract information on urban trees. Satellite-supported infrared (IR) scanning images of the wavelengths reflected by vegetation can also be used to collect information at single-tree level (e.g., Jansen et al. 2006). Satellite-supported data collection at single-tree level was used in two of the studies included in the review (Ardila et al. 2012; Cavayas et al. 2012) and to identify trees for subsequent field surveys in two other studies (Thaiutsa et al. 2008; Ningal et al. 2010) (Table 2).

Airplane-supported methods also enable data collection over large areas (Ryherd and Woodcock 1990; Mausel et al. 1992). Like satellites, airplanes can be equipped with appropriate devices, such as an IR scanner or different types of cameras (Goldberg 1981; Mausel et al. 1992; Andarz et al. 2009). However, only two of the studies reviewed adopted these methods (Miller and Winer 1984; Jutras et al. 2009) (Table 2).

Compared with the aerial methods, data collection and processing from on-the-ground digital scanning (Patterson et al. 2011) or photography (Abd-Elrahman et al. 2010) are restricted to rather small areas because each scanning/photography image is restricted to a single tree or a small group of trees. Although this technology is developing rapidly, it is still time-consuming. Of the 57 studies included in the review, five had applied methods in this typology (Abd-Elrahman et al. 2010; Park et al. 2010; Patterson et al. 2011; Rutzinger et al. 2011; West et al. 2012) (Table 2).

Field survey methods comprise direct measurements and/or visual inspection of individual trees by field staff (Adkins et al. 1997; Martin et al. 2011; Östberg et al. 2012). Although field surveys are labor-intensive and time-consuming, 46 of the 57 papers reviewed applied this method to collect their data, making it the most common of the four types. In the search for papers, a subtype of field survey was identified where the data collection is limited to visual inspection of appearance and damage (to inform assessment of hazard status) from a car driven at low speeds. This method has been called windshield survey (Bassett 1976; Rooney et al. 2005) or drive-by survey (Pokorny 2003). However, this subtype was not applied in any of the articles meeting the inclusion criteria (Table 2).

Relationship Analysis

Analysis of the relationship between study focus, inventory method, and parameters collected from each tree showed that data on the three parameters, crown size/density, tree size (other than crown size and DBH), and species information had been collected by studies falling into 12 different study focus classes, while the corresponding number for DBH was 11. Data on the remaining parameter groups, especially tree age information and tree coordinates, were collected by studies with fewer focus classes (two studies each) (Table 3).

Turning the perspective to the study focus, studies testing urban tree inventory methods,

Table 2. Typology of urban tree inventory methods and related technical aids used in collection of data at the single-tree level.

Typology	Technical aid	Description	References	No. of articles
Satellite-supported methods	QuickBird, Panchromatic and multispectral images. Very High Resolution images (VHR)	QuickBird is a high-resolution earth observation satellite. Panchromatic produces a realistic picture as it appears to the human eye. VHR images are taken by satellites (e.g., urban landscapes).	(Ardila et al. 2012)	3
	Google Maps and Google Maps TM API	Google Maps TM API (API = Application programming interface) (Google). Allows users to create thematic maps.	(Thornhill et al. 2009)	1
Airplane-supported methods	Airborne LIDAR data collection and Terrestrial Laser Scanning (TLS) Airborne Laser Terrain Mapping (ALTM)	LIDAR (Light Detection And Ranging, also LADAR) is an optical remote sensing technology that can measure the distance to, or other properties of, targets the use of laser. TLS works in a similar way by registering data using lasers. ALTM maps the surface and thereby acquires maps equivalent to those of GPS.	(Jutras et al. 2009)	1
	Aerial photos	Photos taken from aircrafts from different heights.	(Miller and Winer 1984)	1
Ground scanning/ photos	Customer grade cameras or digital photos	Photos taken by professional or digital cameras.	(Buhyoff et al. 1984; Abd-Elrahman et al. 2010; Patterson et al. 2011)	2
	Mobile Laser Scanning (MLS)	MLS is a technology in which objects are mapped by laser distance measurement from driving vehicles (e.g., road vehicles, ships, or railway trains). The data are then transformed into a 3D point cloud using GPS/IMU data.	(Rutzinger et al. 2011)	1
	Mobile Augmented Reality (AR)	AR is a way of viewing digital information which has been superimposed or augmented onto a live view of the real-world environment.	(West et al. 2012)	1
	Terrestrial Laser Scanning (TLS)	TLS analyses an object or environment to collect data on its shape. The collected data can then be used to construct digital, two-dimensional drawings or three-dimensional models.	(Park et al. 2010)	1
Field survey	Urban vegetation surveys (e.g., GPS receiver or handheld computers)	Field staff conduct direct measurements and visual inspections of individual trees, where position data can be supported by a GPS navigation device and data reporting supported by a handheld computer.	(Starr 1990: Lesser 1996; Sudol and Zach 1987; Adkins et al. 1997; Hsu 1997; Jim and Liu 1997; Poracsky and Scott 1999; Martin et al. 2011)	46
	Windshield method	Field staff conducts visual inspection of trees from a car driven at low speed (approx. 3 km/hr).	(Rooney et al. 2005).	0

tree vitality, arboricultural management, and tree architecture and amenity values had collected a much wider range of parameters, 13, 13, 12, and 11, respectively, compared with studies falling within the remaining 10 study focus areas (Table 3).

Concerning the inventory methods, field surveys had been applied for data collection by all 14 types of study focus areas and as the method for collection of all 15 tree parameter groups (Table 3). In comparison, data collection by use of satellite-supported methods was restricted to the parameter groups 'tree location', 'tree coordinates', and 'tree appearance', and this type of data collection was limited to studies testing the method. Airplane-supported methods were restricted to the testing and use of aerial photos as an aid to tree species identification and estimation of urban tree canopy cover. Ground scanning and digital photography was tested as a method to collect a wider range of tree parameters, and also applied to collect data on crown size/density, DBH, and other size parameters in studies focusing on CO_2 storage and/or digitalization of tree shapes.

Table 3. Type of tree inventory method used for each of the objectives and number of studies using the methods for each of the objectives. Type of tree inventory method: A, satellites; B, aerial photos; C, ground scanning/photos; D, field survey (windshield method not included). The numbers of studies using the methods for each of the tree inventory parameter groups are listed as subscripts.

Subject specific focus Subject of a specific focus	Number of publications that have this objective/purpose	Age or year of planting	Coordinates	Crown size, density	Damage, insects, and pests	DBH	Hazard	Infrastructure or buildings close to the tree, damage to these	Location	Maintenance need and history	Management information	Planting/growing site	Size (except crown and DBH)	Species	Tree appearance and use	Vitality	Total	Amount of parameter groups
Test of tree inventory methods	13	D_3	A_1	C_3D_5	C_1D_2	C_2D_7		C_1D_1	$A_1C_1D_2$	D_1	D_2		C_2D_5	B_1D_5	$A_1C_1D_2$	C_1D_4	$A_3B_1C_{12}D_{39}$	*13*
Species distribution and diversity	7		D_1	D_1		D_5			D_1				D_2	D_6	D_1	D_3	D_{12}	*7*
Arboricultural management	5			D_1	D_1	D_4	D_1	D_2	D_4	D_1	D_1	D_2	D_2	D_4		D_3	D_{26}	*12*
Tree vitality	5			D_2	D_3	D_4	D_1	D_2	D_3	D_2	D_1	D_1	D_4	D_4	D_1	D_5	D_{33}	*13*
Transmission of VOC	5	D_1		D_4									D_4	D_4		D_2	D_{15}	*5*
Cost-benefit analysis of urban trees	4			D_3	D_2	D_4					D_1		D_4	D_4		D_3	D_{21}	*7*
Effect on urban climate, greenhouse gases, and C storage	3			C_1D_1	D_1	D_3		D_1					D_2	D_2			C_1D_{10}	*6*
Biodiversity aspects	3					D_1							D_1	D_3			D_5	*3*
Digitalization of tree shape	3			C_3		C_1							C_2				C_6	*3*
Tree architecture and amenity values	2			D_1	D_1	D_2	D_1	D_1	D_1		D_1	D_1	D_1	D_2	D_1		D_{13}	*11*
Land use and land-use change	2			D_1		D_1			D_1				D_1	D_2			D_6	*5*
Comparisons of models	2			D_1									D_1	D_1		D_1	D_4	*4*
Urban tree canopy cover	2			B_1D_1								D_1					B_1D_2	*2*
Comparison of trees in different types of urban greenspace	1					D_1								D_1		D_1	D_3	*3*
Total	*57*	D_4	D_1A_1	$B_1C_3D_{21}$	C_1D_{10}	C_3D_{32}	D_3	C_1D_7	$A_1C_1D_{12}$	D_4	D_6	D_5	C_4D_{27}	B_1D_{38}	$A_1C_1D_5$	C_1D_{22}		
Number of objectives		*2*	*2*	*12*	*6*	*11*	*3*	*5*	*6*	*3*	*5*	*4*	*12*	*12*	*4*	*8*		

Table 4. Rating of the accuracy of measurements at single-tree level obtained from different inventory methods. The rating is based on synthesis of results from studies focusing on methods into four levels of precision: 0 = not possible to measure or very low precision, 1 = low precision, 2 = moderate precision, 3 = high precision. Field surveys were used as a reference for high precision.

Type of method	Literature															
Satellites – QuickBird, Panchromatic and multi-spectral images, VHR satellites	Thaiutsa et al. 2008; Arroyo et al. 2010^z; Ardila et al. 2012; Cavayas 2012		2	2					2					0		
Satellites – Google Maps	Thornhill et al. 2009^z; Abd-Elrahman et al. 2010^z; Ningal et al. 2010		2	1	0	0		3	3				0		2	
Airplane – supported LIDAR and Terrestrial Laser Scanning, Optech Laser Terrain Mapping 2050	Jutras et al. 2009			2		2							1			
Airplane – supported methods – aerial photos	Goldberg 1981^z; Miller and Winer 1984; Hathout and Simpson 1986; Mausel et al. 1992; Holopainen et al. 2006^z			2	3				2							2
On ground scanning/photos (Terrestrial Laser Scanning)	Park et al. 2010			3		1							3			
On ground scanning/photos (Mobile Laser Scanning)	Rutzinger et al. 2011			2		2							2			
Ground scanning/photos – customer grade cameras, digital photos, augmented reality	Tait et al. 2009^z; Thornhill et al. 2009; Abd-Elrahman et al 2010^z; Patterson et al. 2011; West 2012^z		3	2	2	1		3					2	3	3	
Field survey – windshield survey	Rooney et al. 2005^z				2		2								2	
Field survey (e.g,. supported by GPS receiver or handheld computers)		3		3	3	3	3	3	3	3	3	3	3	3	3	3

^{z} Article not included in the first selection process.

Tree Inventory Method Accuracy

In the papers reviewed, testing and methodological discussions of measurement accuracy were restricted to 3–5 parameter groups for each inventory method, with on-the-ground digital photography methods and satellite-supported Google Maps being the exceptions. Regarding the latter, accuracy of measurement had been tested for eight parameter groups (Table 4).

Species information has been identified as the most important data parameter (Östberg et al. 2013). However, only satellite-supported images and on-the-ground costume graded photogrammetry had been tested as alternatives to field inventory for species identification. Abd-Elrahman et al. (2010) found that inventories using Google Maps as data source were unable to identify tree species, while species could be identified from close-range photogrammetry solutions of tree images taken with consumer-grade cameras.

Studies on the accuracy of measurement mostly concentrated on the three size parameter groups 'Crown size/density', 'DBH', and 'Tree size other than crown size and DBH'. The following summarizes the findings of studies testing these key parameters, while Table 4 provides the results of the rating of measurement accuracy for these as well as other parameters tested by the different inventory methods.

The different satellite-supported methods were either unable to measure tree size parameters or provided low levels of accuracy. Abd-Elrahman et al. (2010) found that Google Maps were unable to determine tree height and DBH, while crown diameter measurements on average deviated by 1.67 m from field data. Only crown-size data had been extracted from other types of satellite images. For example, Ardila et al. (2012) used geographic object-based image analysis of QuickBird images and found crown diameter to be generally overestimated (no numerical values reported). However, many trees, especially with crown diameter <4.7 m, were not identified.

In studies applying data from airplane-supported LIDAR (Light Detection and Ranging), Jutras et al. (2009) found that the average Pearson prediction coefficient (r) for DBH and crown volume was >90% when analyzed in artificial intelligence multilayer perception network scenarios. In the same study, prediction coefficients of tree height had low accuracy (<90%). Other studies of airborne laser and aerial photos had not been able to establish DBH and tree height information (Table 4).

Concerning on-the-ground scanning, Park et al. (2010) found that modeling of 3D point cloud data from a terrestrial laser (Leica HDS6000 TLS) could reconstruct crown diameter with high accuracy, with only 0.05 m (2%) difference from field survey data. Reconstruction of tree height also had high accuracy, with an average of 0.22 m (3%) deviation from field survey data. However, the reconstruction of DBH (trunk size) at 1 m above ground had low accuracy, with a deviation 0.16 m (22%) from field survey data (Park et al. 2010). In models based on measurements obtained from on-the-ground mobile laser scanning (Optech LYNX System), Rutzinger et al. (2011) found that the DBH on average deviated by 0.8 cm and crown diameter by 0.87 m from field survey data. The paper did not provide sufficient data to recalculate these results to percentage deviation.

In a test of close-range photogrammetry solutions of tree images taken by consumer-grade cameras, Abd-Elrahman et al. (2010) found crown width to deviate by 0%–28% from field measurements. Quantification of DBH was only possible for two out of four trees and varied by up to 19% from field measurements. Quantification of tree height was only possible for three out of the four trees included in the study, and deviated by up to 12% from actual tree height (Abd-Elrahman et al. 2010). Using UrbanCrowns image analysis software, Patterson et al. (2011) found that the error in estimates of crown volume increased with increasing tree size.

DISCUSSION

This review showed that the geographical scope of scientific studies relying on data from urban tree inventories at single-tree level has expanded from being primarily North American during the 1980s and 1990s to now spanning all continents except Africa. The dominance of North American research during the 1980s and 1990s (mostly published in *Arboriculture & Urban Forestry*) reflects the overall expansion in the field of urban forestry, which developed in North America during the 1960s as an integrative, multidisciplinary approach to the planning and management of all forest and tree resources in and near urban areas. It was not until the mid-1990s that the concept was adopted in Europe and elsewhere, following pioneering work by the U.S. Forest Service on quantifying and modeling urban forest benefits in the Chicago Urban Forest Climate Project (Konijnendijk et al. 2006). It is clear that this work in Chicago stimulated the adoption of urban forestry and urban tree research in Europe and elsewhere, supported by networks such as COST Action E12 on Urban Forests and Trees, which ran from 1997–2002 (Konijnendijk et al. 2005; Schipperijn et al. 2005; Konijnendijk et al. 2006; Konijnendijk et al. 2007), and the re-initiation of an urban forestry unit under the International Union of Forest Research Organizations (IUFRO) in 1986.

In 1983, Smiley and Baker rightfully argued that not until the 'why' has been clearly defined can specific data be collected at single-tree level. The findings of the present review indicate that the 'why' question remains relevant and may be more imperative than ever, not only for city authorities and urban tree managers (Smiley and Baker 1988), but also for the scientific community. The analysis reveals how data from urban tree inventories at single-tree level have found applications in research with a steadily growing number of different study focus areas. The fact that the 57 articles included in the review are published in 36 journals with differing scientific scope underscores the use of urban tree inventory data across disciplinary borders.

A notable current trend is the use of data at single-tree level in studies focusing on the ecosystem services provided by urban trees (including their economic value), as a supplement to studies linked more directly to daily arboricultural management and planning by city authorities. In fact, all cost-benefit studies and nearly all studies on the regulating environmental aspects of urban trees have been published since 2001, thus coinciding with, and are probably prompted by, the popularization and formal definition of the ecosystem services concept by the United Nations Millennium Ecosystem Assessment 2001–2005 (Millennium Ecosystem Assessment 2000). In a wider perspective, one can therefore argue that the concept of ecosystem services has facilitated an overall change in the scientific use of urban tree inventory data from an applied focus (Sudol and Zach 1987; Smiley and Baker 1988; McBride and Nowak 1989) to the current situation, where it also includes more strategic research (e.g., Dimoudi and Nikolopoulou 2003; Nowak et al. 2006b), as defined by OECD (1994). However, the work in Chicago during the early 1990s pioneered such research and the development of current models, such as STRATUM (now i-Tree Streets) and UFORE (now i-Tree Eco). The very recent increase in studies focusing on technological development and modeling studies also adds to this gradual shift towards more strategic considerations. However, most of the studies reviewed here focus on regulating ecosystem services related to the urban heat island effect, CO_2 sequestration, storm water runoff, urban biodiversity, and VOC gases. An interesting perspective for the future would be to explore how tree inventory data at single-tree level can support more strategic research into the cultural ecosystem services provided by urban trees (e.g., non-material benefits related to cultural heritage, social cohesion, recreational experiences, and aesthetic experiences).

The main contribution of the present study is that it goes beyond the 'why' question and establishes a typology of 'how' urban inventories are conducted (at least, those applied as the main data sources in current peer-reviewed research in the area) and 'how' the different contemporary inventory methods and technical aids affect the parameters that can be collected at single-tree level and their accuracy of measurement. Four main types of urban tree inventory methods were identified. With 46 out of 57 articles, the 'classical' field surveys, where ground staff carried out direct measurements and visual inspections, dominated. One concern in relation to this inventory method is that it is labor-intensive and generally limited to public trees, simply because of the difficulties in obtaining access to trees on private land (Nowak 2008). Satellite- and airplane-supported methods are less labor-demanding and have the potential to provide easy 'access' to trees on private land. It is therefore exciting to see the many recent publications using/testing satellite- and airplane-supported methods (e.g., Jutras et al. 2009; Arroyo et al. 2010; Ardila et al. 2012), ground scanning (e.g., Park et al. 2010; Rutzinger et al. 2011), and digital photography methods (e.g., Patterson et al. 2011; West et al. 2012) for data collection at single-tree level. The application and testing of these technologies may give an indication of coming advances.

Key Parameters and their Accuracy of Measurements

In total, 15 parameter groups were applied in the studies reviewed. Studies focusing on tests of tree inventory methods, tree vitality, arboricultural management, and tree architecture and amenity values in particular cover a wide range of parameters (11–13). This corresponds well with the number of parameters typically collected in city authority inventories. For example, Keller and Konijnendijk (2012) found that six major cities in North America and Europe collected data on 8–20 parameters. However, the number and type of parameters varied greatly between studies with different focus areas, with only species information and the three size parameters (crown size/density, DBH, and tree size other than crown size and DBH) being consistently determined. These parameters also obtained a high rating in a recent Delphi study in which city officials, arborists, and academics evaluated the relative importance of tree parameters for inclusion in large-scale urban inventories (Östberg et al. 2013). In addition, these parameters are essential input in the modeling and quantification of the ecosystem services that urban trees provide to the community and their economic value (i-Tree 2012). These four parameters therefore appear to be fundamental, and it is not surprising that size parameters have been the focus of tests of inventory methods that are less labor-intensive than field surveys (i.e., methods supported by satellite images, aerial photos, terrestrial laser scanning and mobile scanning, and on-the-ground digital photography methods). While satellite- and airplane-supported technical aids have found a wide range of applications in land-use and vegetation inventories at coarser scales, current image resolution and laser equipment limit the accuracy of the measurements to the level of single trees. Ground scanning by use of terrestrial laser provided the highest level of accuracy of tree size measurements. However, Park et al. (2010) found that the data processing time varied from 39 to 87 minutes per tree, indicating that it is questionable whether the method is less labor-intensive than the direct measurements and visual inspections applied in field surveys. In contrast, the accuracy of species information data has scarcely been tested, and the test results for satellite-supported images show low levels of precision (Cavayas et al. 2012). In terms of tree health status parameters (categorized in this study as 'Damage'; 'Hazard'; 'Insects, pest, fungi'; and 'Vitality'), the satellite- and airplane-supported methods and on-the-ground scanning methods again appear to have significant limitations, although their accuracy has not been tested in the papers reviewed. This constitutes an important barrier to application of these inventory methods by city authorities, for whom tree vitality assessment and hazard tree management are among the main reasons for inventory (Keller and Konijnendijk 2012; Thomsen 2012).

LIMITATIONS OF THE REVIEW

The four main types of tree inventory methods identified can be combined to overcome the shortcomings discussed above. This has been done in several studies on emissions of VOC gases by urban trees (Geron et al. 1995; Benjamin et al. 1997; Drewitt et al. 1998; Karlik and Winer 2001; Zhihui et al. 2003; Wang et al. 2003; Wang et al. 2005), where aerial methods have been combined with field surveys to collect high-quality data for extrapolation. In this regard, satellite-supported methods appear to be the typology most frequently combined with another inventory method, primarily field surveys (Diem and Comrie 2000), but also historical documentation (Mickler et al. 2002). While such 'mixed inventory methods' were beyond the scope of this review, they offer interesting perspectives that future research ought to explore (e.g., extrapolate inventories to larger areas). Furthermore, the review was restricted to articles written in English and published in peer-reviewed scientific journals. However, tree inventory methods and findings at the local or national level may also be published as reports, guidelines, and 'gray' literature, and thus a number of studies in which urban tree inventory methods are described and/or used as data sources may have been overlooked. An obvious example of this is the windshield method applied in practice (Pokorny 2003; Rooney et al. 2005; Escobedo and Andreu 2008), but not as part of the peer-reviewed research included in this review. With this exception, to the knowledge of the study authors, the scientific literature provides a reliable profile of the current status of urban tree inventories. Thus this review provides a useful comparative analysis of the different methods used to collect data at single-tree level.

CONCLUSIONS

This review shows that the scope of scientific studies relying on data from urban tree inventories at single-tree level has recently expanded in geographical and scientific terms. A notable current trend is the emergence of studies focusing on the ecosystem services provided by urban trees, as a supplement to studies more directly linked to arboricultural management and planning practices. The comparative analysis of contemporary inventory methods showed that available technology and current data processing limit the reliability of data obtained from satellite- and airplane-supported inventory methods and on-the-ground scanning or digital photography. The authors therefore recommend further technological development and scientific testing before these methods replace field surveys in urban tree inventory programs at single-tree level.

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Zusammenfassung. Mit einer wachsende Anzahl von Straßenbaumerfassungsmethoden und diversem Gebrauch von erhobenen Daten durch die Stadtverwaltungen und Forscher, wächst auch ein Bedarf, die vorhandenen Erfassungsmethoden zu bewerten und besprechen sowie kritisch zu überprüfen. Diese Studie überprüfte Studien, die sich mit Baumkatastern auf einer Basis der Einzelbaumerfassung beschäftigen. Basierend darauf wurde ein bibliographischer Überblick etabliert und eine Typologie temporärer Baumerfassungsmethoden kreiert und als ein Rahmenwerk zur Evaluierung und Diskussion der Messmethoden und der mit unterschiedlichen Methoden erreichten Akkuratesse verwendet. Die Autoren fanden heraus, dass Daten aus Straßenbaumkatastern gegenwärtig in Forschung eingebunden werden mit einem wachsenden Fokus auf einen geographischen Rahmen, der alle Kontinente außer Afrika umspannt. Vier Haupttypen von Straßenbaumerfassungsmethoden wurden unterschieden: satelliten-unterstützte Methoden, flugzeug-unterstützte Methoden, Vor-Ort-Scannen oder Digitale Fotographie und Felderhebung. Eine Zusammenstellung der Ergebnisse aller Studien und die Bewertung der in diesen Inventuren gesammelten Parameter und die Präzision der Messungen zeigten, dass die Technologie selbst und die gegenwärtigen Datenprozess-Methoden die Verlässlichkeit der Daten, die aus allen Methoden bis auf die Felderhebungen gewonnen wurden, begrenzen. Die Autoren dieser Studie empfehlen weitere technologische Entwicklung und wissenschaftliches Testen, bevor diese Methoden Felderhebungen ersetzen können.

Resumen. Con un número cada vez mayor de métodos de inventario de árboles urbanos y la diversificación del uso de los datos del inventario por las autoridades de la ciudad y los investigadores, existe la necesidad de evaluar y revisar críticamente los métodos de inventario disponibles. Este estudio examinó los estudios que utilizan los inventarios de árboles urbanos a nivel de un solo árbol como fuente de datos. Sobre esta base, se estableció un panorama bibliográfico y una tipología de los métodos de inventario de árboles urbanos contemporáneos como marco para la evaluación y discusión del tipo de medición y precisión alcanzable con los diferentes métodos. Los autores encontraron que los datos de los inventarios de árboles urbanos en la actualidad se están empleando en la investigación con un número creciente de enfoques a través de un ámbito geográfico que se extiende por todos los continentes, excepto África. Se distinguen cuatro tipos principales de inventarios de árboles urbanos: métodos satelitales, métodos por avión, fotografías digitales y encuestas de campo. La compilación de los resultados a través de los estudios, la evaluación de los parámetros recogidos por estos métodos de inventario y su exactitud de medición revelaron que la tecnología en sí y los métodos de procesamiento de datos actuales limitan la fiabilidad de la información obtenida de todos los métodos, excepto los estudios de campo. Los autores del estudio recomiendan un mayor desarrollo tecnológico y pruebas científicas antes de que estos métodos puedan sustituir a los estudios de campo.

APPENDIX.

Tree information parameters

Age or year of planting

- Age
    - Age class
    - Number of years after transplantation
- Maturity class

Coordinates

- Coordinates

Crown size, density

- Crown size
    - Average crown width
    - Canopy drip line width
    - Canopy width
    - Crown diameter
    - Crown radius
    - Crown size
    - Crown spread
    - Crown width
    - Crown volume and diameter
    - Crown dimensions
    - Diameter and shape
    - Dimensions of the leafy crown or canopies
    - Foliar volumes
    - Form
    - Shape and dimensions of the tree crown
    - Spread
    - Tree canopy
    - Tree crown height
    - Width of crown
- Canopy condition
    - Canopy transparency
    - Crown damage
    - Crown density
    - Crown dieback
- Crown location
    - Crown light exposure
    - Crown position in relations to other trees

Damage, insects, and pests

- Damage
    - Damage to the tree
    - Dieback
    - Discolored leaves
    - Healed damage
    - Mechanical damage
    - Percent and diameter of dead wood
    - Percent missing tree canopy
    - Tree mortality
    - Various trims and repairs on the tree
- Presence/absence of chlorosis
- Presence of insects/disease
- Presence of epicormic twigs

DBH (diameter at breast height)

- DBH
    - Circumference
    - DBH 1.4 m above ground
    - Diameter
    - Diameter at breast height
    - Diameter at breast height (1.1 m aboveground)
    - Diameter at breast height (1.37 m aboveground)
    - Diameter class

Hazard

- Hazard status
    - Existence of girdled roots
    - Hazard tree rating
    - Tree part most likely to fail

Interaction with infrastructure or buildings

- Proximity to building
    - Distance to building
    - Building direction (N, S, E, W)
    - Distance and direction from buildings for those trees >7 m tall and = 20 m from the buildings
    - Distance to nearest building
    - Number of buildings within 18.3 m
- Conflict with infrastructure
    - Overhead utilities
    - Presence of overhead wires
    - Presence of utility lines within or above the crown
    - Whether the sidewalk is raised
- Tree position in relation to traffic

Location

- Amenity to landscape
- Available planting spaces
- Location
    - Geographical location
    - Local name
    - Location (street name and address)
    - Location of the trees
    - Rural or urban
    - Street name
    - Street tree (y/n)
    - Street tree and park tree location
- Sides of the crown that are exposed to light
- Topography

Planting site

- Amount of impermeable surface cover
- Growing space
- Land use
    - Land use type
    - Planting strip
    - Primary land use
- Site condition

Maintenance needs and history

- Maintenance needs
  - Recommended intervention
- Pruning
- Replacement
- Tree history (topped or not)

Management information

- Placement (problem with the placement)
- Possible planting places for new trees
- Tree spacing
- Vacant planting space

Size (except crown and DBH)

- “Basic size”
- Base and trunk
  - Basal area
  - Basal diameter
  - Bole diameter
  - Trunk diameter
  - Trunk size
  - Number of trunks
- Height
  - Distance from the ground to the bottom of the crown
  - Height
  - Height class
  - Height from base to living crown
  - Height to base of live crown
  - Height to top of tree
  - Tree height
  - Total height and crown base elevation
  - Specimen height
- Size class

Species

- Genus and species
  - Species
  - Species composition Native or alien

Tree appearance and use

- Cavities
- Cut-out
- Fruit
- Impact on landscape
- Nuisance (undesirable characteristics of the tree)
- Photos
- Ornamental or shrub
- Shade
- Windbreak width

Vitality

- Condition
  - Condition (vitality)
  - Condition class
  - Condition of tree
  - Health
  - Health condition
  - Health status/decline symptoms: degree of defoliation
  - Health status
  - Foliage transparency
  - Relative tree condition rating
  - Transparency of crown
  - Tree condition rating
- Live/green crown ration
- Percent dieback

Data-based and related parameters

Inventory information

- Block number
- Date of inventory
- Digital photos
- Direction of travel of data collector
- Foliage present/absent
- Name of person conducting the inventory
- Planting site identification
- Plot number
- Sketches of the planting

Free text

- Comment

Identification number

- ID number
  - Tree ID
  - Tree identification
  - Tree inventory number