Use of LiDAR technology for quantification and design of park, garden and urban tree structure

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Abstract. It is essential to know the parameters of trees making up a city’s green infrastructure for evaluating the functions of its ecosystems and ecosystem services being provided. Traditional methods of creating tree inventories proved to be slow and costly, while not being able to provide sufficient data for ecosystem services mapping. Laser scanning methods can be used to obtain accurate measurements of tree dimensions, crown size measurements and overall tree structure details. They can be used to analyze large forested areas at a fraction of the time needed to measure each tree individually by hand. The goal of this study was to conduct an approbation of ground-based 3D scanning methods and test their capabilities of obtaining tree parameters for use in green infrastructure inventories. The research is based on scans and analysis of sites of the green fund of Moscow, Russia, during the vegetation periods of the years 2019-2020. LiDAR scanning allows automatic georeferencing of data and creates detailed 3D geometry of tree objects. This enables previously impossible measurements of tree dimensions to be taken and calculated: aboveground biomass and crown area. Such methods can automate the process of creating tree inventory databases, while eliminating subjective bias when recording measurements.

1. Introduction

The green infrastructure of a city, consisting of a network of multifunctional open spaces, parks, gardens, singular street trees and masses of forested areas, greatly contributes to its economy [1]. It provides an array of benefits for the urban inhabitants. This includes improvements in air quality, reduction of the heat island effect, biodiversity conservation, positive influence on mental health, contribution to the recreation qualities of spaces and much more [2-12]. The green infrastructure is in turn greatly shaped by the surrounding city structure: building density, design and configuration of spaces, anthropogenic factors etc [13]. All this leads to great discrepancies in size, amount and structure of green spaces. Such qualitative and quantitative variations have their effects on the evaluation of city ecosystem functions and ecosystem services – both of which are critical for planning and adapting cities, increasing sustainability and making urban spaces resilient to current climate change trends [14–16]. Due to this, modern cities have begun to develop and utilize systems for green infrastructure benefit evaluation and monitoring. This helps attract investments and achieve the most prominent economical profits, while protecting and maintaining high quality green infrastructure.

Quite often traditional ways of data acquisition for planting inventory in the city can be a lengthy and costly process. This leads to inventories being incomplete, outdated and having a lack of useful data for ecosystem services mapping [17]. In addition to this, the manual method of tree measurements
in the field cannot directly evaluate the amount of aboveground biomass of a tree. This parameter is later derived through the use of allometric equations. But research shows [18, 19] that allometric equations typically produce values that are 36–85% lower in comparison to reference data. The key statistics, which area needed from a tree inventory for practical greenspace management, are: the trunk diameter at breast height (DBH), tree height (H), basal area of trees per hectare, growing stock volume and the aboveground biomass (AGB). Thus, urban planning is in search of more efficient methods for field measurements of tree biomass and is looking upon modern multidisciplinary technologies [20–22].

3D laser scanning enables users to obtain detailed measurements of individual trees and large tree masses simultaneously. The level of detail allows for tree crown structure and trunk parameters to be properly mapped and quantitatively evaluated to calculate the amount of ecosystem survives provided [23–25]. This method ensures accurate interpretation of both objects and surfaces. Additionally, broad use of LiDAR technology for tree parameter measurements will generate a vast database of corelated information about tree growth patterns in various city environments. These datasets can then be analyzed for correcting and enhancing allometric formulas and predicting future tree growth in different urban landscapes [26]. Unfortunately, no data repositories of this sort currently exist to benchmark such algorithms. Providing open access to analytical algorithms and information banks of LiDAR obtained data from around the world could potentially revolutionize this area of research [27, 28].

Methods of automated data extraction and interpretation of individual trees, vines and deadwood has been developed for field use in tree inventory scenarios [29–45]. Virtual 3D models can be reconstructed and analyzed based on laser scanning data. This can then facilitate modeling future growth of city planting. LiDAR technology is already being utilized for planning urban landscaping projects and evaluation of future ecosystem services benefit potential.

The goal of this study was to conduct an approbation of ground-based 3D scanning methods and test their capabilities of obtaining tree parameters for use in green infrastructure inventories. The research is based on scans and analysis of sites of the green fund of Moscow, Russia, during the vegetation periods of the years 2019–2020. The study was conducted within the scope of a research contract with the Department of Nature Management and Environmental Protection to “develop a scientifically based methodology for intellectual management of the green fund of Moscow”. The research objective consisted of: 1. analysis of the different methods for conducting ground-based 3D scanning of various urban sites and locations; 2. productivity evaluation of the different 3D scanning methods using a constant site for benchmarking purposes; 3. conversion of the point clouds into tree parameter datasets; 4. comparison of the urban planting parameter data obtained through 3D scanning during the vegetation periods of the years 2019–2020.

2. Methods and Materials

2.1. Study area and data collection

The city of Moscow is situated on the banks of the Moscow river in the middle of the Eastern-European plain. 2561 км² of land area is taken up by the city [46]. Many diverse landscapes, each with its own unique natural qualities, have formed the present-day image of the city. The climate can be described as temperate-cold. Meteorological data from the past 10 years shows the average yearly temperature to be only 6.6°C with approximately 719 mm of precipitation. July is the hottest moth of the year: the average temperature comes out to be 20.7°C with also the largest amount of precipitation – 78 mm. The green fund of the city incorporates a rather large portion of green space, which makes up over 49% of the total city area. Besides the readily available and publicly accessible green spaces like parks, squares, boulevards, and courtyards, Moscow was able to preserve large portions of urban forests. These areas comprise a network of specially protected natural territories (SPNT) with unique natural landscapes.
Moscow is developing an ecosystem services-oriented system for intellectual green fund management. This system will implement the use of laser scanning of the city’s green spaces to obtain and update tree inventory data used in ecosystem services calculations. Such an approach allows to greatly enhance the process of tree inventory, applying georeferenced data for each tree and shrub element and increasing the overall speed and preciseness of measurements, making the results less biased and subjected to human error. The scanning data can then be integrated into the city’s green space registry database, performing regular updates to certain key morphological parameters of trees (trunk diameter DBH and height H). This will also allow to compare unified data among different sites, between years of growth and locate any irregularities like missing or illegally cut trees.

For conducting testing and research in 2019 and 2020, 8 experimental sites were established in mutual agreement with the Department of Nature Management and Environmental Protection of the city of Moscow. One site has been selected for testing and comparing different scanning methods while 7 more were selected to represent an array of various city landscapes and test 3D scanning in multiple scenarios. The key goal of scanning these 7 sites was to repeat the 3D scanning process and acquire individual tree measurements by interpolating the point cloud data. The area of the smallest site totaled 617.1 m², while the largest being 103 000 m². Zaryadye park complex, a modern and highly maintained park with complete and up to date inventories of trees and other planting was selected for benchmarking different scanning methods. The 7 other sites included: a courtyard within a residential building cluster, “Hermitage” garden, “Bauman” garden for culture and recreating, Tsvetnoi boulevard (figure 1), green space within the grounds of a public city school, and portions of Komsomolskiy and Leningradskiy prospect for street tree planting.

Figure 1. Cloud model of a scanned site.

2.2. Methods of LiDAR field data acquisition and interpretation

2.2.1. Mobile scanning method. For conducting 3D scanning on the move a compact Leica Pegasus Backpack was used. The whole system fits in a backpack and can be easily carried around the site. Five built in cameras provide photo-panoramic images along-side the point cloud model.
Georeferencing and positioning is carried out by a global navigation satellite system (GNSS) module along with an inertial measuring system to identify and track movement in relation to its previous locations. This combination of sensors allows the scanner to achieve accurate positioning data both in the open (using GNSS) and in forested areas, where the horizon is obstructed and GNSS can’t produce reliable readings.

2.2.2. Stationary scanning method. Leica RTC360 was used for the stationary scanning method. The device was selected due to its high rate of scanning (2 million measurements a second) compared to similar products. It is also equipped with GNSS and an inertial measuring system that enables tracking of device movement between stationary locations and stitching data in a singular coordinate system. The setup weight is around 6 kg, making it lightweight and portable for easy use on different terrain and in different weather conditions.

2.2.3. Programs and applications for data interpretation. 3D Reality Capture or 3D scanning is the process of obtaining 3D information of the geometry of an object. The captured raw data is in the form of a “cloud” of points, each of which is georeferenced and is accurately placed on the coordinate system in relation to other points. Each point is a single measured distance from the device to an obstacle the laser reaches. The result of processing the “raw” data is stitching the points in the clouds together in order to form 3D geometry. Based on this, it is possible to produce digital plans and drawings of scanned environments that have accurate dimensions. The plans can be used for length and volume calculations. When the process is repeated multiple times over several time intervals, the overlay of models can be used to track and analyses change in the scanned site or environment.

Leica Pegasus Manager is program with a wide range of functions from rout planning to vectorization of data and its export to web-resources. Within the project the software had been used to align scanned areas together and for referencing the geo-position to the local coordinate system. Leica Cyclone SURVEY module was used to edit the point cloud models and prepare them for further analysis. Leica Cyclone 3DR was then used to build detailed digital models of the landscape and layer them on one another to monitor site changes over time intervals.

3. Results and Discussion

3.1. Testing of mobile and stationary scanning methods

Zaryadye park complex had been extensively scanned by a team of professionally trained operators using both stationary and mobile scanning equipment. A total area of 103 000 m$^2$ of the park was scanned. Comparison data for each type of scanning method is displayed in table 1.

| Parameter                                      | Stationary scanning | Mobile scanning |
|------------------------------------------------|---------------------|-----------------|
| Area measured in 2 hours, ha                   | 0.5                 | 10              |
| Tolerances of stitched/geopositioned data, cm  | <1                  | 5               |
| Level of detail: smallest object that can be measured from the point cloud model, cm | <1 | 2–3 |

As can be observed, mobile scanners show a much higher efficiency in speed compared to the stationary scanning method. With this comes a drawback of a much higher measurement tolerance and a lower level of detail in the final model. When processing the 3D model, tree diameter, height and other morphological parameters were clearly visible on both models and were easy to interpretate. The output measurements from models of both methods were comparable.
Extensive speed comparisons for all methods were additionally conducted and compared to the speed of acquiring tree inventory parameters by classical instrumental measurements by hand. Stationary laser scanning, including time to post process the data, was 4–5 times faster than the standard hand measurements. Mobile scanning was able to produce results that are dozens of times faster than hand measurements and can be made even faster when the equipment is mounted on a service vehicle and driven along the route. The speeds and accuracy are achieved by a high density of measurements and process automation what greatly reduces errors and contributes to measurement objectiveness. The height and trunk diameters of trees is measured to a tolerance to 10-20 mm. Typically height measurement data is notorious for having the largest discrepancies when conducting hand measurements and this bias can be completely avoided with the use of laser scanning methods. The crown area and volume of aboveground biomass is completely impossible to measure by hand, while these calculations are easily done simultaneously with other measurements when using both mobile and stationary scanning. Besides this, processing 3D models allows for the analysis of tree geometry: analysis of truck crookedness and irregularity, allocation of biomass throughout the crown, identification of large defects in trunk or branch structure etc.

Having analyzed and compared the benefits of both the mobile and stationary scanning methods, it was concluded that mobile scanning provided a more practical use case for the massive amount of green infrastructure that needed regular inventorying for the Department of Nature Management and Environmental Protection of the city of Moscow. Due to this, the scanning of the other 7 experimental sites had been scanned utilizing the mobile scanning method.

3.2. Site scanning and data comparison

Monitoring of greenspace planting was conducted on all 7 test sites during the vegetation period of 2019 and 2020. All the locations had been scanned with mobile 3D scanning upon the trees reaching the yearly maximum growth for both years (September-October). The data was later processed and key tree parameters derived. The models and datasets had been organized for comparison between the two years of vegetation to identify parameters of growth, loss and new planting (figure 2).

![Figure 2](image_url)

Figure 2. Process of scan interpretation to identify tree objects and conduct measurements.

3.2.1 Identifying loss. To identify elements that had been lost over the one-year period, the 2019 scan was programmed to display a gradient of yellow to red in areas where the points of the 2020 scan
deviated more than 1 meter away or were entirely lost. This method located any objects or parts of objects that had been removed, broken or fell over. Each site map was automatically populated with indications of areas were portions of object loss occurred, specifying the following information: plot number, coordinates, element type (tree, shrub, tree crown or part of tree crown). In addition, an image of the area snipped from the panorama image was attached to provide more context for further analysis or inspection of the lost objects.

3.2.2. Identifying new elements. To locate and display areas of growth or new planting, the logic for the scan overlays had been programed to display a yellow gradient where the 2020 point cloud deviated from the 2019 point cloud more than 0.2m. This would indicate objects that represent new growth, new planting and enlargements in crown size. Information of new plant growth or of new planting is again labeled on the site map and accompanied with screenshots and images of the object.

3.2.3. Calculating changes in size. Evaluation of tree growth can be established using the same overlay type as in the case of identifying new elements. Dominating yellow color can be observed when examining the point cloud model overlay from the top view. Areas of tree height changes of over 0.5 m are marked on the site map and height elevation change is specified in the details (figure 3). Additionally, other tree attributes like crown size, trunk size etc. are calculated and specified in the same fashion for all of the trees.

![Figure 3](image_url)  
Figure 3. Overlaying of models to identify yearly growth. Section elevation.

After analyzing and comparing point clouds for the yearly change for all of the 7 established sites, it was possible to compare and contrast the acquired statistical data. For example, the largest amount of tree removal had been located in Bauman garden (11 trees removed) and 19 new trees were planted
as compensation. The largest crown growth compared to the previous year (12% increase) was on Tsvetnoi boulevard. Crown and tree growth on Komsomolsky prospect and Leningradskiy prospect was 11% and 9.6% respectively. The least amount of change was observed in the Hermitage garden, only 0.5% growth, what can be attributed to the old age of the trees.

3.3. Discussion
As a result of the research and scanning work, a geodatabase containing 8 fully scanned and analyzed sites was created. Each site represents a typical Moscow landscape and has a level of detail that enables each tree and its attributes to be distinguished and examined individually. The vector data contains the following information layers: site boundaries, areas of lawn, tree nodes, shrub nodes, flowerbeds and other various decorative materials and objects. It was shown that the method of site scanning and 3D cloud analysis can provide readily available data needed to create and update site inventories as well as provide detailed information for design and planning. By using actual metric data of tree parameters and their state, it is possible to make informed and scientifically justified decisions regarding their management, removal or even the redesign of certain areas of green infrastructure [47–50]. The 3D plans can be easily edited to add newly planted trees or to see the amount of change that removal of an old-age or dying tree will have on both the spatial structure and amount of ecosystem services provided. In a similar manner it is possible to completely model changes in a green space – compare and contrast the economic and ecological value of creating open spaces in woodland or creating curtain and denser planting. The models can be used to predict change over time based on analyzed growth patterns. This way it is possible to use this method for understanding the amount of ecosystem services produced in a timespan ranging many decades forwards.

Accurate laser scanning using LiDAR technology has the potential to become a fundamental aspect of landscape planning and design. Scanning and creating an inventory through 3D point cloud analysis of all the green infrastructure in a city will enable automation in the decision-making processes of green space management for both new and already constructed sites. Besides predicting growth and calculating the amount of compensation needed after tree removal, locating dieback, identifying areas of risk and establishing proper trimming or pruning activities automatically will save time and ensure proper maintenance work is being carried out. Another point of interest may be informed dialogue with the public regarding tree health and sanitary replacement of city trees. Based on inventory data off of scans, it is possible to articulate and justify why certain measures must be taken to ensure the health of the green infrastructure. Tree growth models with reference to the amount of ecosystem services provided in relation to age, size and health of a tree can clearly illustrate how removing old dying trees and compensating with healthy new ones will improve the economic benefit provided.

4. Conclusion
Technology used for 3D scanning projects in various construction and engineering industries can be fully applied in the field of green infrastructure inventory and maintenance. Site scanning allows to obtain accurate data of tree parameters for calculating ecosystem services, which is less biased and has a greater level of detail than traditional measurement and inventory methods. 3D scanning creates a digital point cloud model of a site and obtains all needed inventory information 4–5 times to dozens of times faster, depending on the scanning method used. The point cloud can be analyzed to calculate parameters like crown size, volume and amount of aboveground biomass, which previously could not be calculated by traditional inventory methods. These parameters are critical for ecosystem services calculations and possess great value for intellectual management systems.

Using Zaryadye park as benchmark site, it was established that the most time effective method of scanning that produces results with a sufficient level of detail is mobile laser scanning. Although the mobile method was inferior to the stationary method in terms of detail, the amount of detail produced and the margin of error was sufficient for point cloud analysis and tree parameter recognition.
Therefor this method was chosen and recommended for green infrastructure scanning and analysis based on its high efficiency and ability to produce accurate inventory data.

Further use of the mobile scanning method on 7 test sites had shown its effectiveness in identifying principal changes in greenspaces over a one-year growth period. The technology was able to identify missing and removed trees, identify newly planted trees and calculate the amount of new growth. Some tree attributes that are associated with growth, like change in trunk diameter (DBH) and change in overall tree height in some cases produced rather small values that lie within the scanning margin of error. Therefore, it was recommended to compare reading of scans with greater time intervals to get more accurate results.

Scanning and 3D registration with the use of georeferencing of data allows for great automation in the process of greenspace inventory while eliminating human error and any sort of bias.

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