Arboricultural Journal
The International Journal of Urban Forestry

ISSN: 0307-1375 (Print) 2168-1074 (Online) Journal homepage: www.tandfonline.com/journals/tarb20

Using unoccupied aerial systems (UAS) and photogrammetry to estimate tree height and trunk diameter of urban American elm trees

Christopher A. Copeland , Richard W. Harper , Nicholas J. Brazee , Charles M. Schweik & Forrest J. Bowlick

ARBORICULTURAL JOURNAL
https://doi.org/10.1080/03071375.2026.2691646

Check for updates

Using unoccupied aerial systems (UAS) and photogrammetry to estimate tree height and trunk diameter of urban American elm trees

Christopher A. Copeland[a], Richard W. Harper [a], Nicholas J. Brazee[b], Charles M. Schweik[a,c], and Forrest J. Bowlick[a,d]

[a]Department of Environmental Conservation, University of Massachusetts, Amherst, MA, USA; [b]Center for Agriculture Food and the Environment, University of Massachusetts, Amherst, MA, USA; [c]School of Public Policy, University of Massachusetts, Amherst, MA, USA; [d]Department of Earth, Geographic and Climate Sciences, University of Massachusetts, Amherst, MA, USA

ABSTRACT

Urban forest health may be monitored and supported with the implementation and maintenance of an accurate community tree inventory. The longitudinal recording of a tree's attributes (i.e. diameter and height) may inform potential inputs and activities related to maintenance, health, and the establishment of a tree protection zone. Urban tree inventories feature barriers to implementation including resources (i.e. labour, time, and finances), competing priorities, and gaps in knowledge. The objectives of this case study were to investigate the feasibility of structure-from-motion (SfM) approaches to measure tree height and trunk diameter (1) with oblique RGB imagery, (2) with and without GCP, and (3) during leaf-off and leaf-on conditions. Structure-from-Motion datasets were obtained using Unoccupied Aerial Systems (UAS) – "drones" and related components – to collect oblique aerial imagery, which was processed with photogrammetry software Agisoft Metashape. Tree height measurements using leaf-on imagery (R2 = 0.58, RMSE = 1.34 m) were more accurate when compared to leaf-off imagery with Ground Control Points (GCP) (R2 = 0.47, RMSE = 3.41 m) and leaf-off imagery without GCPs (R2 = 0.43, RMSE = 3.49 m). Tree height measurements during the leaf-off period had no significant difference when comparing imagery with and without GCPs. Trunk diameter measurements using leaf-off imagery were not significantly different with the use of GCPs (R2 = 0.68, RMSE = 6.39 cm) compared to those without (R2 = 0.68, RMSE = 7.85 cm). This case study highlights the applicability and accuracy of Unoccupied Aerial Systems and Structure-from-Motion methods when collecting important urban tree inventory parameters, and presents an accessible, reliable, and replicable workflow for urban forestry practitioners with limited photogrammetry-related experience.

ARTICLE HISTORY
Received 9 December 2025
Accepted 16 June 2026

KEYWORDS
Unoccupied aerial systems; tree height; trunk diameter; photogrammetry; geospatial

CONTACT Richard W. Harper rharper@eco.umass.edu Department of Environmental Conservation, University of Massachusetts, Amherst, MA 01003, USA

Introduction

An urban tree inventory is a valuable tool used to measure and monitor urban forests over time (Morgenroth et al., 2017). Understanding the services and costs that trees generate for a community begins with understanding their location, size, health condition, and situational context (Cimburova & Barton, 2020; Roman et al., 2021). Tree inventory databases record qualitative characteristics like species, condition rating, and structural defects as well as quantitative attributes that include trunk diameter, canopy height, and canopy spread (Ma et al., 2021). Longitudinal observation of tree measurements may describe the vigour and overall health of an urban tree population. Key measurements help increase understanding and inform management decisions pertaining to tree maintenance needs, appraisal values, plant health care applications, tree risk assessments, and the establishment of tree protection zones (Dainelli et al., 2021; Hamilton et al., 2018; Pike et al., 2021; Vinci et al., 2023).

Urban tree inventories and data collection initiatives may be performed by professional or citizen stakeholders, and may include public employees, outside vendors, and trained volunteers (Bloniarz et al., 1996; Elton et al., 2023; Morgenroth et al., 2017). A review of the literature of tree inventory strategies in the US (Ma et al., 2021) concluded that 62% of communities utilised municipal staff to conduct an urban tree inventory. Reasons for conducting inventories included planning for planting (78%), tree species selection (66%), tree removal (65%), scheduling pruning (57%), policy development (37%), and canopy cover analysis (18%) (Ma et al., 2021).

Barriers to conducting an urban tree inventory include investments related to time, personnel, finances, and technical knowledge (Bancks et al., 2018; Hamilton et al., 2018). The understanding and need for an urban forest inventory may be best viewed through a long-term lens – a vision that may not be captured without an urban forest management plan (Hauer & Johnson, 2008). Without a long-term plan in place, it can be challenging for some communities to justify the need for an urban forest inventory. Of the communities surveyed in the United States, only 50% of respondents indicated that they had an urban forest management plan (Ma et al., 2021). Because time needed to complete a manual urban forest survey can be prohibitive, most communities (57.2%) attempt to mitigate this burden by conducting only sample inventories (Bancks et al., 2018; Ma et al., 2021).

In recent years, the study and incorporation of basic visual surveys, geospatially based approaches (e.g. GIS), and virtual surveys have become more common in relation to conducting urban tree inventories (Ward & Johnson, 2007). These novel approaches offer the potential to supplement traditional efforts with the use of vehicles and/or street-level imagery that enable the accurate and efficient identification of urban trees, and their diameter-class and health status (Berland et al., 2019; Cromwell et al., 2021; Elton et al., 2023). The combination of unoccupied aerial vehicles (UAV), remote sensing technology, and the operational approaches to systematically collect aerial imagery, known collectively as "unoccupied aerial systems" (UAS) have also generated increasing interest in relation to urban forestry and other natural resources management sectors (Cromwell et al., 2021; Olson et al., 2025). Applications have included pest and disease detection, crown delineation, measuring of trunk diameter and crown dimensions, and invasive species identification (Cromwell et al., 2021; Dainelli et al., 2021; Duarte et al., 2022). As UAVs become increasingly affordable (< $2000 USD), their acquisition and application have become increasingly preferred to other systems that may be substantially more costly, like LiDAR (light detection and ranging) (Alonzo et al., 2018; Dandois & Ellis, 2013). Unoccupied aerial vehicles may improve upon satellite and airborne imagery taken from planes by enabling a higher frequency of strategic flights. They also require less time than traditional in-person field measuring, readily enable the surveying of large or inaccessible areas, and provide visibility and perspectives not captured from the ground (Alonzo et al., 2018). Low-cost, visible-light cameras capture high-resolution (sub-decimetre), two-dimensional images which are used for three-dimensional spatial reconstruction (Lisein et al., 2013; Nasiri et al., 2021).

The efficacy of UAV use may be enhanced by implementing UAS strategies that include low-altitude flights and the use of photogrammetry software. Low-altitude flights have been shown to facilitate the generation of detailed imagery from which a high density of latitude, longitude, and elevation coordinates (i.e. point clouds) may be obtained (Alonzo et al., 2018; Dandois & Ellis, 2013). Photogrammetry software (e.g. Agisoft, ArcGIS Pro) may feature structure-from-motion (SfM) options that scales, rotates, and translates aerial images into realistic models of an object or space (Fang & Strimbu, 2017; Lisein et al., 2013; Westoby et al., 2012). Features that are photographed using UAVs with sufficient overlap and from multiple geolocations may be matched and represented in a three-dimensional spatial reconstruction (Cromwell et al., 2021). Accurate geographic location of each image may be obtained using: (1) Ground Control Points (GCPs) established in a ground survey at the time of flight that can be referenced in the imagery and/or (2) real-time corrected GPS information that is stored in the metadata of each image, if the drone has an onboard GPS. Ground control points are visual markers on the ground with precise geographic coordinates. Dense point clouds may be created after GCPs are obtained and an orthomosaic may then be systematically constructed by taking pixels from images that are at the best 3D location (Carbonneau & Dietrich, 2017; Oniga et al., 2018).

There are common barriers and limitations to establishing tree inventories and proceeding urban forest management plans (Bancks et al., 2018; Hauer & Johnson, 2008; Ma et al., 2021). Across the body of UAS literature, there are many different approaches to forest imagery acquisition such as LiDAR (Isibue & Pingel, 2020) and drone-based video (Olson et al., 2025). There are also differences in data extraction, which commonly involves model algorithms (Nasiri et al., 2021; Thinley et al., 2025). Existing research gaps include simplifying UAS and photogrammetry procedures and exploring optimal urban flight parameters. Because urban forests are broadly defined, not enough research has explored and demonstrated UAV public safety considerations along urban roadways. The objectives of this case study were to investigate the feasibility of structure-from-motion (SfM) approaches to measure tree height and trunk diameter (1) with oblique RGB imagery, (2) with and without GCP, and (3) during leaf-off and leaf-on conditions (Table 1). The workflow presented in this study aims to provide an accessible, reliable, and replicable template for other urban forestry practitioners who may be interested in incorporating UAVs into their urban forest management practices and, specifically, to collect attributes of trees as part of an urban forest inventory initiative in coordination with FAA regulations (Figure 1).

Methods

Study site

The main campus of the University of Massachusetts Amherst, (Amherst, Massachusetts, USA) is an ArbNet Level 4 accredited arboretum with over 500 temperate woody taxa growing throughout the 6 square kilometre area. The arboretum is divided into several management zones, representing a core urban campus, managed landscape, and unmanaged campus perimeter with protected forests and wetlands. The

Table 1. A comparison of data collection methods, status of foliage.

Table 1.	Date collected	Total trees	Leaf condition	Ground control points (GCP's)	Tree measurements
Manual field measurements	March 2024	37	*Leaf-on*	NA	Tree height (m); Trunk DBH (cm)
UAS Flight 1	December 2023	37	*Leaf-off*	0	Tree height (m); Trunk DBH (cm)
UAS Flight 1	December 2023	37	*Leaf-off*	8	Tree height (m); Trunk DBH (cm)
UAS Flight 2	August 2024	37	*Leaf-on*	8	Tree height (m); Trunk DBH (cm)

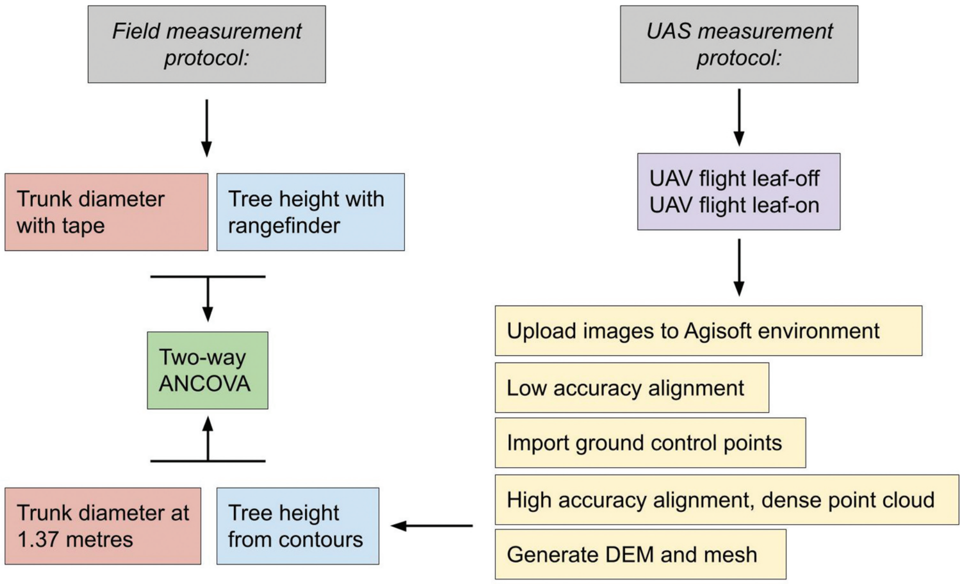

Figure 1. A graphical summary of the structure-from-motion (SfM) workflow used to measure tree inventory parameters compared to a traditional field survey protocol.

American elm (*Ulmus americana* L.) is a prominent urban tree on campus, with dozens of recently planted cultivars and a handful of mature specimens that require inventorying and frequent monitoring (Copeland et al., 2023). Governors Drive is lined with "Washington" elm trees (*Ulmus americana* "Washington") ($n = 37$) which were the primary subjects of this study. The section of Governors Drive is approximately 0.5 kilometres in length – a typical street tree layout with established trees and urban infrastructure (pedestrian walkways, bus stops, and building infrastructure) (Figure 2). Its sloping elevation of approximately 76 metres represents a geographic challenge for collecting consistent inventory data such as tree height. A construction worksite was established within the study area in the autumn of 2023, which impeded access to trees and resulted in several tree removals.

Ground measurements

Trees at the study site were initially inventoried on 15 January 2023, using ArcGIS Collector (California, USA) – a mobile geospatial data collection app. Field measurements were collected before bud break (13 March 2024) and the commencement of secondary growth. Trunk diameter of 37 elm trees was collected at 1.37 metres (i.e. Diameter at Breast Height or DBH) over a period of 90 minutes using a standard diameter tape. Tree height was collected using a Nikon Forestry Pro II rangefinder, at approximately 20

Figure 2. Study area of the trees sampled across the University of Massachusetts Amherst, Massachusetts.

metres distance from each tree, using the mean of three measurements. This process took 120 minutes. Both metrics were recorded using ArcGIS Collector and managed using an ArcGIS web map.

Unoccupied aerial vehicle flights

To capture detailed imagery of the structure of the trees in question, while minimising the impact to vehicular and pedestrian traffic, two low-altitude flights were executed. Altitude as a flight parameter was balanced with the specifications of the UAV camera to optimise ground sampling distance (GSD). The smaller the GSD value – measured in centimetres per pixel – the higher the resolution of the photogrammetry product. In compliance with campus drone use policy, the authors submitted a written pre-flight operations plan with the University of Massachusetts Amherst Police Department. The operations plan includes proof of valid FAA registration, date, time and purpose of flight. On flight days, safety signage was placed at parking lot junctures, pedestrian walkways, and building entrances along Governors Drive. Per FAA guidelines, B4UFLY and Aloft (developed by Kittyhawk, San Francisco, California) were used to obtain FAA-approved UAS Service Suppliers of the Low Altitude Authorisation and Notification Capability (LAARC). Altitude was kept well below the maximum 122 metres (400 feet) and visual line-of-sight was maintained with the UAV with the help of a spotter. Each flight was conducted by a DJI Phantom IV 2.0, a professional-grade drone typically used for photogrammetry and other aerial photography. The heavier payload (over 1 kg) provides better stability than smaller drones but does requires an experienced pilot. Flight features include Obstacle Avoidance and Terrain Awareness, the latter of which compensates for slope to maintain a consistent image capture altitude. There was approximately 76 metres in gradient change, according to the digital elevation model (DEM), which is a three-dimensional estimation of the site's terrain and non-ground surfaces (Nasiri et al., 2021). Drone Deploy (San Francisco, California) was used to establish flight parameters and automate the flight using waypoints within the study site (Figure 2). Imagery was collected using a standard 1-inch CMOS camera which allows for 20-megapixel resolution.

The first aerial flight (Table 1) was conducted mid-morning, 17 December 2023, to capture leaf-off conditions. Imagery collected during the leaf-off season can capture terrain and tree architecture with minimal visual obstruction. The leaf-off aerial survey yielded 553 images at 45 metres, which were uploaded in Agisoft Metashape. Upon taking flight, the DJI Phantom IV ascended to a height of 45 metres, an altitude that was chosen to maximise image resolution and battery efficiency. To generate accurate models of individual trees, images were collected by flying in a cross-hatching pattern at a speed of 11.2 km/hr (7mph) (Figure 2). The gimbal pitch was set at 45 degrees to capture oblique images with a front and side overlap of 80%. Perimeter photos were also captured to improve edge detail. The total flight time was 30 minutes, 43 seconds, and required the use of two batteries.

A second aerial flight (Table 1) was conducted midday under overcast skies on 9 August 2024, to capture leaf-on conditions. The leaf-on aerial survey was conducted using Drone Deploy and yielded 550 images, which were uploaded in Agisoft Metashape. Altitude was set at 45 metres and enabled with Terrain Awareness, to compensate for site slope. Upon taking flight, the DJI Phantom IV ascended to a height of 45 metres and collected images by flying in a cross-hatching pattern at a speed of 11.2 km/hr (7mph) (Figure 2). The gimbal pitch was set at 45 degrees to capture oblique images with a front and side overlap of 80%. Perimeter photos were also captured to improve edge detail. The total flight time was 30 minutes, five seconds, and required the use of two batteries.

The length of time between data collection should be noted. Leaf-on imagery was collected 4 months after the trees were measured on the ground. The authors anticipated poor growth rates from the mature American elm study specimens due to their spatial constraints, construction injury, heat island effect, and poor air quality (Gao et al., 2023). Muscas et al. (2023) discuss the decrease of tree growth rate at the onset of spatial constraints. This is supported by many years of campus tree inventory data that includes height and trunk diameter measurements.

Ground control points (GCPs)

Nine GCP's were collected on 15 May 2024, using a Trimble R10 (Westminster, Colorado) total station (Oniga et al., 2018). This survey tool was used to collect latitude, longitude, and elevation data at centimetre-level accuracy. Southwest corners of parking lot lines and utility covers were georeferenced using ArcGIS Collector because these features were easily identifiable from aerial images, have fixed X, Y, and Z locations, and were evenly distributed within the flight pattern.

Building photogrammetry products

Imagery taken during each flight (Table 1) was processed with Agisoft Metashape, a widely used photogrammetry development environment with SfM capabilities. After the removal of unsuitable imagery (i.e. photos that were irrelevant or of a quality of less than 0.65 units), 553 final images for flight one and 550 final images for flight two remained for processing. All imagery was set to the same coordinate system, NAD83/UTM zone 18N. Spatial reconstruction was completed in the following steps:

(1) For each of the flights, a low-accuracy alignment was developed to generate a sparse point cloud. Adaptive camera model fitting was used for the DJI Phantom 4 camera. This step helps to identify the quality and size of the project before committing to more time-consuming and computationally intensive processes, like high-accuracy alignments. Sparse point clouds also identify camera positions and areas of insufficient overlap.
(2) Nine GCP's (i.e. markers) were imported into the sparse point cloud and set to the same coordinate system, NAD83/UTM zone 18N (EPSG:26918). Marker locations were identified and corrected in each of the images that were aligned. This grounds the imagery in real-world coordinate data and enables more accurate scaling in subsequent steps.

(3) A highest-accuracy alignment was developed, with markers checked in the Reference tab.
(4) A dense point cloud was developed on the highest reconstruction settings. Depth filtering settings were set to "Ultra high quality" with "Aggressive filtering". An ultra-high quality point cloud was produced. High resolution products should maximise the capacity to collect measurements.
(5) A digital elevation model (DEM) was reconstructed on the highest settings using the dense point cloud as the source datum.
(6) A mesh was created for both flights (Figure 3 and Figure 4). The mesh is a continuous texture that connects and smooths vertices of the dense point cloud, allowing for measurements to be taken directly from the surface of the mesh.
(7) A 2D orthomosaic (TIFF) was created which was used as a spatial reference for both flights. The orthomosaic can be checked for discontinuity patterns.

Collecting measurements from photogrammetry products

Tree height measurements were collected using the three-dimensional photogrammetry products created in Agisoft Metashape. First, contours were generated within the mesh product in 1 metre intervals (Figure 5). Contours are vector polylines that represent lines of constant elevation, and are based off the DEM. In the Model view pane, the contour closest to the

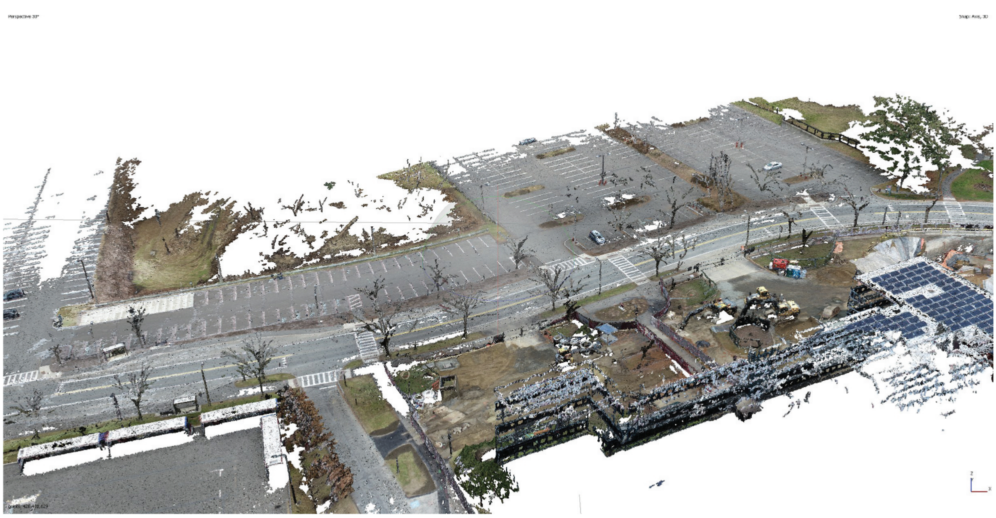

Figure 3. Structure-from-motion 3D model using leaf-off imagery in Agisoft Metashape. Governor's Drive, Amherst, Massachusetts.

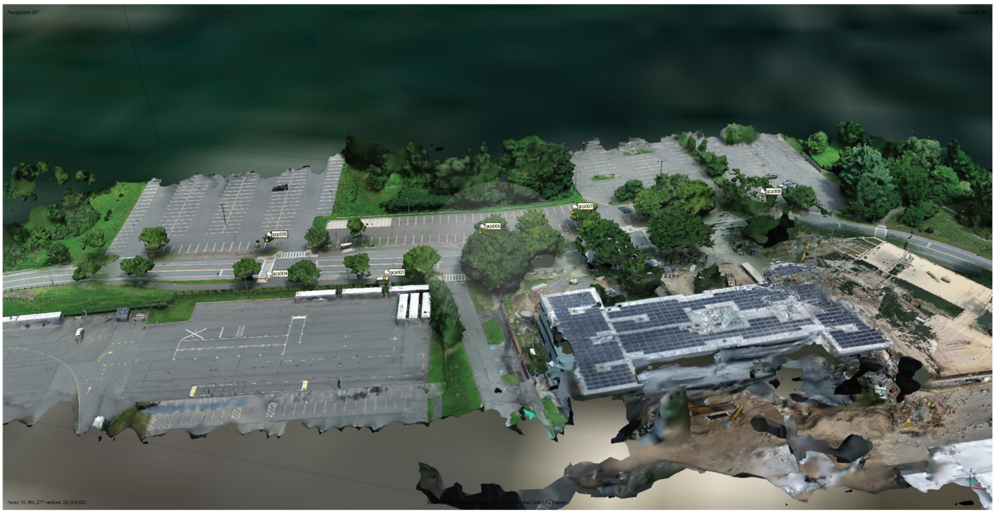

Figure 4. Structure-from-motion 3D model using leaf-on imagery in Agisoft Metashape. Governor's Drive, Amherst, Massachusetts.

Figure 5. Measuring tree height using contour generation in Agisoft Metashape.

apex of each tree was observed and recorded, representing tree height. This tree height was then subtracted by the elevation of the terrain surrounding the base of each tree, yielding the true estimated height of each individual tree. All measurements were recorded in the ArcGIS web map.

Trunk diameter measurements were also measured directly from the mesh. First, sampling height was established by measuring 1.37 metres from the soil line of each tree using the built-in ruler tool. Trunk diameter was measured by recording the linear distance across the trunk, at a height of 1.37 metres, using the ruler tool (Figure 6). No automation was used and all measurements were recorded in the ArcGIS web map.

Figure 6. Measuring diameter at breast height (DBH) using the ruler tool in Agisoft Metashape.

Statistical analysis

A factorial (two-way) analysis of covariance (ANCOVA) was performed using RStudio (Posit PBC, Boston, Massachusetts). Survey types (leaf-on, leaf-off, with GCP, without GCP) represent independent variables while the height and diameter measurements represent dependent variables. Manual measurements, which function as the covariate, were taken from the ground prior to UAS models. This type of analysis of variance (ANOVA) controls the linear effect of covariate variables by using regression analysis.

Results

Photogrammetry products

During the production of the ultra-high-quality point cloud, the total number of points produced for each model was: (1) 426,776,067 for leaf-off without GCPs; (2) 426,721,426 for leaf-off with GCPs; and (3) 436,501,641 for leaf-on with GCPs. The resolution of the DEM was 1.33 cm/px for the leaf-off model and 1.43 cm/px for the leaf-on model. The resolution of the leaf-off orthomosaic was $40{,}439 \times 18{,}529$ cm/px and $32{,}217 \times 16{,}943$ cm/px for leaf-on orthomosaic. The average error of GCP's was −0.02 m in the leaf-off flight and 0.4 m in leaf-on flight.

Trunk diameter

The success of trunk diameter measurements was dependent on the presence of foliage. During the leaf-on flight, none of the trees had reliably reconstructed stems to take measurements and trees with foliage were obstructed given the altitude of the camera. Additionally, several trees were physically removed from the study site due to their declining health while this experiment was being conducted, reducing the sample size to 37 specimens. Measuring trunk diameter was not significantly different between GCPs (R2 = 0.68) (Figure 7) and without GCPs (R2 = 0.68) (Figure 7). Trunk diameter measurements during leaf-on were not possible (R2 = 0) due to the limited imagery of tree stems. Of the stems that did reconstruct during the SfM workflow, the root mean square error (RMSE) for trunk diameter from the leaf-off with GCPs was 6.39 cm. Of the canopies that were reconstructed, the RMSE for trunk diameter during leaf-off without GCP's was 7.85 cm. A multiple regression analysis was performed for diameter measurements in RStudio. The null hypothesis states that there is no relationship between the estimated (UAS) and observed (manual) trunk diameter measurements. Because the *p*-value is very small and the F-statistic is large (F (3,50) = 35.79, *p* = 1.69e-12), there is a statistically significant effect that at least one group considerably contributes to explaining the outcome. In this case, the manual diameter group had a very low *p*-value (1.27e-07) and a high *t*-value (6.15). These measurements indicate a strong relationship between the dependent (measurements) and independent (survey type) variables and support the rejection of the null hypothesis.

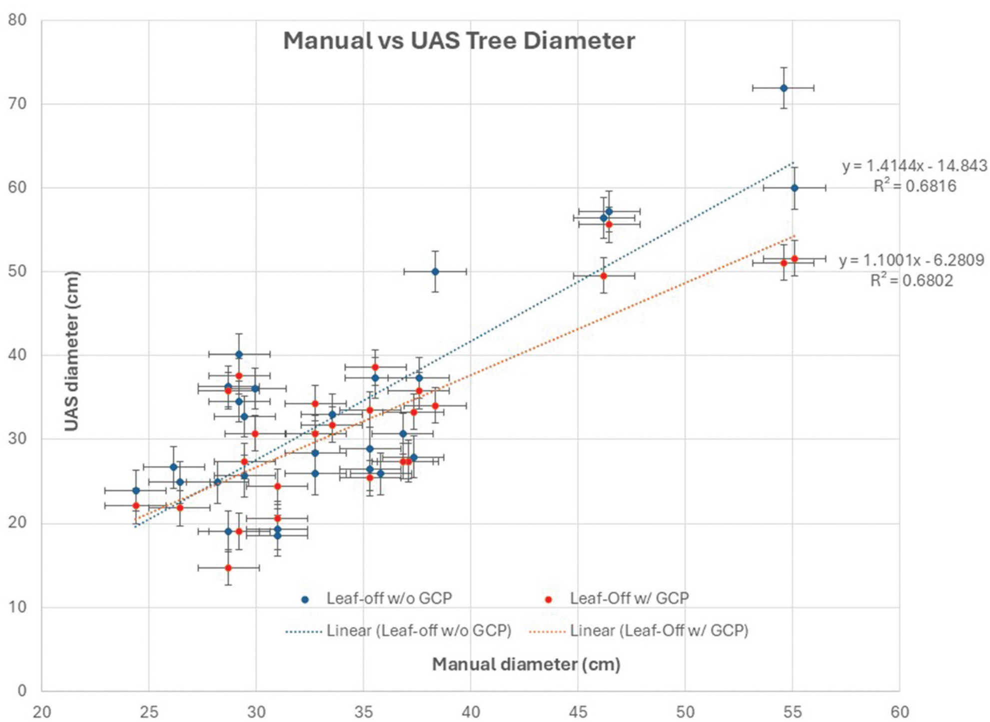

Figure 7. A comparison of traditional trunk diameter measurements and two SfM models.

Tree height measurements

When compared, tree height measurement models produced similar outcomes. Comparing the imagery with GCPs, tree height was slightly more accurate with leaf-on (R2 = 0.58) compared to leaf-off (R2 = 0.47) (Figure 8). All leaf-off tree height measurements were similar with GCPs (R2 = 0.47) (Figure 8) compared to without (R2 = 0.43) (Figure 8). The (RMSE) for tree height from the leaf-off without GCPs was 3.45 metres and 3.33 metres for leaf-off with GCPs. The root mean square error for tree height from the leaf-on with GCP flight was 1.34 metres. There are a relatively high estimation error and differences between root mean square errors suggesting differences in model accuracy.

A multiple regression analysis was performed for height measurements in RStudio. The null hypothesis states that there is no relationship between the estimated (UAS) and observed (manual) tree height measurements. Because the *p*-value is very small and the F-statistic is large ($F\ (5,104) = 44.01$, $p = 2.2e\text{-}16$), there is a statistically significant effect that at least one group considerably contributes to explaining the outcome. In this case, the manual tree height group had a very low *p*-value (2.24e-7) and a high *t*-value (5.55). These measurements indicate a strong relationship between the dependent (measurements) and independent (survey type) variables and support the rejection of the null hypothesis.

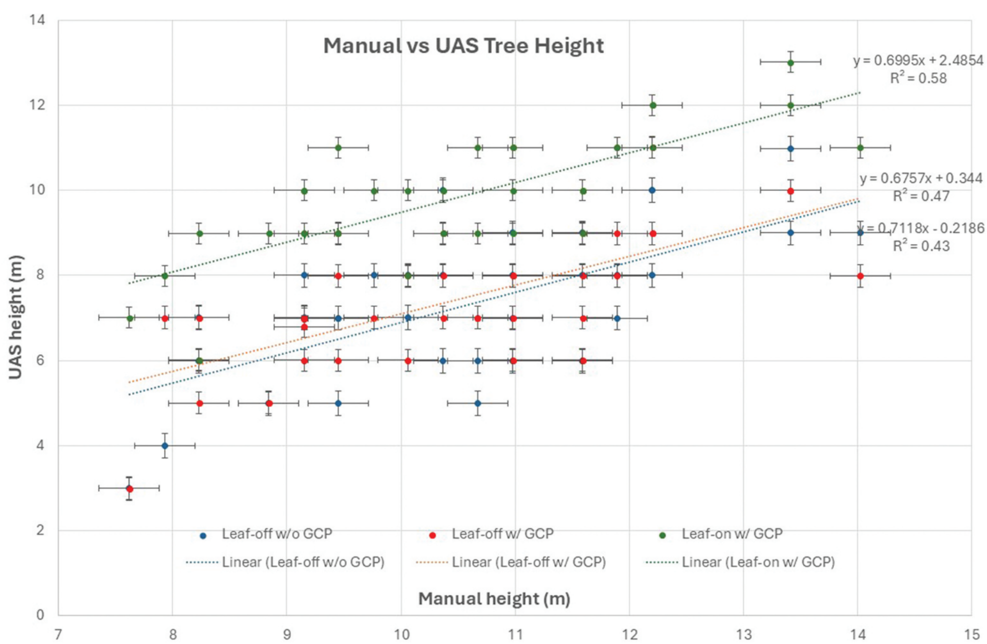

Figure 8. A comparison of traditional tree height measurements and three SfM models.

Most of the slopes of each height model's regression line remain parallel, therefore there is no significant interaction between treatment (UAS method) and covariate (manual measurements) (Figure 8). However, the leaf-on with GCP model has a different slope, suggesting there will at some point be interaction between the independent variable and covariate. Therefore, the relationship between the dependent variable is different at different levels of the independent variable, as seen in the large errors between several measurements from taller trees. The higher intercept on the leaf-on height model might reflect a higher estimation in tree height given the increase in canopy volume compared to leaf-off conditions.

The survey type (e.g. leaf-off with GCP, leaf-on with GCP) had a statistically significant effect on the measured heights, even after controlling for the manual height (by taking the mean of three measurements). The *p*-value (2.2e-16) is much smaller than 0.05, indicating a significant difference between methods. The very small *p*-value shows that actual manual height correlates strongly with estimated height values.

It should be noted that because there were 8 months between leaf-off and leaf-on flights (Table 1), study trees are likely to have experienced changes to their canopy (branch growth and dieback).

Discussion

Applications of aerial SfM have been systematically explored in the traditional forestry and agriculture sectors (i.e. natural and managed forests, agroforestry and conventional crop settings), yet its use is still relatively novel (Alonzo et al., 2018; Hadas et al., 2020; Tu et al., 2019). There is, however, a dearth of formal research that has been conducted in the urban forest (Isibue & Pingel, 2020) due – in part – to several key barriers and limitations to UAV use in highly-populated settings. When flying over urbanised settings that typically feature substantial vehicular and pedestrian traffic, several factors need to be carefully considered and planned for, namely, equipment malfunction, battery failure, interactions with inclement weather (i.e. moisture, gusts, cloud cover), and/or pilot error. These factors may lead to an unintended impact by a UAV, resulting in potential injury to a person or damage to property. To mitigate risk, safety precautions must be taken including the use of proper signage, communication with local regulators (i.e. law enforcement, Federal Aviation Administration (FAA)), and coordination with individuals in the locale. Best practices during the flight include managing flight altitude, maintaining line-of-sight with the UAV, designating a flight spotter and, depending on the urban circumstances, one or more individuals closely monitoring vehicular and pedestrian safety. While there are some published studies exploring the measuring of trees using UAV photogrammetry, our study contributes to best practices in logistical planning of aerial flights in an urban area under current FAA regulations, (2) demonstrates a manual photogrammetry workflow without algorithms, and (3) uses oblique RGB imagery to measure tree parameters.

Aerial image acquisition and structure-from-motion (SfM)

Barriers existed throughout the study area, such as heavy vehicular and pedestrian traffic, that limited the timing and length of flights. The altitude of both flights was limited to 45 m to maximise image resolution and efficiently capture as many trees as possible. The gimbal pitch was set to 45 degrees for the flights to maximise visibility of the main stems. Flights were conducted when wind conditions were under 4.5 metres per second to preserve image quality. Operators should consider cloud conditions on the day of the flight. Cloudy or overcast conditions minimised shadows and helped to achieve consistent lighting throughout the imagery.

There were clear advantages and disadvantages to both leaf-off and leaf-on flights. Canopy reconstruction was slightly better in leaf-on than leaf-off imagery. Fine branches in leaf-off imagery were not fully reconstructed, especially if shadows were present. In contrast, leaf-on imagery observed that foliage inhibited the visibility of trunks. To increase accuracy of trunk reconstruction, future studies could supplement aerial imagery that included understory imagery. Lower flight altitude may improve the accuracy of all tree parameters, particularly fine branches, however, frequent low-altitude flights in urban spaces do pose substantive risk to the public. Other methods of image acquisition might also be explored to obtain sub-canopy imagery. Leaf-off condition is an optimal time to view the interior structure of a tree when foliage is not obstructing the visibility of the trunk and branches (Nasiri et al., 2021). In temperate regions such as New England, obtaining measurements during winter months permits the visual detection of structural defects and enables responsive planning for the upcoming growing season. In contrast, height measurements may be best captured after canopies have fully emerged foliage.

Impact of ground control points (GCPs)

It is important to note that image alignment issues may arise with repeated features or patterns in the flight area. To mitigate this concern, UAV operators should allocate adequate time to collect enough GCPs to ensure accurate image alignment per Cromwell et al. (2021). Adding markers requires time and expense and implies the need for survey equipment access to collect GCPs; therefore, a trial without the use of GCPs was conducted for comparison. It was often difficult to detect GCPs in the leaf-on imagery because foliage blocked visual lines-of-sight. There was a slight difference between the number of points generated in the leaf-off flights when comparing the use of GCPs to without (426,776,067 and 426,721,426 respectively). There was also an insignificant difference in resolution between leaf-off imagery (1.33 cm/pix) and the leaf-on imagery (1.43 cm/pix).

The presence of GCPs did not appear to have an impact on the results. The authors speculate that because a high number of pictures were taken at low altitude with high percentage of overlap, the resulting point clouds were dense and had low ground sampling distances. The addition of ground control points may have provided diminishing value to the accuracy of the model. It should be underscored that models and maps rendered without GCPs may be visually accurate but do not relate to a real-world coordinate system. Despite having a low ground sampling distance, the authors emphasise the need for ground control points especially when integrating new flights into existing georeferenced maps. If time and access to survey equipment is a serious constraint, some drones come equipped with real-time differential correction. Although costly, it precludes the need to collect manual GCPs.

Measurement limitations

Extracting tree inventory parameters with UAS requires knowledge and availability of GIS, photogrammetry and associated software environments (i.e. DroneDeploy, ArcGIS, Agisoft Metashape). Although many procedures may be automated, demonstrating an accessible and comprehensive manual workflow would be necessary for its replication in the urban forestry community. It should be noted that leaf-on UAS measurements were collected 4 months after the manual measurements, which may bias comparisons. Re-collecting manual measurements on the day of the leaf-on flight would have been a better approach.

The time required to manually extract measurements from photogrammetry products proved to be commensurate with field measurements, if not slightly faster (~2 hours). Although data extraction was only slightly more time efficient than traditional data collection, the aerial perspective of the UAV imagery proved essential during active urban construction when physical access and visibility of the main stems of many of the subject trees was not possible from the ground. The contour intervals in Agisoft Metashape were set to 1 metre, which the authors chose to balance loading time and visual noise throughout the workspace. The sample size of trees was small ($n = 37$), which will limit the generalisability of the findings. However, the flight map covered almost 5% of the campus arboretum area. If extrapolating across the larger campus forest, the authors estimate that comprehensive data collection would require a practical number of safe, strategic flights. Scaling up the flight area might prove to increase the efficiency of maintaining an inventory across a larger space. It would be interesting to investigate the accuracy of tree measurements captured from oblique imagery in a fixed-wing, high-altitude UAV (Díaz et al., 2020). Furthermore, the steps taken to generate an accurate point cloud, which involves verifying GCPs (markers) in each image, proved to be the most timing-consuming (~5 hours per flight) element of this study.

Management implications

In 2008, a clear majority (58.9%) of state urban forestry coordinators indicated that while federal support for urban forestry-related tasks – including conducting local inventories – had increased, state support declined and more resources were needed, overall (Elton et al., 2023; Hauer & Johnson, 2008). Additionally, inventory needs vary depending on the municipality and their tree care priorities. Traditional tools required to conduct an urban tree inventory typically include a diameter tape or caliper to measure trunk diameter (DBH), as well as telescopic height rods, hypsometers, and laser rangefinders to measure tree height (Morgenroth et al., 2017). Geospatially based approaches have the potential to reduce time spent in the field, improve documentation of urban forest conditions, dedicate more expertise towards analysis instead of data collection, and engage a broader demographic of volunteer stakeholders (Vinci et al., 2023). Three-dimensional visualisation can increase the frequency and accuracy of tree measurements to assess maintenance needs, calculate appraisal values, determine plant health care applications, perform tree risk assessments, establish appropriate tree protection zones, and perform ecosystem analyses to determine benefit to cost ratio of management strategies (Hauer & Johnson, 2008).

Technical expertise, cost of acquiring UAS technology (UAV, photogrammetry software), and the spatial complexity of urban forests remain as barriers to incorporating UAS into day-to-day urban forest management (Dandois & Ellis, 2013; Zhang et al., 2015). A significant barrier to UAS application in the urban forestry sector relates to user-training. Though there may be a substantial automated component to the actual flying of a UAV, urban foresters and arborists should obtain both many hours of hands-on flight time as well as their formal UAV pilot's licence. Additionally, current UAS workflows are complex and often require intensive geospatial software training. Protocols to automate the measurement extraction process are available but are limited to the remote sensing expertise of the user. Allometric equations and other automated modelling methods, such as machine learning, may be less predictable in the urban forestry sector because urban trees often exhibit atypical growth and development due to the variation in growing conditions and human manipulation/management. The more urban forestry practitioners are involved in applying UAS to management programmes, the more accessible the workflows will become, ultimately streamlining results for end users. A literature review by Paneque-Gálvez et al. (2014) investigated community-based forest monitoring programmes in countries with tropical forests. The authors suggest that adopting UAS technology is feasible only if there is some degree of existing community forestry management, where there is personnel infrastructure in place to make data-driven decisions. Ma et al. (2021) designed an urban forestry questionnaire for Sweden ($n = 290$) and the United States ($n = 1{,}727$) involving communities with a population of 50,000 or more and a random sample of communities below 50,000. Approximately 50% of urban forestry operations have a management plan (Ma et al., 2021). Establishing management goals and clear intentions for implementing inventory data should be prerequisites before investing in robust data collection efforts that may include UAS.

Management decisions should also consider public safety and privacy. Although regulations are continuously being refined and developed, it is the responsibility of the UAV operator to ensure flights are planned and executed with professionalism. The operator, or remote pilot, must consider and comply with federal and regional regulations, in addition to ethical considerations (Paneque-Gálvez et al., 2014). Special permission is typically required to protect other aircraft, people, and property in the event of a loss of control of a UAV. The FAA does not currently address privacy concerns, however state and local laws may exist and warrant careful investigation, consideration, and adherence. There is an expectation of privacy over private property, and the appropriate consent and communication must be provided through a flight plan, and operators must adhere to no-fly zones in public spaces.

Future research directions

Additional studies are needed to continue to assess the utility of UAS in urban forest settings. Larger sample sizes are essential to discuss the efficacy of flight parameters. Implementing a diversity of tree species and age classes across a study area can be helpful in illuminating limitations of the technology or approach. This study defined a manual photogrammetric methodology to extract quantitative variables of mature street trees using oblique RGB imagery. Additional experimentation is needed to observe how flight altitudes can influence image resolution, orthorectification, and ultimately precise measurements. Other parameters such as gimbal pitch, weather conditions, flight speed, and the presence of shadows affect the reconstruction of fine branch tips that enable accurate tree measurements. Flight speed and changes in site elevation should also be investigated for their influence on consistent image overlap. The collection of ground control points requires expertise, time, and access to surveying equipment. Although GCPs did not make a meaningful difference in measurements for this particular study – regardless of survey type – they should be used in professional orthorectification applications. Further study is needed to develop qualitative protocols for risk assessment, and pest and disease monitoring, which has a developing body of research (Dainelli et al., 2021; Duarte et al., 2022; Roberts & Slater, 2023; Walker & Dahle, 2023). Remote sensing research will continue to refine methodology using deep learning and neural networks (Beloiu et al., 2023).

Conclusions

Accurate tree measurements are essential for making data-driven urban forest management decisions. Tree measurements taken on the ground using traditional methods may be time-consuming and difficult to collect and curate depending on scalability (i.e. forest size), survey conditions, and access to trees and resources (i.e. workers, technical expertise). Remote sensing and UAS may be low-cost investments that could supplement an urban tree inventory programme, yielding comparably accurate results to traditional ground-based measuring techniques. In select scenarios, communities may consider urban forest data collection via the use of UAV under specific circumstances that consider the limitations of budget and personnel, value of target trees, and public safety. Practitioners should be well-advised to critically examine data collection accuracy, workflow productivity, and cost-effectiveness when evaluating new instruments and techniques – including UAV – in relation to the collection of traditional field measurements.

Acknowledgments

The authors would like to thank Ryan Wicks, co-director of flight operations at UMassAir, Department of Environmental Conservation at UMass Amherst and the UMass Transportation Center, for their collection of GCPs and flight planning assistance. Dr. Megan Graham MacLean, Senior Lecturer of Quantitative Ecology at the University of Massachusetts Amherst for guidance on statistical analysis. Roxann Cormier, editing and writing support. The aerial imagery was collected in coordination with Ian Cyr, Police Deputy Chief at UMass Amherst. Additional support was provided by Burt Ewart, Senior Project Manager for the Department of Design & Construction Management at UMass Amherst.

Author contributions

CRediT: **Christopher A. Copeland:** Conceptualization, Formal analysis, Writing – original draft; **Richard W. Harper:** Funding acquisition, Supervision, Writing – review & editing; **Nicholas J. Brazee:** Formal analysis, Writing – review & editing; **Charles M. Schweik:** Resources, Writing – review & editing; **Forrest J. Bowlick:** Writing – review & editing.

Funding

This research was supported by the USDA National Institute of Food and Agriculture, McIntire Stennis Project #46, Accession #7003678.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Notes on contributors

Christopher A. Copeland, MSc., is pursuing a PhD in Forest Resources & Arboriculture at the University of Massachusetts. Research interests include tree surveying and evaluation using GIS and UAS technology. He earned his BSc and MSc at the University of Massachusetts, and focused on urban forestry and sustainable agriculture, respectively. He is the manager of plant production at the Arnold Arboretum of Harvard University.

Richard W. Harper, PhD., is an Extension Professor of Urban & Community Forestry in the Department of Environmental Conservation. He teaches courses and administers an applied integrated research and extension programme in urban forestry.

Nicholas J. Brazee, PhD, is an extension plant pathologist in the Center for Agriculture, Food and the Environment, University of Massachusetts, Amherst. He directs the UMass Plant Diagnostic Laboratory and conducts applied research in urban forestry.

Charles M. Schweik, PhD, is a Professor of Environmental Conservation & Public Policy, Director of the UMass Amherst Information Technology Program, and Co-Director of UMassAir, a cross-campus UMass group that focuses on the use of unoccupied aerial systems (UAS) to support environmental policy and management.

Forrest J. Bowlick, PhD, is a lecturer in the Department of Geosciences and the Department of Environmental Conservation at the University of Massachusetts – Amherst. His research investigates how students learn GIS in various classroom contexts, especially at the interface of geography, GIS, and computer science.

ORCID

Richard W. Harper http://orcid.org/0000-0002-9522-4562

References

Alonzo, M., Andersen, H. E., Morton, D. C., & Cook, B. D. (2018). Quantifying boreal forest structure and composition using UAV structure from motion. *Forests*, *9*(3), 119. https://doi.org/10.3390/f9030119

Bancks, N., North, E. A., & Johnson, G. R. (2018). An analysis of agreement between volunteer-and researcher-collected urban tree inventory data. *Arboriculture & Urban Forestry*, *44*(2), 73–86. https://doi.org/10.48044/jauf.2018.007

Beloiu, M., Heinzmann, L., & Rehush, N., Gessler, A., Griess, V. C. (2023). Individual tree-crown detection and species identification in heterogeneous forests using aerial RGB imagery and deep learning. *Remote Sensing*, *15*(5), 1463. https://doi.org/10.3390/rs15051463

Berland, A., Roman, L. A., & Vogt, J. (2019). Can field crews telecommute? Varied data quality from citizen science tree inventories conducted using street-level imagery. *Forests*, *10*(4), 349. https://doi.org/10.3390/f10040349

Bloniarz, D. V., Amp, R., & H, D. (1996). The use of volunteer initiatives in conducting urban forest resource inventories. *Arboriculture & Urban Forestry*, *22*(2), 75–82. https://doi.org/10.48044/jauf.1996.010

Carbonneau, P. E., & Dietrich, J. T. (2017). Cost-effective non-metric photogrammetry from consumer-grade sUAS: Implications for direct georeferencing of structure from motion photogrammetry. *Earth Surface Processes and Landforms*, *42*(3), 473–486. https://doi.org/10.1002/esp.4012

Cimburova, Z., & Barton, D. N. (2020). The potential of geospatial analysis and Bayesian networks to enable i-tree Eco assessment of existing tree inventories. *Urban Forestry and Urban Greening*, *55*, 126801. https://doi.org/10.1016/j.ufug.2020.126801

Copeland, C. A., Harper, R. W., Brazee, N. J., & Bowlick, F. J. (2023). A review of Dutch elm disease and new prospects for *Ulmus americana* in the urban environment. *Arboricultural Journal*, *45*(1), 3–29. https://doi.org/10.1080/03071375.2022.2082177

Cromwell, C., Giampaolo, J., Hupy, J., Miller, Z., & Chandrasekaran, A. (2021). A systematic review of best practices for UAS data collection in forestry-related applications. *Forests*, *12*(7), 957. https://doi.org/10.3390/f12070957

Dainelli, R., Toscano, P., DiGennaro, S. F., & Matese, A. (2021). Recent advances in unmanned aerial vehicles forest remote sensing-a systematic review. Part II: Research applications. *Forests*, *12*(4), 397. https://doi.org/10.3390/f12040397

Dandois, J. P., & Ellis, E. C. (2013). High spatial resolution three-dimensional mapping of vegetation spectral dynamics using computer vision. *Remote Sensing of Environment*, *136*, 259–276. https://doi.org/10.1016/j.rse.2013.04.005

Díaz, G. M., Mohr-Bell, D., Garrett, M., Muñoz, L., & Lencinas, J. D. (2020). Customizing unmanned aircraft systems to reduce forest inventory costs: Can oblique images substantially improve the 3D reconstruction of the canopy? *International Journal of Remote Sensing*, *41*(9), 3480–3510. https://doi.org/10.1080/01431161.2019.1706200

Duarte, A., Borralho, N., Cabral, P., & Caetano, M. (2022). Recent advances in forest insect pests and diseases monitoring using UAV-based data: A systematic review. *Forests*, *13*(6), 911. https://doi.org/10.3390/f13060911

Elton, A. J., Harper, R. W., Bullard, L. F., Griffith, E. E., & Weil, B. S. (2023). Volunteer engagement in urban forestry in the United States: Reviewing the literature. *Arboricultural Journal*, *45*(2), 96–117. https://doi.org/10.1080/03071375.2022.2030620

Fang, R., & Strimbu, B. M. (2017). Stem measurements and taper modelling using photogrammetric point clouds. *Remote Sensing*, *9*(7), 716. https://doi.org/10.3390/rs9070716

Gao, X., Zhao, B., Chen, Z., Song, W., Li, Z., & Wang, X. (2023). The impact of urbanization on tree growth and xylem anatomical characteristics. *Biology*, *12*(11), 1373. https://doi.org/10.3390/biology12111373

Hadas, E., Kölle, M., Karpina, M., & Borkowski, A. (2020). Identification of peach tree trunks from laser scanning data obtained with small unmanned aerial system. *ISPRS Annals of the Photogrammetry, Remote Sensing & Spatial Information Sciences*, *2*, 735–740. https://doi.org/10.5194/isprs-annals-V-2-2020-735-2020

Hamilton, K., Koeser, A., & Landry, S. (2018). Accuracy of volunteer-derived data from a single-day inventory event built around a crowdsourced tree mapping application. *Arboriculture & Urban Forestry*, *44*(6), 248–254. https://doi.org/10.48044/jauf.2018.022

Hauer, R. J., & Johnson, G. R. (2008). State urban and community forestry program funding, technical assistance, and financial assistance within the 50 United States. *Arboriculture & Urban Forestry*, *34*(5), 280–289. https://doi.org/10.48044/jauf.2008.038

Isibue, E. W., & Pingel, T. J. (2020). Unmanned aerial vehicle based measurement of urban forests. *Urban Forestry and Urban Greening*, *48*, 126574. https://doi.org/10.1016/j.ufug.2019.126574

Lisein, J., Pierrot-Deseilligny, M., Bonnet, S., & Lejeune, P. (2013). A photogrammetric workflow for the creation of a forest canopy height model from small unmanned aerial system imagery. *Forests*, *4*(4), 922–944. https://doi.org/10.3390/f4040922

Ma, B., Hauer, R. J., Östberg, J., Koeser, A. K., Wei, H., & Xu, C. (2021). A global basis of urban tree inventories: What comes first the inventory or the program. *Urban Forestry and Urban Greening*, *60*, 127087. https://doi.org/10.1016/j.ufug.2021.127087

Morgenroth, J., Östberg, J., & Konijnendijk van den Bosch, C. C. (2017). Measuring and monitoring urban trees and urban forests. In F. Ferrini & A. Fini (Eds.), *Routledge handbook of urban forestry* (1st ed. pp. 33–48). Routledge.

Muscas, D., Fornaciari, M., Proietti, C., Rugam, L., & Orlandi, F. (2023). Tree growth rate under urban limiting conditions. *European Journal of Forest Research*, *142*(6), 1423–1437. https://doi.org/10.1007/s10342-023-01599-0

Nasiri, V., Darvishsefat, A. A., Arefi, H., Pierrot-Deseilligny, M., Namiranian, M., & Le Bris, A. (2021). Unmanned aerial vehicles (UAV)-based canopy height modeling under leaf-on and leaf-off conditions for determining tree height and crown diameter (case study: Hyrcanian mixed forest). *Canadian Journal of Forest Research*, *51*(7), 962–971. https://doi.org/10.1139/cjfr-2020-0125

Olson, L. G., Coops, N. C., Moreau, G., Hamelin, R. C., & Achim, A. (2025). The assessment of individual tree canopies using drone-based intra-canopy photogrammetry. *Computers and Electronics in Agriculture*, *234*, 110200. https://doi.org/10.1016/j.compag.2025.110200

Oniga, V.-E., Breaban, A. I., & Statescu, F. (2018). Determining the optimum number of ground control points for obtaining high precision results based on UAS images. *Proceedings*, *2*, 352. https://doi.org/10.3390/ecrs-2-05165

Paneque-Gálvez, J., McCall, M. K., Napoletano, B. M., Wich, S. A., & Koh, L. P. (2014). Small drones for community-based forest monitoring: An assessment of their feasibility and potential in tropical areas. *Forests*, *5*(6), 1481–1507. https://doi.org/10.3390/f5061481

Pike, K., O'Herrin, K., Klimas, C., & Vogt, J. (2021). Tree preservation during construction: An evaluation of a comprehensive municipal tree ordinance. *Urban Forestry and Urban Greening*, *57*, 126914. https://doi.org/10.1016/j.ufug.2020.126914

Roberts, J., & Slater, D. (2023). Miniature UAVs and photogrammetry--a novel approach to collecting aerial inspection data from mature broadleaf trees. *Arboriculture & Urban Forestry*, *49*(2), 75–89. https://doi.org/10.48044/jauf.2023.007

Roman, L. A., Conway, T. M., Eisenman, T. S., Koeser, A. K., Ordóñez Barona, C., Locke, D. H., Northrop, R. J., Bardekjian, A., van Doorn, N. S., Grove, J. M., Kremer, P., Martin, D. G., McLean, D., Mundel, T., Sonti, N. F., Steenberg, J. W. N., Threlfall, C. G., Vogt, J., & Östberg, J. P. A. (2021). Beyond 'trees are good': Disservices, management costs, and tradeoffs in urban forestry. *Ambio*, *50*(3), 615–630. https://doi.org/10.1007/s13280-020-01396-8

Thinley, J., Pickering, C., & Ndehedehe, C. (2025). Comparing lidar-generated above-ground biomass with field data in an old-growth native urban forest in Australia. *Sustainable Horizons*, *15*, 100147. https://doi.org/10.1016/j.horiz.2025.100147

Tu, Y. H., Johansen, K., Phinn, S., & Robson, A. (2019). Measuring canopy structure and condition using multi-spectral UAS imagery in a horticultural environment. *Remote Sensing*, *11*(3), 269. https://doi.org/10.3390/rs11030269

Vinci, A., Brigante, R., Traini, C., & Farinelli, D. (2023). Geometrical characterization of hazelnut trees in an intensive orchard by an unmanned aerial vehicle (UAV) for precision agriculture applications. *Remote Sensing*, *15*(2), 541. https://doi.org/10.3390/rs15020541

Walker, M., & Dahle, G. A. (2023). Literature review of unmanned aerial systems and lidar with application to distribution utility vegetation management. *Arboriculture & Urban Forestry*, *49*(3), 144–156. https://doi.org/10.48044/jauf.2023.011

Ward, K. T., & Johnson, G. R. (2007). Geospatial methods provide timely and comprehensive urban forest information. *Urban Forestry and Urban Greening*, *6*(1), 15–22. https://doi.org/10.1016/j.ufug.2006.11.002

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. (2012). 'Structure-from-motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology*, *179*, 300–314. https://doi.org/10.1016/j.geomorph.2012.08.021

Zhang, C., Zhou, Y., & Qiu, F. (2015). Individual tree segmentation from LiDAR point clouds for urban forest inventory. *Remote Sensing*, *7*(6), 7892–7913. https://doi.org/10.3390/rs70607892