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Testing the accuracy of imaging software for measuring tree root volumes

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ABSTRACT

Manually measuring tree root characteristics can be inefficient and limiting. To test the application of a new digital technology in tree root architecture research, root systems from 29 green ash (*Fraxinus pennsylvanica* 'Patmore') trees were unearthed, cleaned, and photographed to create 3D models using structure from motion (SfM) photogrammetry. Three root segments from each root system were selected, marked, and removed after being photographed. The volumes of these segments (derived from the 3D models) were compared against volumes measured using water displacement. In addition to the root segments, model and water displacement volumes were compared for three complete root systems. Regression analysis showed a strong linear relation between the two volumes measurements (adjusted $R^2 = 0.97$ for the root segment data). The RMSE for the root segment volume estimates was 40.37 cm^3 (12.3%), with a bias of 17.2 cm^3 (5.3%). This error rate was similar to previous published work and suggests the technology used may allow researchers to improve efficiency in data capture, add new measurements (i.e., surface area) to their modeling efforts, and digitally preserve tree root systems for future study.

1. Introduction

Root systems are integral to tree health and survival—providing the mechanisms needed to access belowground water and mineral resources, store carbohydrates produced via photosynthesis, produce and respond to hormonal signals, and provide anchorage to support the above-ground structure (Pallardy, 2008; Day et al., 2010). Root distribution and architecture are the most commonly used metrics for describing the spatial properties of root systems (Lynch, 1995). Past research has assessed both the impact of the physical soil environment on root distribution and architecture (Day et al., 2010) and the impact of this growth on whole tree stability (Gilman and Grabosky, 2011; Gilman and Harchick, 2014). In these whole-tree stability studies, basic measures such as root cross-sectional area have partially explained differences in rooting strength among trees (Gilman and Grabosky, 2011; Gilman and Harchick, 2014).

Manual characterization of root architecture is labor-intensive and somewhat limited in the measurements that can be effectively quantified. Having the ability to easily and accurately record characteristics like root location, root volume, and root surface area in contact with the soil can potentially improve predictive models of root stability. Similarly, accurate root measurements (volume in particular) can be used to calculate belowground biomass, carbon dynamics, and nutrient cycling (Lal, 2005). Furthermore, accurate assessments of tree root architecture and biomass can be used to quantify tree-related ecosystem services like water attenuation, non-point source pollutant uptake, and soil stability (Nowak et al., 2008; Stokes et al., 2009).

The water displacement method can be used to measure root volume if destructive harvest is possible (Harrington et al., 1994). This method provides highly accurate results, but can be imprac-

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tical depending on field conditions, root system size, and available equipment. As an alternative to this traditional method, programs (e.g., AMAPmod, GROGRA, SimRoot FSPM, etc.) have been developed for modeling three-dimensional (3D) root systems to provide estimates of volume (Danjon and Reubens, 2007). These approaches have additional error not associated with direct measurement.

Recent advances in terrestrial remote sensing have made it possible to digitally record and render 3D structures. Currently, two main methods for 3D data acquisition exist: laser scanning (i.e., LiDAR) and structure from motion (SfM) photogrammetry. While LiDAR units are generally expensive, SfM can be accomplished using a standard digital camera and a relatively inexpensive image post-processing program (Morgenroth and Gomez, 2014). Close-range SfM photogrammetry is increasingly being used to accurately render digital surface models (DSMs) (Fonstad et al., 2013), hydrological and geological features (Westoby et al., 2012; Javernick et al., 2014), archeological sites (Green et al., 2014), architecture (Maiellaro et al., 2015), heritage objects (Alsadik et al., 2015), and vegetation (Zarco-Tejada et al., 2014). With regard to trees, Morgenroth and Gomez (2014) initially demonstrated that relatively accurate metrics (root mean square error (RMSE) < 4%) for tree height and stem diameter could be attained with this method and later showed that aboveground volume was estimated with a RMSE of 12% for the main stem, but 47.5% for branches (Miller et al., 2015). Similarly, Liang et al. (2014) found that SfM photogrammetry could model diameter at breast height (DBH) with an acceptable RMSE of 2.39 cm—an error rate on par with terrestrial laser scanning.

Photogrammetric root models can be a helpful tool for a variety of studies, especially for field sites with limited access or other conditions that prevent the transport of root systems. Once the photogrammetric model is created, the 3D rendering is stored digitally, offering the ability to archive past data sets for potential future analyses while disposing of the actual root systems. Beyond research, 3D models provide valuable visualization for educational purposes. With the advent of 3D printers, portable root models could be developed for interactive demonstrations.

Noting these potential benefits, this study was conducted to test the ability of a commercially available photogrammetric imaging software package for creating 3D models of root systems from which accurate estimates of root volume can be derived (root surface area was also calculated, but no suitable comparison was identified). Even when cleaned and pruned to remove small diameter roots, root system complexity creates a unique set of challenges, increasing the potential for error from blocked line of sight and shadow. As such, this paper serves as a proof of concept to show the potential of SfM in modeling tree root systems. To test accuracy, volumes derived from SfM were compared to those measured via water displacement. This work offers insights into the methodology from initial image capture to model processing. It also serves a preliminary evidence for the utility of SfM in whole-tree biomechanics research.

2. Methods

PLANTING. On April 12, 2004, a total of 60 Patmore green ash (*Fraxinus pennsylvanica* 'Patmore') bare root liners, were planted in horticultural research plots at the University of Illinois at Urbana-Champaign (40.1097° N, 88.2042° W). The soil at the planting site is a Drummer silty clay loam with a 0–2% slope (U.S. Dept. Agr. Natural Resource Conservation Serv., 2013). Trees originated from a wholesale bare-root liner nursery in the Pacific Northwest (J.F. Schmidt and Sons, Boring, OR, United States) and were planted in rows spaced 4.6 m (15 feet) apart. Within rows, trees were spaced 3.7 m (12 feet) apart. At planting, all trees were between 2–2.75 m (7–10 feet) in height and were selected so that the distance between the graft union and trunk flare was similar. Broken or kinked roots were removed prior to planting.

2.1. Root excavation

Of the original 60 liners planted in 2004, 29 survived an earlier destructive harvest (a random sub-sample) or other injury and were available for use in this study. The trees were felled in October 2013 and their root systems were excavated in May 2014 using a 244-cm (96-in.) hydraulic tree spade. Once harvested, the soil inside the root ball was removed using air excavators (Airspade 2000, Guardair Corporation, Chicopee, MA, United States; X-LT; Supersonic Air Knife, Inc., Allison Park, PA, United States). After bare-rooting, all small-diameter roots (i.e., roots <1 cm in diameter) were identified with a fixed caliper gauge (i.e., a piece of metal with a 1 cm notch cut into it) and removed with a hand pruner. Any remaining soil was washed away with water.

2.2. Preparation of samples

Excavated root systems were, in turn, inverted and centered on a plywood work surface. Paper coded targets were attached to the work surface at known distances from one another to provide a reference scale for measurements made on the final computer-generated root models (see Graphical abstract). Prior to collecting images, three randomly-selected root segments (one vertical, one horizontal, and one with abnormal growth or defects) from each root system were marked with orange electrical tape. A series of digital images was taken for each root system at a distance range of 1–2 m, entirely circumnavigating the roots system in three different planes (i.e., slightly above the root system, parallel to the root system, and slightly below the root system). Approximately 120 digital images were taken for each root system using a digital single-lens reflex camera (lens = Nikon AF-S DX NIKKOR 12–24 mm f/4G, Nikon Corporation, Tokyo, Japan; body = D7000, Nikon Corporation, Tokyo, Japan). Photographs for the sampled root systems were shot outside over the course of three days with light conditions varying from partly cloudy to overcast. After capturing each series of images, the three randomly-selected root sections were harvested from each root system for comparative volumetric analysis (i.e., compared against the volume measured by the water displacement method). Additionally, three entire root systems were completely dismantled for comparative volumetric analysis.

2.3. 3-DIMENSIONAL computer modeling

Images were imported into photogrammetry software (PhotoScan, Agisoft, LLC, St. Petersburg, Russia) to create the 3-dimensional root models. Images that were visibly over-exposed or under-exposed were omitted from the data set prior to processing. Model generation was a multi-step process. Key stages of model generation are highlighted in the Graphical abstract. First, photosets of root systems were imported and photos were aligned, allowing the software to determine camera positions and feature matching to generate a sparse point cloud. A dense point cloud was then constructed using the previously generated sparse cloud, camera positions, and photos in the photoset. The next step in the model construction was mesh creation. A network of 3D polygons was overlaid on the object surface using the dense cloud as a template. A watertight model (i.e., all holes in the mesh are sealed) was then created from the mesh construction. The final step was texture mapping. This process involved overlaying the photos back onto the model to give the model a realistic appearance.

The tree was modelled along with the plywood work surface and the aforementioned paper coded targets, which were then used to