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3-D Modeling of tree root systems - a fusion of 3-D Laser scans and 2-D tree-ring data

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ABSTRACT

Most studies addressing woody plant roots deal specifically with geology, topology or biomass approximations, and estimations for root biomass remain particularly rough. To address questions such as what role tree roots play in the carbon budget, accurate estimates of root biomass are essential. Biomass models that include information about root development through time are also needed, as most biomass models represent only the present state of a tree’s developmental stage. The aim of this study is to develop an annually resolved 3-D growth model for tree root systems. A 3-D surface model of a root system was first captured, and then combined with tree-ring width data. Different scanning methods, including terrestrial laser scanning, Scan-Arm and Inhand-scanning, were used and evaluated as devices to acquire a 3-D image of the root surface. Once the root surface was successfully modelled, we calculated root volume with a volume-computation algorithm. Moreover, a first attempt to add age information to the 3-D surface model by integrating tree-ring data was made. The accuracy of the volume calculations for the surface models varies depending on the complexity of the scanned objects, the used scanner type and the modelling techniques. While volume computations for simple shapes (e.g., cylinders) differed by less than 5 % from the actual volume the calculations for complex root structures differed by up to 15 %. The most accurate root model differed by < 5 %. The first models demonstrate that distances can readily be surveyed within the models using point to point computations. Hence, root length and distribution patterns can be measured virtually and no longer need to be performed manually. In addition, surface models with integrated ring borders enable reconstruction of root development and provide additional information on bifurcation and root length patterns.

KEYWORDS: laser scanning, root development, root biomass, tree rings

1. INTRODUCTION

Within the last 40 years there has been much progress in modeling plant roots, but most studies focus only on particular sub areas such as topology, geometry (Danjon & Reubens 2008, Godin et al. 1999) or biomass accumulation. Attempts to assess the global carbon cycle - particularly in relation to global warming - are manifold, but these computations remain uncertain (Heimann & Reichstein 2008). Tree roots serve as significant storage mechanisms within the terrestrial carbon cycle but biomass estimations remain rough and little is known about the relationship between root growth and stem increment. A model of annual root development would be a big step forward in providing detailed information about growth patterns and biomass accumulation in roots. Since the end of the 1990s, new imaging techniques and devices (automated and semi-automated systems) have become available for the acquisition of the 3-D architecture of root systems (Danjon & Reubens 2008). Among these techniques are x-ray devices, ground penetrating radar, 3-D digitizing devices and sound-emitter sonic digitizers. While these methods provide valuable information for potted plants or small root systems, the results for bigger structures are often poor. Laser scanner techniques have been applied in forestry for acquiring the aboveground structure of trees (Aschoff & Spieker 2004) and an entire root system was scanned for the first-time by Gärtner and Denier (2006). This root model and those mentioned before successfully reproduced root structure at the time of uprooting but provided no information regarding the spatio-temporal development of the root system. This new effort will integrate the annually resolved ring-width information into a surface model and will develop and improve the methods for developing a viable model. Therefore, the aim of the study is to develop an annually resolved 3-D growth model for coarse roots. The method will initially be developed for a root segment and then expanded to encompass an entire root system. To realize this, a 3-D surface model of a root system has to be acquired and will be combined with tree-ring data. For the acquisition of the root surface different scanning methods will be used and evaluated. These results will allow an accurate quantification of root development, thereby providing fundamental data for quantifying the belowground carbon cycle and the relationships and couplings between above- and belowground productivity. Moreover, bifurcation patterns and root length can be analyzed easily within the models. Fine roots will be excluded from this study because the laser scanner cannot accurately capture such fine elements.

2. METHODS

2.1. Acquisition and modeling of root surface

After the exposure of a root system, the surface of individual roots was scanned with a terrestrial-laser Scanner (Imager 2005), a Scan-Arm and an Inhand-Scanner to find the most appropriate and accurate way to represent root surfaces in 3-D. The basic principle behind the scanner devices is similar. A laser beam is emitted and reflected by the surface of an object. The return signal is captured by a receiver and 3-D high resolution point clouds are produced. Each point has an x, y and z coordinate and an additional coefficient that is a function of the object's reflectivity. The total amount of points is dependent on the resolution and the distance from the object. The scanner itself and the scan procedure are influenced by several factors (range measurement principle, scan position, angle of influence, swabbing of rotation axis etc.) which can cause measuring errors such as scattering- , missing data due to shadowing effects (Schulz 2007). To determine the test sensitivity to these factors, simple shapes and objects with different surface characteristics were also scanned. The generated point clouds contained data noise due to scattering effects, which was removed with different filter techniques (reduce noise, remove outliers etc.) available in Geomagic Studio 2009 software. Moreover, the impact of applied filters was tested and evaluated. Afterwards, closed surfaces were generated for all point clouds by generating meshes via triangulation or using NURBS (Non-uniform rational B-Splines) models. The volumes of the surface models were computed from the models and validated by water replacement experiments.

2.2. Tree ring measurements

After the root surface was modeled, the root was cut into segments to obtain cross sections with which tree-rings were measured. Ring-width was measured at four radii per cross section according to standard techniques used in Dendrochronology (Cook & Kairiukstis 1990) using WinDendro software. The resulting data to be integrated into the 3-D model are ASCII data representing the position and the size of the annual rings. In addition, the distances between the starting points of radius measurements at the bark side were measured (d1-d4; Figure 1).

3. RESULTS

3.1. Volume computations

There was a noticeable difference in modeled to reference volume depending on the particular shape of the acquired object. The deviation for the simplest shapes was in the range of 0.2 to 4%.

Deviation increases with complexity of the scanned structures, as can be seen for the scanned root (Table 1). In this case, the volume calculated for the Imager 2005 model was up to 15 % higher than the actual volume. The highest deviation (15 %) was an exception and the result of remaining inclusions within the model. In general, the results for the Inhand-scanner and the Scan-arm are more precise and require less modelling effort. Most accurate root models differed by 5 % from the actual volume.

Table 1. Deviations of volume calculations from actual volumes for the different scanner devices.

Scannertype	Shapes	Root Segments
Imager 2005	1-5 %	5 - 15 %
ScanArm	<1 %	5 - 7 %
Inhand - Scanner	-	5 %

3.2. Fusion of data sets

One of the main results of this study was the transformation of ring-width data (measured on cross sectional discs) into a 3-D coordinate system. Using Geomagic, corresponding cross sections were set within the surface model and then aligned with the z-plane. Hence, the z coordinate for each single point of a cross section is constant and can be handled as a 2-D coordinate system. In conjunction, ring data of the corresponding real cross sections were exported to Matlab and coordinates calculated for all ring boundaries. To retain the correct orientation of the single radii, the starting point (P1) of radius 1 was set manually within the model (Figure 1). The starting point of radius 2 (P2) was defined by the intersection between the circumference of the model cross section and the measured distance (d1) between P1 and P2 (Figure 1). The intersection point (Pn) of the two radii, representing the growth origin of the cross section, was calculated using trigonometric formulas for single point calculation (Gruber and Joeckel 2007). The same calculations were used for P3 and P4, whereas Pn was then used as a second input value for these calculations. As soon as the correct orientation of the radii (r) in the coordinate system of the model was realized, the coordinates of the ring boundaries (Rn) along the radii were calculated as follows:

$$\mathbf{y_{Rn}} = y_{Px} + y_{Pn} - y_{Px} / r^*(r - rw) \qquad (1)$$

$$\mathbf{x_{Rn}} = x_{Px} + x_{Pn} - x_{Px} / r^*(r - rw) \qquad (2)$$

Px = Starting point of respective radius (P1, P2, P3, P4); rw = distance ring boundary to Px

Hence, ring–width data was transformed into a 2-D Cartesian coordinate system and each cross section had its own coordinate system. Following the calculations in Matlab, data were exported back into Geomagic. There it was possible to realign the cross sections back into their original position. However, although this method works quite well if the cross section is the same as in reality, deviations resulting from filter techniques applied or other error-introducing reasons (cutting angle etc.) can lead to deformations of the radii and their orientation. Currently, several different approaches being explored to most accurately adjust and approximate the position of the radii.

4. DISCUSSION

It was possible to determine the volume of coarse roots at the time of uprooting, but it was shown that knowledge about the impact of shadowing or scattering effects and different filters is indispensable for an efficient application of the scanning technique.

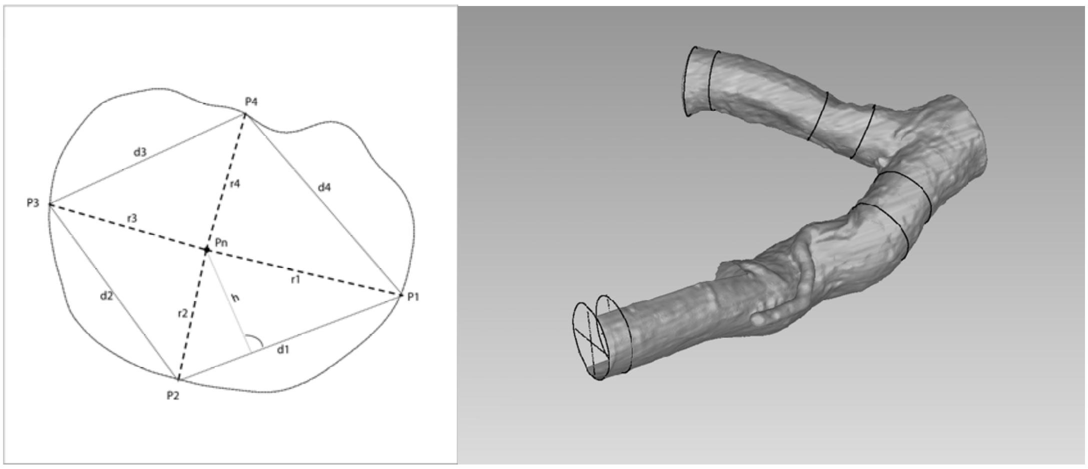

Figure 1: Left: Scheme of ring-width data integration in the model section (dashed lines: radii) Right: Surface model of root segment with ring-width measurements.

Depending on the scanner used, deviations for roots were between 5 and 15 % above the reference volume. Inhand-scanner and Scan-arm showed accurate results, this can be explained by the fact that both are close-range scanners (< 4 m). In contrast, the Imager 2005 has a range from 2 - 80 m. Laser scanning is a rapidly developing technique and it is therefore likely that new devices with even higher resolutions will soon enter the market (Sternberger 2007). However, we achieved good results with the Scan-Arm and decided to go on with this technique. Moreover, measured ring-widths were successfully transformed into a 3-D coordinate system which is the precondition for ongoing interpolation techniques. Currently, several interpolation techniques are being explored to generate for each growth year a closed surface. The ability to survey a root system in a 3-D space enables the user to gather additional information about root growth and bifurcation patterns within an all-embracing model.

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