CURRENT APPLICATIONS OF GPR IN FOREST RESEARCH

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Abstract

Forests, both naturally regenerated stands and plantations are complex, long-lived systems, which can be difficult to assess and monitor over time. This is especially true of belowground biomass and internal features of trees which are inaccessible except by destructive sampling. Traditional methods are expensive, destructive, time-consuming, usually yield a small sample size and are not conducive to long-term monitoring. Since GPR was first used to map tree roots ten years ago, a variety of new applications have been introduced. On soils suitable for radar studies, root biomass surveys have been valuable means to quantify belowground biomass, spatial distribution of roots, measure root diameters and even map individual roots. Methods include collecting linear transects in reflection mode, interlacing grids of transects in order to create 3D reconstructions of roots and applying high frequency borehole antennas used in transmission mode to model vertically oriented roots. One of the more difficult problems we are currently considering is how to analyze permanently marked transects over time to monitor root development while soil moisture, temperature and surface conditions change seasonally. In a departure from subsurface analysis, we have recently employed a method using GPR to detect defects and moisture gradients in stems.

Introduction

Forests are complex, long-lived systems which present many challenges to analysis and inventory. Over the past hundred years, numerous methods of inventorying aboveground biomass have been developed ranging from allometric equations used to extrapolate wood volume from tree diameter to satellite-based sensors which can measure canopy height and density over a wide area. Methodology to quantify belowground biomass has lagged behind, until recently destructive excavations were the only option. Unlike annual crops; trees live for decades or longer, so destructive sampling is usually undesirable and not repeatable. The investment trees make in roots is considerable, up to half of the biomass in trees may be hidden belowground. Ground-penetrating radar (GPR) has been demonstrated to be a rapid means of detecting tree roots and measuring lateral root mass in well-drained, electrically resistive soils (Butnor et al. 2001; Butnor et al. 2003; Barton and Montagu 2004; Cox et al. 2005; Stover et al. 2007; Samuelson et al. 2008). Today, tree root biomass studies provide valuable insight into belowground productivity in forest systems and are used to test the effect of tree species, genetic selection, and subsequent management on carbon (C) allocation. In this paper we discuss several successful applications where GPR was used to quantify root mass, map root distribution, assess vertically oriented tap roots with borehole radar and detect defects in stems. Our purpose is to present how the technology is currently being used and highlight areas where the research is headed.

Detecting and Estimating Tree Root Mass

Tree roots have been detected in a variety of soil types with GPR. While electrically resistive soils like coarse sands provide the best medium for detecting and analyzing roots, loams and clay-loams may also be surveyed provided the soil is relatively dry. GPR is a great tool for locating and delineating the extent of major discontinuities in electrical conductivity, but mass estimation of reflectors is more complex. Our approach to detecting tree roots and surveying root biomass has 3 phases: 1) optimizing dielectric, range and gain settings, 2) calibrating radargrams to root mass collected with soil cores, 3) collecting transect data and scaling with calibration equations. Figure 1 shows a 1500 MHz antenna mounted on to a skateboard deck and equipped with a survey wheel and connected to a SIR radar system (GSSI Inc., Salem, NH, www.geophysical.com). After any surface debris (i.e. logs, branches etc.) are cleared away, the survey rig can easily be pulled through a site. The interaction between roots, root architecture and soil properties can be quite dynamic, so the selection of gain settings is important (i.e. don't use autogain). Experience has shown that using as few points as necessary and testing the settings in high rooting areas near trees and low rooting areas away from trees to ensure detection and avoid clipping. While GPR is frequently used to locate reflectors, determine their depth and estimate the diameter of regular shaped objects (pipes, rebar etc.), roots are complex reflectors which overlap, intertwine and move vertically through the soil making interpretation difficult. It has been demonstrated that radargrams can be precisely linked to root mass and buried biomass mass collected with soil cores (Figure 2) using the methodology described by Butnor et al. (2003).

Figure 1: GPR data is collected using a 1500 MHz antenna (marked with arrow) connected to a survey wheel.

Figure 2: In order to calibrate for root mass, cores are collected and compared to the GPR Index.

Calibration equations are specific to the site and settings used during collection. To date, all of our surveys have been done as a single point-in-time collections to compare experimental treatments in forests (i.e. fertilizer applications, species, genotype, and spacing), so it is not clear whether these calibrations can be used over time for repeated measures. Temporal changes in soil moisture will likely interfere with the detection small changes in root density. There is a major need to better understand how soil properties, soil moisture and root density affect reflectivity in order to develop calibrations which do not require destructive verification.

Under amenable soil conditions roots make excellent hyperbolic reflections (Figures 3 A&B). Figure 3.A shows the location of three 10 year old loblolly pine (*Pinus taeda* L.) trees along a survey transect in Bainbridge, GA. Root density is much greater adjacent to trees than in between trees, a characteristic common to young plantings. This site was in row crop production for decades prior to conversion to plantation forestry; consequently there is no interference from buried debris, dead roots or any other plants. As trees mature, the distribution of lateral roots is no longer confined to the area adjacent to the base of the tree as in a 50 year old loblolly pine plantation in Hawaii (Figure 3.B). Despite having higher root mass than the GA site, the root resolution in HI was noticeably lower. Though both sites were well drained, the GA soil (sandy, Grossarenic Paleudult) provided better contrast with roots than the soil in Hawaii (granular loam to subangular silty clay loam).

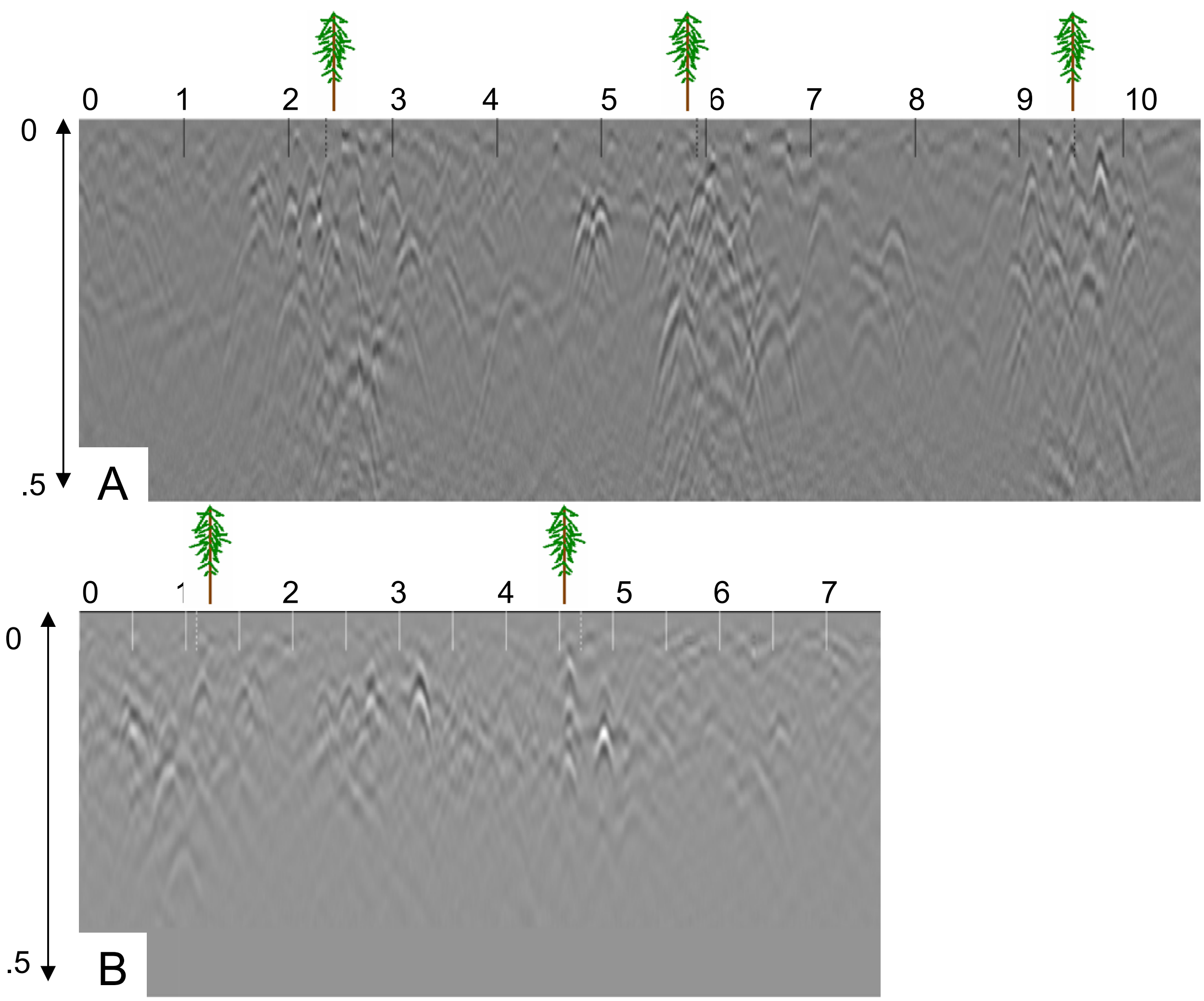

Figure 3: Radargrams collected with a 1500 MHz antenna in loblolly pine plantations in Bainbridge, GA (A) and on the island of Maui in HI (B). Tree locations are marked with the tree icons. Distance and depth units are in meters.

To date, GPR has been applied to study the effect of irrigation and fertilizer on pine root density (Butnor et al. 2003, 2005, Samuelson et al. 2008), measure root diameter (Barton and Montagu 2004), quantify residual root mass after peach orchard clearing (Cox et al. 2005) and demonstrate increasing levels of CO_2 in the atmosphere would stimulate carbon storage in roots (and aboveground components) in a scrub oak ecosystem (Stover et al. 2007).

Mapping Spatial Distribution of Roots

Why map tree roots? Reasons for mapping root density or root architecture range from tree health and protection concerns in urban environs to scientific inquiry into belowground carbon (C) sequestration, functional ecology and morphology of root systems. As C cap and trade markets develop in the United States, data related to belowground C storage in forested systems will become more important. In plantation forestry, analysis of root distribution and density shows how trees use resources and respond to management operations. Mapping usually entails creating a set of linear transects arranged in a grid, which intersect at 90° angles. Roots can be tricky targets, from one angle, the cross section may appear as a cylinder giving a clean hyperbola on a radargram, while the perpendicular approach may follow horizontally along the root or miss it altogether. Creating finely scaled grids under field conditions is difficult, since all intersecting points need to be properly interlaced. An a example of a 1 m by 1 m collection grid with 10 cm grid spacing in a loblolly pine plantation (Carolina Sand Hills, Marston, NC) is shown in Figure 4. Root density is displayed as a contour plot, the control is an area which was undisturbed and has areas of high and low root mass (Figure 4.A). The other plot was excavated 30 months earlier and regrowth can be seen from the margins of the plot, while the center remains lightly colonized (Figure 4.B). In this example the control plot has a mean root density of 982 g m^2, while the root in-growth plot has 331 g m^2 30 months after root removal. On sandy soil, roots as small as 0.5 cm may be detected with a 1500 MHz antenna, so the 10 cm grid spacing is inadequate to map individual roots. Development of automated scanning systems would make imaging root architecture more practical. For stand-level analysis in forests a rapid method for creating root mass distribution maps which delineates the distribution and quantity of mass, but does not attempt to detail

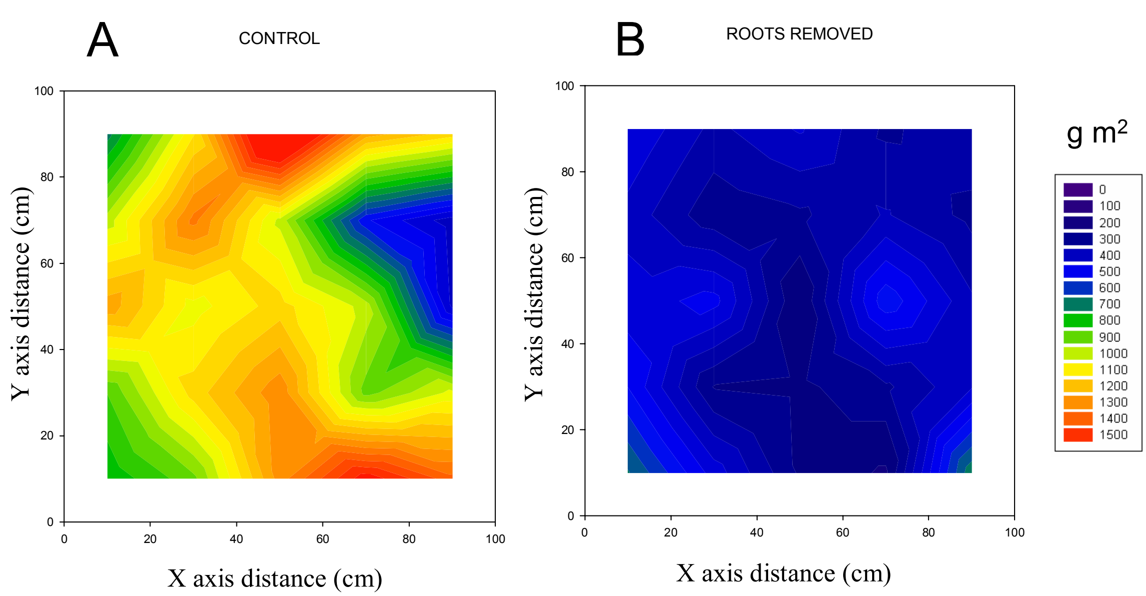

Figure 4: Root density contour maps collected in a loblolly pine plantation the in Marston, NC. The control treatment was undisturbed (A) and the other shows root in-growth after 30 months (B).

the orientation of individual roots is the best option. Examples of root mass distribution maps created with data collected from a replicated, intensive culture forestry experiment planted with loblolly pine in Bainbridge, Georgia (Samuelson et al. 2008) are presented in Figure 5. Five 15 m scans spaced 0.25 m apart were collected on either side of a row of four trees, creating a measurement 2.5 m by 15 m plot equivalent to collecting 1000 soil cores. Data were collected in one polarity to save time (transects vs. grids). Figure 5.A shows raw spatial data where each filled circle is a "virtual" soil core and Figure 5.B is a contour map created with kriged data.

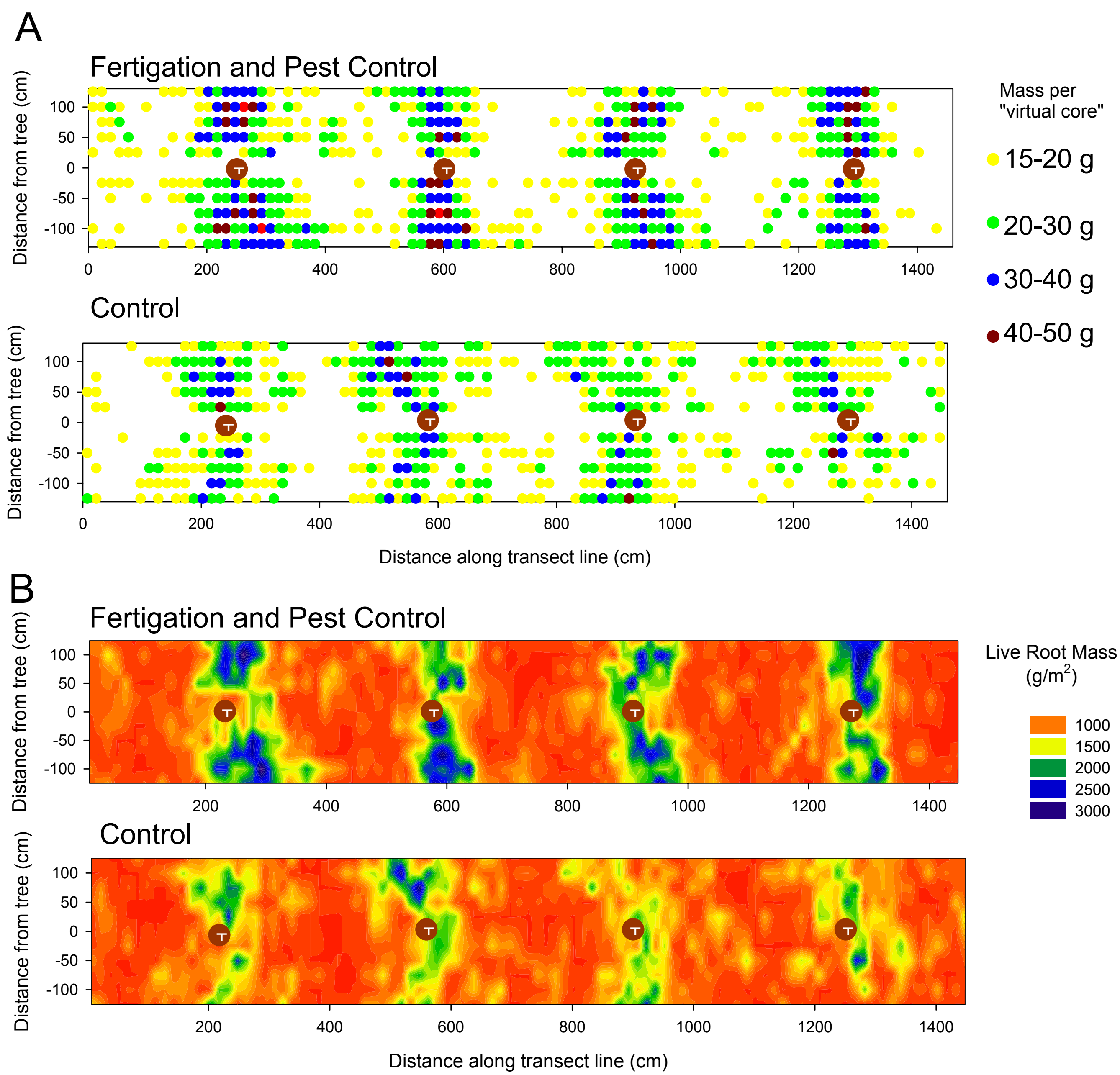

Figure 5: Root distribution data represented in its raw form as a virtual cores (A) and contour maps generated using kriging methods to spatial interpolate areas between transects (B).

Both illustrations show the location of trees within a study area and the lateral root mass, concentrated near the trees and diminishing as the distance from the tree increases. This method only requires transect spacing of 25 cm, allowing a row of 4 or 5 trees to be sampled in approximately 20 minutes. The virtual core map seems somewhat easier to interpret patterns than the contour. An artifact of this design may be that roots crossed at 90 degrees resolve more distinctly than those following the path of the scan longitudinally. An alternative would be scanning concentric circles around trees. Roots radiating out from the tree would be contacted at similar angles, allowing the creation of polar plots with trees at the plot center.

Assessing Vertical Roots with Borehole Radar

Surface based antennas can provide excellent resolution of lateral roots, but they are unable to detect tap roots or root masses directly beneath a tree. In southern pines, tap root morphology varies from large cylindrical carrot-like roots which extend several meters in the ground to the more common root ball or root cluster of several large branching vertical roots. These roots represent 40-90% of the total root biomass in pine plantations. Commonly available bistatic antennas are unable to delineate the size and shape of these structures. Borehole radar allows investigation of reflectors using access holes drilled in the ground, allowing a unique perspective of vertically oriented targets unaffected by signal attenuation associated with depth. In reflection mode, the transmitter and receiver are lowered into a borehole. The resulting radargram is very similar to surface antennas, except the antenna travels into the ground along the y axis and the distance to the reflector is represented on the x axis. In transmission mode, the transmitter and receiver are separated and located in opposite boreholes or placed on the soil surface. By varying the depth or surface locations a variety of ray paths can be created. The simplest variable to measure and model is travel time between the antennas, though accuracy may be increased by monitoring secondary, tertiary arrivals and their corresponding amplitudes.

A collaborative effort by the USDA Forest Service, Southern Research Station, Radarteam AB and the Swedish University of Agricultural Sciences (SLU), was undertaken in August 2003 to assess the potential of high-frequency borehole radar to detect vertical, near-surface reflectors (0-2 m) resulting from tree roots (Butnor et al. 2006). The equipment used was a 1000 MHz borehole transducer (Tubewave-1000, Radarteam AB, Boden, Sweden www.radarteam.se), a 900 MHz GSSI antenna along with a GSSI Sir-20 ground-penetrating radar unit (Geophysical Survey Systems Inc., Salem, NH, USA). Initial trials with the TW-1000 in reflection mode did not seem to yield useful information on these large roots, so the two antennas were configured in transmission mode. Five Scots pine (*Pinus sylvestris*) trees 50 to 193 years old with diameters at breast height ranging from 12 to 37 cm, were selected for study at the Vindeln Experimental Forest northern Sweden. The deep sandy soils are characterized by low silt and clay contents. The TW-1000 was the transmitter (Tx) and the 900 MHz antenna was configured with a splitter box to be the receiver. The design involved digging a borehole on either side of a tree and a series of crosshole rays were created by raising and lowering the antennas at intervals of 5 cm (Figure 6.A). Then the antennas were moved to opposite holes and the process was repeated creating 1152 unique travel paths per tree. Borehole to surface measures were collected in a similar fashion, though the Rx was moved across the soil surface (10 cm interval) and the Tx was manipulated below ground (5 cm interval), generating 2400 travel paths per tree (Figure 6.B). The traveltime data sets were combined to create a master set composed of 3552 manually collected observations per tree.

Tomographic reconstruction of the root systems was accomplished using Reflex software published by Sandmeier Scientific Software (www.sandmeier-geo.de) (Figure 7). Three of the five tomograms compared favorably with root distribution maps made using destructively sampled data. However, the other two trees were misinterpreted, one was sharply underestimated, the other overestimated. Crosshole tomography provided excellent information on the depth of tree roots, but was less useful for imaging near surface features. Borehole to surface measures provided the best information on the near surface, where the bulk of roots are found (0-0.3 m). The technique has promise in forest research, but the development of new high frequency borehole antennas, and modeling software that allows concurrent processing of travel time and amplitude data is necessary to further this research.

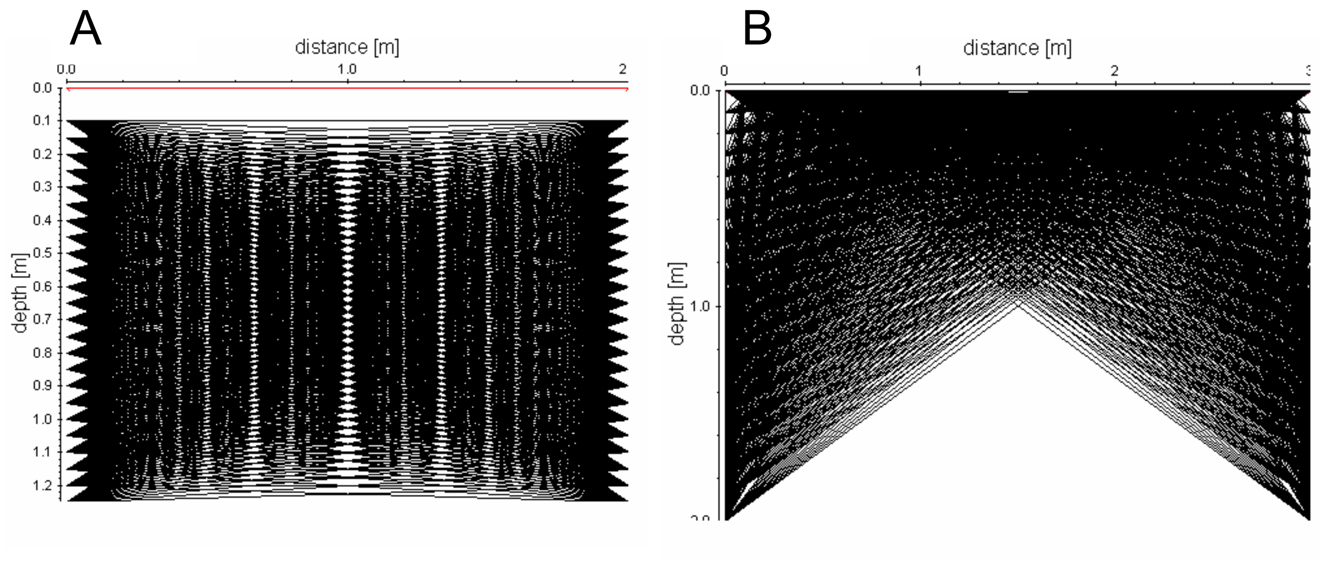

Figure 6: Diagram showing ray paths of crosshole (A) and borehole to surface (B) configurations.

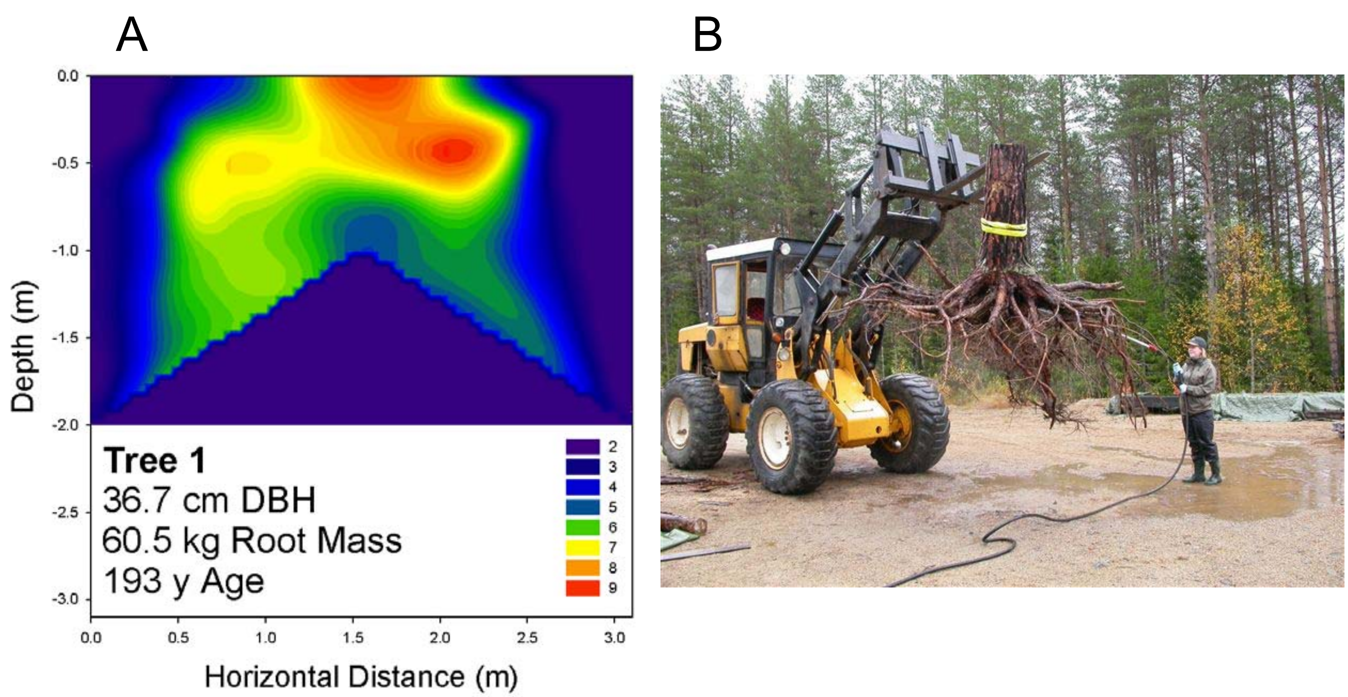

Figure 7: Tomographic reconstruction of the root system of a 193 year old Scotts pine tree (A) compared with a photograph of the excavated tree (B).

Detecting Decay in Living Trees

Decay detection in living trees is useful for assessing tree health in both urban and forest systems, surveying habitat for wildlife as well as understanding the biology of climax communities in ancient forests. While a departure from the usual subterranean targets, defects in living trees can be detected with GPR as long as there is some change in electrical conductivity between healthy and compromised wood (Miller and Doolittle, 1990). Truly nondestructive means of determining the structural integrity of trees has been somewhat elusive until recently. Prior trials indicated that hardwood species and dried wood products were suitable for GPR analysis, but no reports of using the method on conifers existed in the literature until Butnor et al. (2009) described results from three conifer species in the Pacific Northwest. The goal was to learn if GPR could be used to estimate amount of decay in old trees (up to 450 yr) to quantify standing C reserves and parameterize C cycling models. This information would be used to understand how much carbon is stored in these forests, learn how dynamic the fluxes are and see if they really are net sinks of atmospheric CO_2.

Research was conducted at and near the Wind River Canopy Crane Research Facility located outside of Carson, WA. Expert tree climbers scaled large Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) and made circumferential scans with a 900 MHz antenna equipped with a small survey wheel (Figure 8.A). The crane gondola was used to ferry equipment and supplies to the climbers, while an operator monitored the data collection (Figure 8.B), keeping the Sir 3000 radar unit secure 200 feet above the ground. The radargrams were periodically verified with and increment boring.

Figure 8: Tree climbers made circumference scans of large trees with a 900 MHz antenna outfitted with a spring-loaded survey wheel (A), while the GPR operator monitored the data collection from the comfort of a canopy access crane (B).

The results from these conifers were complex and intriguing. On each radargram, there was strong reflection at the antenna/bark interface were the electromagnetic wave first coupled with the tree and secondary and tertiary reflections associated with internal features. Air-filled hollows were readily detected, a strong reflection was detected at the surface (green line) and very strong second and third reflections closely corresponded with the hollow center of the tree (red line) in Figures 9.A&B.

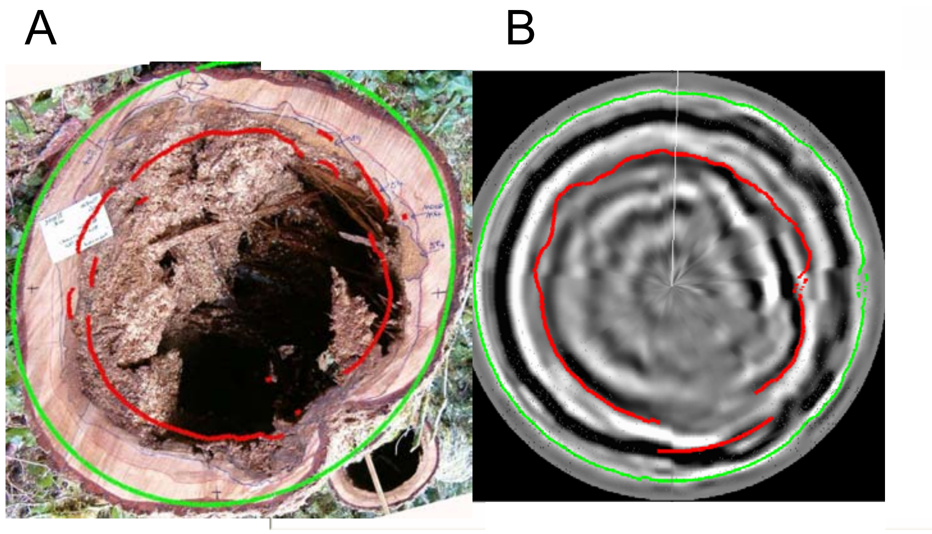

Figure 9: Side by side comparison of a hollow western hemlock (*Tsuga heterophylla*) (A) and a radargram collected from the same tree (B). The green line represents the outer circumference of the tree, while the red line represents the margins of decay.

Though not as strong as reflections associated with hollowness, healthy conifers typically displayed a reflection at the interface of sapwood (newer wood near the surface) and heartwood in the center of the tree. The conifer species studied had very wet sapwood and relatively dry, non-conducting heartwood, setting the stage for a detection of a physiologic feature that is not a defect. This phenomenon made it difficult to identify trees with moderate to severe decay limiting the usefulness of the method in conifers. However, using this feature, it was possible to detect if a section of the trunk or branch had died. Once the sapwood becomes nonfunctional it dries out coming into equilibrium with the heartwood, a radargram would possess a reflection at the bark surface, but would have no internal reflections. Fortunately most hardwood tree species do not have significant moisture gradients between the heartwood and sapwood and are not expected to have "benign" internal reflections. A rapid survey of 15 sugar maple trees (*Acer saccharum*) showed that decay and hollowness were detectable, but the sapwood/heartwood interface was not (Butnor et al. 2009).

Conclusions

On amenable sites, GPR can be an excellent tool to measure lateral root mass and root distribution. The ability to sample large areas rapidly, allows small treatment differences to be resolved non-destructively. While the basic methodology has been established, there is a major need to better understand how soil properties, soil moisture and root density affect reflectivity in order to develop site specific calibrations which do not require destructive verification. If these issues are successfully addressed, GPR will be useful for measuring belowground C accretion in aggrading forests using repeated measures over time. To fully realize the potential of near-surface borehole radar to image tree tap roots or root clusters there needs to be several technical advances in equipment and software: 1) Borehole transmitters need to be refined so that they are able to propagate directional, high frequencies waves from a relatively small point source to enhance resolution, 2) Automated scanning systems are needed to generate and process thousands of single EM pulses while varying ray path trajectories, 3) Improved analysis software which can simultaneously process the travel time of secondary and tertiary arrival times with their amplitude. Detection of defects in conifers may have some limitations which cannot be fully overcome, but the potential in hardwood tree species is very promising.

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