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12.9 USING GROUND-PENETRATING RADAR TO ESTIMATE TREE ROOT MASS: COMPARING RESULTS FROM TWO FLORIDA SURVEYS

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12.9.1 INTRODUCTION

Roots make up 5 to 45 percent of tree biomass in upland forests worldwide (Cairns et al., 1997), but estimates from urban settings are limited. Roots of field-grown trees are difficult to assess and delineate without laborious and destructive excavations. For this reason, relative to studies on above-ground biomass, root systems have rarely been studied; often more is assumed about their nature than is really known. Foresters and ecologists are interested to learn how different management techniques (site preparation, cultural practices, and harvesting methods) and natural disturbances affect tree productivity and carbon sequestration. Tree roots play a dynamic role in sustainable forest productivity and serve as a conduit for atmospheric carbon to enter the rhizosphere. After a harvest,

fire, or other disturbance, the majority of the recalcitrant carbon is retained in roots for a time and slowly released by oxidative processes, and a small fraction becomes a stable constituent of the soil. Research interests aside, trees play an important role in urban environments, providing shade, reducing temperatures, and providing aesthetics. Municipalities, arborists, and property owners are interested in mapping roots to establish protection zones during construction (Jim, 2003), assessing tree health and taking proactive steps to help urban trees thrive.

Ground-penetrating radar (GPR) can be used to detect and monitor roots if there is sufficient electromagnetic contrast with the surrounding soil matrix. This methodology is commonly used in archeology and civil engineering for nondestructive testing of concrete as well as road and bridge surfaces. GPR is ideal for these applications because the electrical properties of concrete and rebar (steel) are very different. Under amenable conditions (i.e., electrically resistive, sandy soils are ideal), tree roots are detectable and can be quantified. GPR has been used to resolve roots and buried organic debris, assess root size, map root distribution, and estimate root biomass (Butnor et al., 2001, 2003; Stover et al., 2007). Being noninvasive and nondestructive, GPR allows repeated measurements that facilitate the study of root system development. Roots as small as 0.5 cm in diameter have been detected at depths of less than 50 cm with a 1500 MHz antenna in well drained, coarse-textured soils (Butnor et al., 2003). There has been considerable interest in mapping tree root systems to understand root architecture and soil volume utilization (Cermak et al., 2000; Hruska et al., 1999; Stokes et al., 2002). However, without intensively detailed, methodical scanning of small grids, it is not possible to separate roots by size class or depth (Wielopolski et al., 2000). Orientations of roots, geometry of root reflective surfaces, and proximity of other adjacent roots presently confound attempts to delineate root size classes in forest soils. In addition, this methodology cannot determine differences in species within a mixed stand.

We present the results of two case studies conducted in Florida which were aimed at determining tree root biomass with GPR in a pine plantation and a native scrub-oak shrubland ecosystem to highlight the technical considerations, successes, and examples of where clutter confounded meaningful interpretation.

12.9.2 MATERIALS AND METHODS

The fundamentals of GPR are described in Chapter 7 and practical considerations are emphasized in Case History 12.7. In the studies presented here, tree roots were the target of interest, and GPR was applied to detect electrical discontinuities between roots and the surrounding soil. A variety of frequencies (400 to 1500 MHz) have been used to locate coarse roots; 400 MHz antenna can resolve discontinuities to a depth of 2 m or more, however the smallest detectable root is 4 to 5 cm in diameter (Butnor et al., 2001; Hruska et al., 1999); 900 MHz antennas consistently resolve roots >2 to 3 cm; and under optimal conditions, while 1500 MHz center frequencies can detect roots as small as 0.5 cm, penetration is usually limited to ~50 cm (Butnor et al., 2001). Using the aforementioned frequencies, it is not possible to resolve fine roots that are commonly classified as <0.2 cm diameter. Because most tree roots are located at relatively shallow soil depths <0.5 m (Hruska et al., 1999; Jim, 2003) the high-frequency antenna is a good choice to maximize root detection. A trade-off exists where low-frequency antennas penetrate deeper in the soil, but provide lower data resolution, and higher frequencies provide greater resolution with decreased depth penetration. Ground-coupled antennas need to be in close contact with the soil surface; this is especially important with higher-frequency antennas (e.g., 1500 MHz) where air-gaps greater than a couple of centimeters will cause a deleterious loss in resolution. This presents problems in forested terrains where the presence of herbaceous vegetation, fallen trees limbs, and irregular soil surfaces impedes the travel of an antenna, requiring additional site preparation before data acquisition (Butnor et al., 2001).

The goals of this study were to test the feasibility of using GPR to quantify root mass and root distribution at two sites that share similar soils but markedly different vegetation types. One site was a scrub-oak ecosystem located on a subtropical barrier island in the northern part of the Kennedy



FIGURE 12.50 SIR 2000 ground-penetrating radar (GPR) system connected to a 1500 MHz antenna mounted on a skateboard deck equipped with a survey wheel encoder.

Space Center (KSC), Merritt Island, Brevard County, Florida. Several oak species (*Quercus* sp.) dominate the system because of a prescribed fire ten years earlier, and they represent most of the aboveground biomass (Stover et al., 2007). The other was a 5-year-old loblolly pine (*Pinus taeda*) plantation in northern Florida near Sanderson. Both sites exhibited sandy soils in the near surface, the KSC being excessively well drained and the Sanderson site being moderately well drained.

In 2005, a SIR-2000 GPR system, manufactured by Geophysical Survey Systems, Inc. (GSSI; Salem, NH) was fitted with a custom-designed sampling rig that steadied the high-frequency antenna (model 5100, 1500 MHz antenna) and incorporated a survey wheel to meter electromagnetic pulses (Figure 12.50) to make measures at Sanderson. Measures at KSC were made with a SIR-3000, using a model 5100, 1500 MHz antenna fitted with a much smaller survey wheel than depicted in Figure 12.50. Before spatial distribution can be assessed, it is necessary to sample test transects to be able to correlate radar data with destructively sampled soil cores. With both systems, measures were made by slowly drawing the survey rig along a measurement transect (200 scans per m) while ensuring that the antenna remained in contact with the soil surface. The locations of the verification cores were electronically marked on the data file during collection. The resulting scan was a two-dimensional profile (transect length by depth) where electromagnetic anomalies are located.

Postcollection processing was accomplished using RADAN 6.5 software (GSSI) with the following steps (Butnor et al., 2001; Cox et al., 2005; Stover et al., 2007):

1. *Crop*. Each radargram was cropped to the diameter of a 15 cm area soil core.
2. *Background Removal*. Root structures appear as hyperbolic reflectors, and parallel bands represent plane reflectors such as ground surface and soil layers. Parallel bands were removed with a horizontal finite impulse response filter (FIR) filtration method called background removal.
3. *Migration*. Kirchoff migration was applied to correct the position of objects and collapse hyperbolic diffractions based on signal geometry (Daniels, 2004).
4. *Hilbert Transformation*. Hilbert transformation was applied to express the relationship between magnitude and the phase of the signal, allowing the phase of the signal to be reconstructed from its amplitude, allowing subtle discontinuities to be detected (Oppenheim and Schaffer, 1975).

Root mass was quantified by converting radargrams to bitmap images and using Sigma Scan Pro Image Analysis software (Systat) with the following steps (Butnor et al., 2001; Cox et al., 2005; Stover et al., 2007):

1. *Gray Scale.* Each image was converted to an 8-bit grayscale image
2. *Intensity Threshold.* Root mass was quantified by using pixel intensity (proxy for amplitude derived from Hilbert transform). Intensity is a relative measure ranging from 0 (black) to 255 (white). An intensity threshold range of 60 to 255 pixels, which was able to delineate roots as small as 0.5 cm was applied.
3. *Statistical Analysis.* Linear regression was performed to quantify the relationship between total root biomass from the soil cores and the GPR-derived index (pixels within the threshold range).

Once transects were scanned, extreme care was used to extract the cores in the correct location to correspond to the radargram. The cores were screened, and the biomass was separated into live roots and dead organic debris, dried and weighed.

12.9.3 RESULTS AND DISCUSSION

Pine roots are usually found in clusters where it can be difficult to separate individual roots, especially when their orientation is unknown and may be confused with plane reflectors (Figure 12.51A). Background removal removes most of the clutter associated with surface reflections, soil horizons, and moisture gradients (Figure 12.51B). Kirchoff migration serves to collapse the hyperbolas closer to their representative size and location (Figure 12.51C). The geometry of reflected signals may be very useful for extracting information about the reflective surface of the root, including diameter if

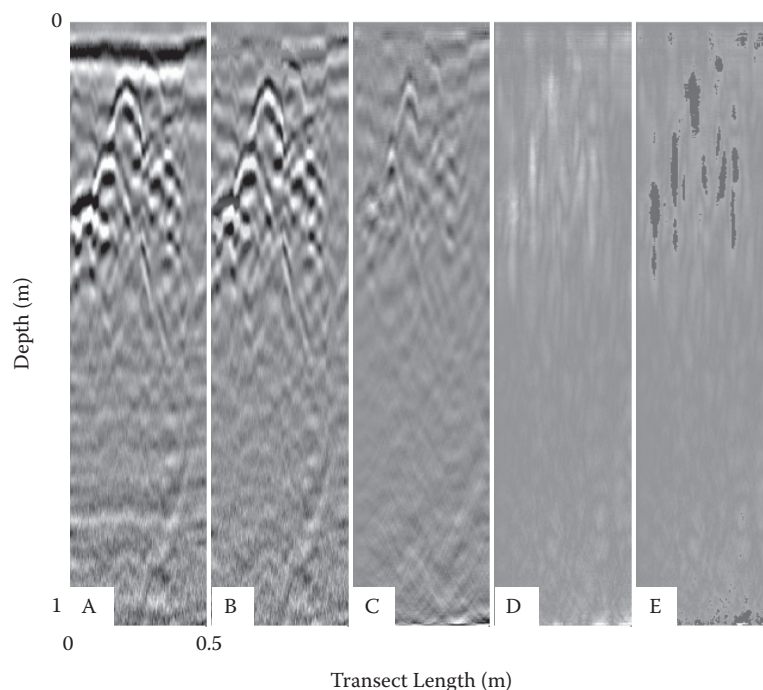


FIGURE 12.51 Example of a radargram collected at the Sanderson loblolly pine plantation (A) and processed using background removal (B), Kirchoff migration (C), Hilbert transformation (D) with RADAN software. Amplitude intensity was visualized and quantified with Sigma Scan Pro software.

the root orientation is known (Barton and Montagu, 2004). When a cylindrical root is scanned at a 90° angle it is possible to calculate diameter, but in the field roots present themselves in a variety of shapes and orientations. The Hilbert transform is a useful means to illustrate and quantify the reflection amplitude apart from reflector geometry (Figure 12.51D).

At Sanderson, the correlation between live root mass collected with cores and GPR data was less than desirable ($r = 0.51$). The roots were almost exclusively pine, and the dead organic debris was composed of decaying palmetto roots, residual slash, and dead roots. Debris from the previous pine plantation had been plowed into the soil and had not decomposed completely after 5 years. From forty cores, more than half of the biomass was classified as dead organic debris. GPR was not able separate out live and dead material. A compelling illustration of this problem is shown in Figure 12.52. Two soil core locations were scanned in a region of high reflectivity, despite having almost the same amount of biomass and a similar number of pixels in the analysis threshold (GPR index), core A contained 17 percent live root mass and core B contained 73 percent (Figure 12.52). When live and dead root mass were combined, a strong positive relationship was observed with the GPR data ($r = 0.80$). The high proportion of buried organic debris at Sanderson limits the utility of the technique to detect live roots. At KSC the correlation between GPR and live roots was much better ($r = 0.84$). The Sanderson findings highlight the fact that presently, it is not possible to separate live and dead buried biomass. At KSC, dead biomass represented only 13 percent of the total buried biomass which clearly enhanced the accuracy of root biomass using GPR. When the live and dead root mass were combined at KSC and compared to GPR-derived predictions the correlation was excellent ($r = 0.82$). Previous forest studies minimized the importance of understanding the reflectivity of organic debris; it was thought that dead roots rapidly took on dielectric properties of the surrounding soil (Butnor et al., 2001). The issue of organic debris never came up at a site in Bainbridge, Georgia, which had been used and plowed for decades in traditional agricultural systems, exposing any residual debris to oxidation (Butnor et al., 2001). GPR has subsequently been used to detect dead root fragments in peach orchards (*Prunus persica*) to specifically identify and quantify organic debris that harbors harmful fungi (*Armillaria* sp.) that could be detrimental to

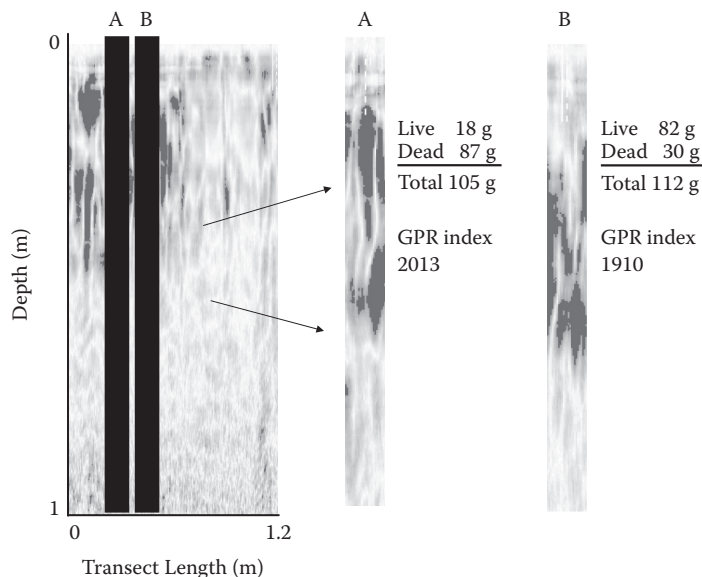


FIGURE 12.52 Two locations (A and B) were scanned in an area of high reflectivity at Sanderson, Florida, and destructively sampled with a 15 cm diameter soil core. Core A had low root density and a large mass of dead material, the opposite ratio was observed in core B. Ground-penetrating radar (GPR) could not discriminate between roots and dead organic material.

new plantings (Cox et al., 2005). At Sanderson, the problem of interfering organic debris resulting from site preparation was likely exacerbated by the preponderance of saw palmetto which is decay resistant compared to other forest slash.

When monitoring root development and accretion over time, it is important for small changes over time to be detected. The sandy soils at KSC drain rapidly, producing little change in radar-gram analysis, except in the case of saturated field moisture conditions. GPR data interpretation and predictive root biomass equations are not limited to just conditions present at the time of core collection on very coarse soils, but this should be verified on a specific sites. The Sanderson site was remeasured in 2003, 2004, and 2005, and a very interesting phenomenon was observed. The primary research goal was to determine the effect of genetic improvement, tree spacing, and fertilizer application on tree productivity (above- and belowground). Between 2004 and 2005, there was an apparent and unexpected drop in belowground biomass as estimated with GPR. Approximately 10 percent of the survey was remeasured with litter in place and again with litter removed to quantify the effects of litter on root resolution. Scanning through the dry, air-filled leaf litter served to defocus the 1500 MHz antenna, it created an offset between the antenna and the soil surface which was largely air filled and degraded the ability to detect roots (Figure 12.53). If litter depth was uniform across all treatments, the defocusing effect could have been mitigated. However, because the experimental manipulations of tree genetics and fertilizer application resulted in differential litter depth (5 cm versus nearly 20 cm of dry newly deposited pine straw), the differences in root mass could not be assessed.

The Sanderson site was expected to be ideal for radar studies, but several unforeseen complications negated the quantitative value of the GPR-derived estimates of root mass. The study was important to highlight potential sources of data clutter in forests. The soil core calibrations at KSC became very useful for analyzing the effect of elevated atmospheric CO₂ concentrations on belowground biomass accumulation in the scrub system. Elevated atmospheric CO₂ concentration has been experimentally increased at the KSC site using open-top chambers (OTC) since 1996 (Day et al., 2006). CO₂ enters the chambers through air blowers and circulates throughout the chamber

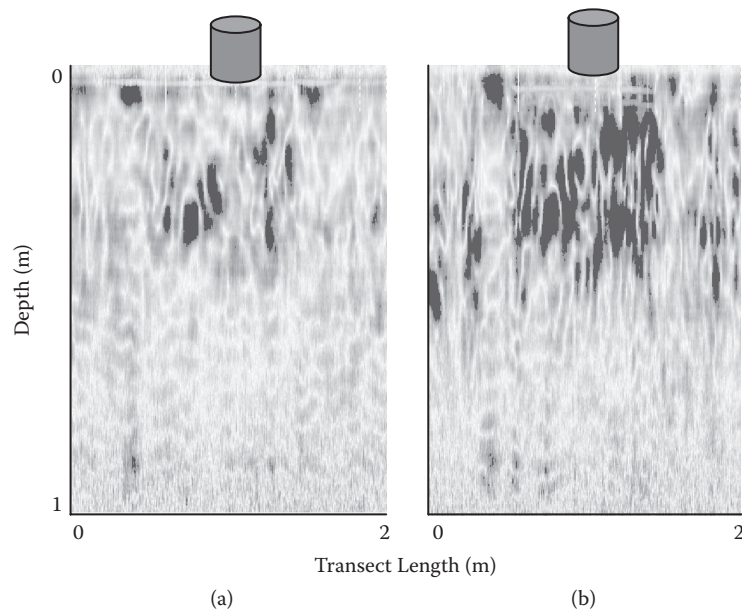


FIGURE 12.53 Example of antenna defocusing near the trunk of a loblolly pine caused by thick, dry pine straw, 20 cm deep on pine root discrimination (A) compared with enhanced discrimination when the pine straw is raked away (B).

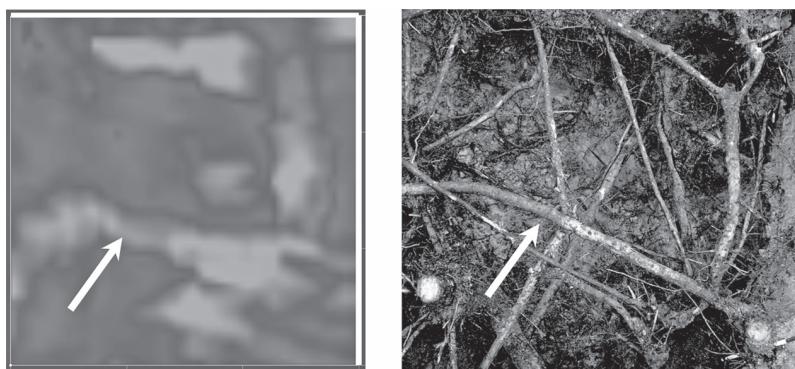


FIGURE 12.54 Visual correlation between ground-penetrating radar (GPR) data and coarse root excavation pits. Large roots spanning the entire length of the validation pit were most likely to be observed in the GPR data. Each GPR data image (left) represents a “slice” of the three-dimensional profile at the appropriately correlated depth with a viewing depth of 15 to 20 cm.

and exits at the open chamber top. During the ninth year of the CO₂ study, sixteen OTCs (eight elevated and eight ambient CO₂) were surveyed with a 1500 MHz antenna. The soil core calibrations at KSC (described earlier) were used to convert GPR index values from the OTC scans to mass of belowground biomass per unit area g m². Significantly greater coarse root biomass was present in plots treated with elevated compared to ambient CO₂ ($p = 0.049$) (Stover et al., 2007).

The scrub ecosystem is dominated by large belowground structures such as stems, lignotubers, and burls that serve as carbohydrate reserves that are critical during regrowth following a disturbance in this fire-controlled system. Approximately 86 percent of total biomass was allocated belowground in the scrub system, suggesting greater carbon sequestration in larger belowground structures under elevated CO₂ conditions. Similar to Sanderson, the KSC site was unable to adequately distinguish and separate live and dead root mass within the data.

The spatial distribution of root systems is important when examining their role in resource acquisition, storage, and structural support. Multiple plots (0.25 m²) were intensively scanned (2 cm scan width) in an intersection grid pattern with a 1500 MHz antenna and later excavated at the KSC scrub-oak site. The data were processed with RADAN software which permits intersections of the X-Y scans to be interpreted as three-dimensional volumetric data. Resulting three-dimensional models were compared to photographs from the excavation for verification of spatial orientation and distribution of roots (Figure 12.54). Smaller objects that were parallel to one another or that were “shadowed” by neighboring root were typically masked or grouped together as a single object. Larger roots having sharp or unique angles were easiest to identify in the data-image comparisons (Figure 12.54). Initial determination of root architecture was limited by lack of adequate sample resolution (i.e., less than 1 cm width) and accurate methods to quantify the object size in the three-dimensional models. However, these results indicate with further refinement that spatial distribution can be quantified under the sandy soil conditions, thus elucidating environmental changes in root deployment, carbon storage and sequestration, and resource foraging in the scrub ecosystem.

12.9.4 SUMMARY

Tree root mass can be accurately estimated with GPR when there is good electromagnetic contrast between soil and roots. Calibrating and scaling GPR data to estimate belowground biomass using destructive sampling with 6 in diameter soil cores can be successful, but sites differ in the type of targets that resolved. Detailed site surveys should be conducted to determine if nontarget reflectors (slash, rocks, buried organic matter, rodent tunnels, and surface discontinuities) will degrade the potential to quantify live tree roots. Natural ecosystems and managed forests present obstacles that

may interfere with acceptable antenna and ground coupling; scanning over leaf litter, especially in treatments that can affect litter depth should be avoided. Overall, the application of ground radar technology to root and forest ecology studies provides unique, nondestructive means to sample root biomass and spatial distribution at least in some ecosystems.

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