

Use of ground-penetrating radar to study tree roots in the southeastern United States

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Summary The objectives of our study were to assess the feasibility of using ground-penetrating radar (GPR) to study roots over a broad range of soil conditions in the southeastern United States. Study sites were located in the Southern Piedmont, Carolina Sandhills and Atlantic Coast Flatwoods. At each site, we tested for selection of the appropriate antenna (400 MHz versus 1.5 GHz), determined the ability of GPR to resolve roots and buried organic debris, assessed root size, estimated root biomass, and gauged the practicality of using GPR. Resolution of roots was best in sandy, excessively drained soils, whereas soils with high soil water and clay contents seriously degraded resolution and observation depth. In the Carolina Sandhills, 16 × 1-m plots were scanned with the 1.5 GHz antenna using overlapping grids. Plots were subsequently excavated, larger roots (> 0.5 cm diameter) sketched on graph paper before removal, and all roots oven-dried, classified by size and weighed. Roots as small as 0.5 cm in diameter were detected with GPR. We were able to size roots (0.5 to 6.5 cm in diameter) that were oriented perpendicular to the radar sweep ($r^2 = 0.81$, $P = 0.0004$). Use of image analysis software to relate the magnitude of radar parabolas to actual root biomass resulted in significant correlations ($r^2 = 0.55$, $P = 0.0274$). Orientation and geometry of the reflective surface seemed to have a greater influence on parabola dimensions than did root size. We conclude that the utility of current GPR technology for estimating root biomass is site-specific, and that GPR is ineffective in soils with high clay or water content and at sites with rough terrain (most forests). Under particular soil and site conditions, GPR appears to be useful for augmenting traditional biomass sampling.

Keywords: GPR, map roots, noninvasive, radar antenna, radar profile, reflector, root biomass, root biomass assessment, root biomass sampling, root detection.

Introduction

Premise

Ground-penetrating radar (GPR) has proved to be a useful geophysical tool for the detection and characterization of features buried within the shallow subsurface (0.25 to 1.5 m

depth). This rapid and noninvasive technique has been used to locate buried artifacts (Conyers and Goodman 1997), drain tiles (Chow and Rees 1989), anti-personnel mines (Bruschini et al. 1998, Daniels 1998), and pipes and cables (Ulriksen 1982, Daniels 1996).

Although roots have commonly been observed in soil profiles (Bevan 1984, Truman et al. 1988, Farrish et al. 1990), they have often been considered an unwanted source of noise that complicates radar interpretation (Doolittle and Miller 1991, Barker and Doolittle 1992). Recently, GPR was used to map the coarse (> 3 cm diameter) root system of 50-year-old sessile oak (*Quercus petraea* Mattl.) trees (Hruska et al. 1999). Typically, coarse tree roots have been measured by destructive excavation of the root system, an extremely labor-intensive endeavor. Because of its noninvasiveness, suitable depth range and resolution, Hruska et al. (1999) considered GPR to be an appropriate tool for the measurement of coarse root systems.

Ground-penetrating radar principles

Ground-penetrating radar is an impulse radar system designed for shallow, subsurface investigations (Morey 1974, Ulriksen 1982, Daniels 1996). The system transmits short pulses of electromagnetic energy into the ground from an antenna. Each pulse consists of a spectrum of frequencies distributed around the central frequency of the transmitting antenna. Whenever a pulse contacts an interface separating layers of differing electromagnetic properties, a portion of the energy is reflected back to a receiving antenna. The receiving unit amplifies and samples the reflected energy and converts it into a similarly shaped waveform in a lower frequency range. The processed reflected waveforms are displayed on a video screen or stored on a disk for later playback, processing or printing.

The system radiates energy in an elliptical cone of divergence and scans a footprint area beneath the antenna (Annan and Cosway 1994, Conyers and Goodman 1997). Because the antenna's radiation pattern forms an elliptical cone of divergence, small features are sensed before and after the antenna is moved directly over them. Because of the initially decreasing and then increasing travel time to a subsurface reflector, small subsurface features, such as roots, often produce hyperbolic patterns (Barker and Doolittle 1992). These hyperbolas are

readily observable on radar profiles and can aid interpretation. The apex of a hyperbola will occur when the antenna is directly over a root. Other linear features, such as buried pipes and drainage tiles, produce visible hyperbolas only when crossed at a traverse line angle greater than 45° (Chow and Rees 1989, Roberts and Daniels 1993). However, when crossed at angles of less than 45°, these features produce images that are elongated, obscured and more difficult to distinguish. These observations also apply to roots.

The footprint area "illuminated" by the radar is considered an elliptical cone and can be approximated by the formula (Conyers and Goodman 1997):

$$A = \lambda/4 + D/\sqrt{e+1}, \quad (1)$$

where A is radius of the footprint area at depth D , λ is the central frequency wavelength of the antenna, and e is the dielectric permittivity of the scanned materials. According to Equation 1, the footprint area varies directly with the wavelength of the antenna (Conyers and Goodman 1997). Higher frequency antennae have shorter wavelengths (time to complete signal waveform) and will provide a smaller or more focused footprint area than lower frequency antennae. Also, the higher the dielectric permittivity of the profiled material, the smaller the illuminated footprint area (Conyers and Goodman 1997). Therefore, wetter soil conditions should result in a more contracted cone of radiation.

Because of the antenna's comparatively broad beam, objects that are located at some distance from either side of the antenna track can be sensed (Conyers and Goodman 1997). Typically, these objects will have lower amplitudes than similar objects that occur directly beneath the path of the antenna. In addition, because of longer pulse travel times to these offset reflectors, they will appear in radar profiles to lie deeper than their actual depths.

Resolution refers to the ability to discriminate between two closely spaced features, as well as the minimum size detectable. Resolution increases with decreasing wavelength (Daniels 1996). Therefore, high-frequency antennae provide higher resolution than low-frequency antennae.

The objectives of this study were to expand on the work of Hruska et al. (1999) and to assess the feasibility of using GPR for field research in the southeastern United States. We examined the ability of GPR to delineate roots under a range of soil conditions and to estimate root diameter, and assessed the relative utility of two antennae. We also tested the ability of GPR to detect nutritional treatment differences in root biomass in a replicated field experiment on a sandy site.

Materials and methods

Radar equipment

We used the Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc. (North Salem, NH). The SIR System-2000 consists of a digital control unit (DC-2000) with keypad, VGA video screen, and con-

ductor panel. We used Model 5100 (1.5 GHz) and 5103 (400 MHz) antennae, which have a bow-tie dipole configuration. This system is backpack portable, is powered by a 12-V DC battery and, with an antenna, typically requires two people to operate. Scanning times used in this study ranged from 10 to 40 ns and depended on site conditions. Daniels (1996) discusses radar systems and principals of operation.

The radar profiles were processed through the WINRAD software package (Geophysical Survey Systems, Inc.). Processing was limited to signal stacking, horizontal scaling, color transforms and table customizing. Color transformation and table customization reduced background noise.

The radar unit was calibrated at each study site before use. To determine an approximate depth scale, a metallic calibration disk was buried in the ground at each site, at a depth of 40 to 50 cm. The known depth and two-way pulse travel time to this interface provided a means to estimate the velocity of propagation and to depth-scale the radar imagery. These estimates were later adjusted, if needed, based on measured depths and two-way travel times to roots that had been detected with GPR and excavated.

Ground-penetrating radar discrimination of roots in various soils

Soil properties have the potential to limit GPR penetration. To study a range in soils typical of the southeastern United States, sites were selected in the Atlantic Coast Flatwoods, Georgia and Carolina Sandhills, and Southern Piedmont Major Land Resource Areas (MLRA) (Austin 1965). Selected sites encompassed a variety of textural and drainage classes. At each site, the radar unit was calibrated and test transects were established and scanned with both the 1.5 GHz and 400 MHz antennae. The resulting waveform diagrams were printed and all point reflectors were identified visually. Select putative locations (where point reflectors were observed) were excavated and any roots observed were measured. Areas where no point reflectors were observed were also excavated to determine if undetected roots were present. The velocity of propagation and the effective depth of penetration for each antenna were determined at each site. Logistical considerations of working in recently harvested sites, young forests and end-of-rotation forests were noted.

Atlantic Coast Flatwoods MLRA Atlantic Coast Flatwoods consist primarily of poorly drained to excessively drained soils formed in eolian and marine sediments. Relief is typically less than a few feet, but as much as 20 feet along stream valleys (Austin 1965). Sites with contrasting soils were selected.

(1) *Lakeland soil*. The site was located near Olar, South Carolina, within an eastern cottonwood (*Populus deltoides* Bartr.) plantation. Deep, excessively drained, rapidly permeable Lakeland soil formed in thick beds of eolian or marine sands. The soil is a member of the thermic, coated Typic Quartzipsamments family (Soil Survey Staff 1999). Lakeland soils have limited profile development. All horizons are sand or fine sand with less than 10% silt and clay. The ground surface was relatively free of debris and litter.

(2) *Lynchburg soil*. The study site was located near Moncks Corner, South Carolina. The deep, somewhat poorly drained soil formed in loamy marine sediments. Lynchburg soil is a member of the fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults family (Soil Survey Staff 1999). The soil has higher water and clay content and greater profile development than Lakeland soil. Lynchburg soil has a subsoil with as much as 30% silt and clay. It is somewhat poorly drained with a water table that is seasonally within depths of 60 cm. Content of coarse fragments ranges from 0 to 7%. Two adjacent sites were selected. The first was in an area that had been harvested 4 years ago and replanted with loblolly pine (*Pinus taeda* L.) 2 years ago. The site was bedded and old stumps were still present. The second site was a 25-year-old loblolly pine plantation that had been recently burned of undergrowth.

Georgia and Carolina Sandhills MLRA The study site was at the USDA Forest Service Southeast Tree Research and Educational Site (SETRES) in Scotland County, North Carolina. The site supported a 15-year-old loblolly pine plantation on Wakulla soil. This deep, excessively drained, rapidly permeable soil formed in sandy Coastal Plain sediments on uplands. Wakulla soil is a member of the sandy, siliceous, thermic Psammentic Hapludults family (Soil Survey Staff 1999). In a typical profile, Wakulla soil contains about 85 to 92% sand and 8 to 15% silt and clay. This coarse-textured soil has low organic matter content and low water-holding capacity.

Southern Piedmont MLRA Two sites were selected in the Duke Forest near Durham, North Carolina, in areas of Appling and Georgeville soils. Transects were scanned in 70-year-old loblolly pine plantations. These deep, well-drained, moderately permeable soils formed in residuum on uplands, and have a fine-textured (> 35% clay) subsoil that is composed predominantly of clays with a low cation exchange capacity. Appling soil is a member of the fine, kaolinitic, thermic Typic Kanhapludults family (Soil Survey Staff 1999). Coarse fragments range from 0 to 35% by volume in the surface layer and 0 to 10% in the subsoil. Georgeville soil is a member of the fine, kaolinitic, thermic Typic Kanhapludults family (Soil Survey Staff 1999). Coarse fragments range from 0 to 20% by volume in the surface layer and 0 to 10% in the subsoil.

Use of GPR to estimate root size and biomass and to map tree root systems

Root sizing with GPR An attempt was made to delineate tree root size by GPR under optimal conditions. Roots 3–4 m long that were 5–7 cm thick at one end and tapered to 0.5 cm were excavated and placed in shallow trenches. Root diameters were measured and survey flags were used to mark the position of each diameter along the trench wall. The roots were reburied in the trenches and scanned with the 1.5 GHz antenna. (Compared with the 1.5 GHz antenna, the 400 MHz antenna was found to have a lower capacity to resolve roots across the various soil types and was not used for root sizing or biomass assessment.) Scans were completed perpendicular to the long axis of the trench and the buried root. This allowed scanning of

a radial “slice” that would provide the best opportunity to estimate root diameter. The buried root test was performed at the Georgia and Carolina Sandhills site (Wakulla soil) with a loblolly pine root and at the Atlantic Coast Flatwoods sites (Lakeland soil) with an eastern cottonwood root. The loblolly pine root was buried at two trench depths (15 and 30 cm) at the Georgia and Carolina Sandhills site. At the Atlantic Coast Flatwoods site, the trench was 20 cm deep.

The qualitative imagery on radar profiles was converted to quantitative data by Optimas image analysis software (Version 5.1a, Optimas Corporation, Seattle, WA). The program calculated the relative area (cm²) of high amplitude reflection that met a threshold luminescence. A minimum and maximum threshold of 40 and 130 units, respectively, were used because they were found to provide the best balance between background noise reduction and discrimination of roots from the soil matrix. These settings are subjective and specific to the software package. Some profiles contained reflections from the trench wall that gave false signals. These reflections were separated with image analysis software and subtracted from the total area. Pearson’s correlation coefficient between the high amplitude area and root diameter was calculated (SAS System Version 8.01, SAS Institute, Cary, NC).

Root biomass assessment Root biomass studies commenced at SETRES in the Georgia and Carolina Sandhills MLRA. SETRES is a 2 × 2 factorial experiment of fertilization and irrigation with four replications in a loblolly pine plantation planted in 1985 with 2 × 3-m spacing. Seven years of fertilization have increased coarse root biomass relative to controls (Albaugh et al. 1998). The fertilization component of the existing study was used to test the ability of GPR to assess root biomass because it provided a wide range of rooting densities. Within each replication, two subplots were selected in the control treatment and two in the fertilization treatment for a total of four subplots per replication and a total of 16 for the entire study. In each subplot, 1 × 1-m grids were established to the northwest of a tree (Figure 1). Each grid was composed of four east–west and four south–north radar transects. The transects that comprised the grid were 25 cm apart. Each transect was made by pulling the 1.5 GHz antenna along the grid line illustrated in Figure 1 at a constant speed.

Radar profiles were assessed by two independent means: manual reflector counts that tally the number of high amplitude reflections suspected to be tree roots, and area of high amplitude luminescence analyzed with the Optimas image analysis software. The grids were later methodically harvested to depth classes of 0–20 and 20–40 cm. All roots greater than 0.5 cm in diameter were sketched on graph paper. The roots were sieved, separated into size classes (0–2, 2–5 and > 5 mm diameter) and further subdivided into live and dead roots. All roots were oven dried at 65 °C for 7 days and weighed.

Manual reflector counts and high amplitude area derived from each radar pass were correlated to actual root biomass harvested directly below each pass. Data from all eight radar passes in each grid were composited and correlated to the total root biomass of the entire grid for the 0–20, 0–40 and 20–

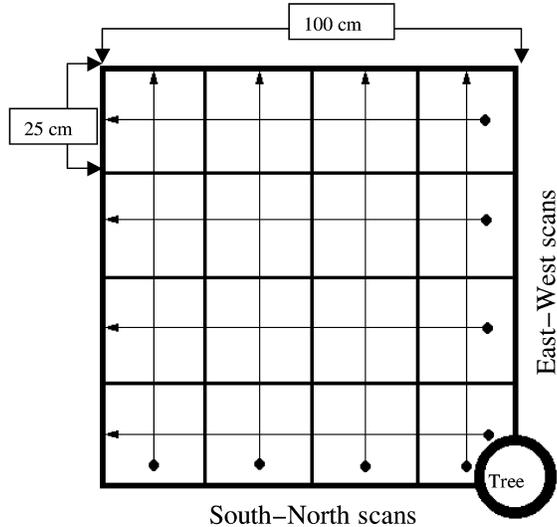


Figure 1. Schematic diagram of root biomass assessment of subplot. Grid is 1×1 m with 25-cm spacing, located northwest of a tree. Four scans were made east to west and four south to north (denoted by arrows) for a total of eight radar passes per subplot.

40 cm depth intervals. Effects of fertilization on root biomass and the two index variables, i.e., reflector tally and high amplitude area, were evaluated by analysis of variance performed with the SAS statistical software package (Proc ANOVA, SAS System Version 8.01, SAS Institute).

Results

Ground-penetrating radar discrimination of roots in various soils

Atlantic Coast Flatwoods—Lakeland soil The 400 MHz antenna provided satisfactory observation depths, but did not satisfactorily detect and resolve roots from 2-year-old cottonwood trees (data not shown). The radar profile provided inadequate data for locating roots along the transect. The 1.5 GHz antenna gave better resolution of subsurface features and satisfactorily detected tree roots within the upper 45 cm of the soil profile. The estimated velocity of signal propagation was 0.1072 m ns^{-1} . Interpretations were verified at three observation points (Figure 2, points A–C). The difference between interpreted and measured depths to these reflectors ranged from 0.7 to 2.0 cm. The radar identified and satisfactorily depth-scaled a 0.6-cm-diameter root at 11 cm (Figure 2, point A) and a 1.7-cm-diameter root at 14 cm (Figure 2, point B). However, three closely spaced roots with diameters of 1.5, 0.7 and 0.7 cm produced a strong subsurface reflection that was misinterpreted as a single root at a depth of 27 cm (Figure 2, point C). In Figure 2, point D, an exposed root produced reverberated signals.

Atlantic Coast Flatwoods—Lynchburg soil The GPR traverses were difficult to conduct in the 4-year-old plantation because of the presence of herbaceous vegetation, fallen tree

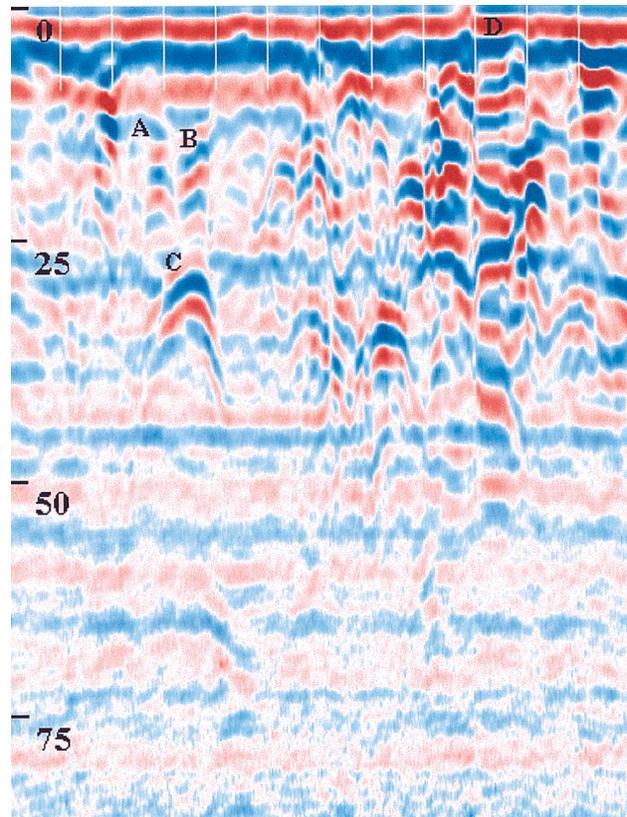


Figure 2. Representative radar profile obtained with the 1.5 GHz antenna from an area of Lakeland soil. Vertical scale is depth (cm). The profile was excavated and the sources of the radar reflections were revealed: (A) 0.6-cm-diameter cottonwood root at 11-cm depth; (B) 1.7-cm-diameter cottonwood root at 14-cm depth; (C) three closely spaced cottonwood roots, 1.5, 0.7 and 0.7 cm in diameter, at 27-cm depth; and (D) exposed surface root.

limbs and irregular soil surfaces. Each traverse line required clearing of some debris before the radar survey began. Even then it was difficult to maintain ground contact because of remaining debris and uneven ground surface of the raised beds. Maintenance of ground contact and uniform speeds of antenna advance are critical to obtain quality measurements.

The performance of GPR at both sites in the Atlantic Coast Flatwoods was poor; images were ambiguous and roots were difficult to distinguish on radar profiles. Although several roots were detected, ground truthing revealed that many roots had been overlooked with GPR. The sites were somewhat poorly drained with a water table at a depth of 45 to 50 cm. Compared with the Lakeland soil, signals from the 400 MHz and the 1.5 GHz antennae were more rapidly attenuated and depth-restricted in areas of Lynchburg soil because of higher clay and water contents. The estimated velocities of propagation were 0.0665 and 0.0738 m ns^{-1} for the 400 and 1.5 GHz antennae, respectively. The signals from the 1.5 GHz antenna were severely attenuated and observation depths were less than 35 cm. With the 400 MHz antenna, observation depths of about 1.3 m were obtained. However, it was impossible to delineate tree roots at this site.

Georgia and Carolina Sandhills MLRA The ability of GPR to detect tree roots was exceptional in this area of Wakulla soil. A calibration transect was scanned with both antennae. The transect began in a cleared area, where a metallic calibration disk was buried, and moved into a loblolly pine plantation, going from an area of low root density to an area of high root density. Figures 3 and 4 are representative radar profiles obtained with the 400 and 1.5 GHz antennae, respectively. The velocity of propagation was 0.1070 and 0.1320 m ns⁻¹ for the 400 and 1.5 GHz antennae, respectively. The dashed, vertical white lines at the top of each radar profile are event markers spaced at an interval of about 30 cm. The metallic calibration disk, buried at a depth of about 48 cm, is evident to the immediate right of "A" in each profile.

Compared with the 400 MHz antenna, the 1.5 GHz antenna provided greater resolution of the upper 50 cm of the soil profile, and a greater number of point reflectors (roots) were distinguishable (cf. Figures 3 and 4). In Figure 4, reflectors are concentrated within the upper soil profile above a depth of about 30 cm. These reflectors are more numerous in the right-

hand portion of both Figures 3 and 4 where the transect went from a clearing into a pine plantation. In this portion of the radar traverse, the antenna passed several trees with many roots in the upper 30 cm. Radar interpretations were confirmed by excavating several small soil pits. In these excavations, roots were encountered at anticipated depths. Roots as small as 0.5 cm in diameter were detected with the 1.5 GHz antenna.

Despite excellent live root detection at this site, dead roots did not produce quality images. Dead, decaying roots < 5 cm in diameter were undetectable, as were remnants of taproots from the previous forest stand (17- to 20-year-old).

Southern Piedmont MLRA Radar signals were rapidly attenuated by the high clay contents of both the Appling and Georgeville soils, and observation depths were restricted. Coarse fragments are common in these soils and their reflections were similar to and easily confused with those of roots. In areas of Appling soils, with the 1.5 GHz antenna, parallel bands of background noise caused by high gain settings obscured some reflectors. The maximum profiling depth was about

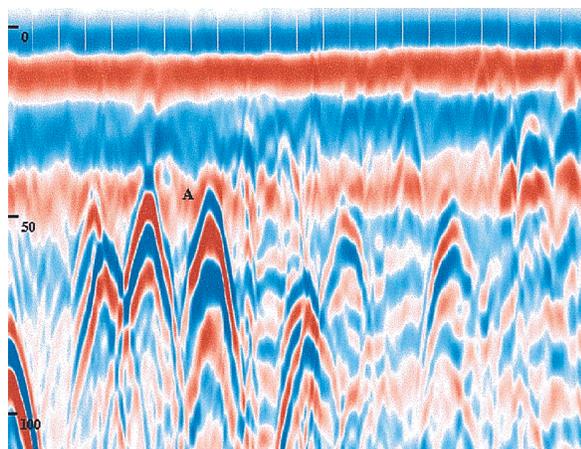


Figure 3. Representative radar profile obtained with the 400 MHz antenna from an area of Wakulla soil. Vertical scale units are cm. White vertical lines at the top of the profile are 30 cm apart. Point "A" denotes the location of the metal calibration disk.

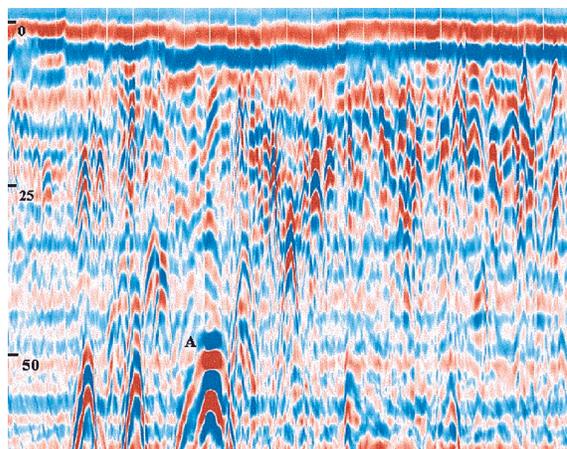


Figure 4. Representative radar profile obtained with the 1.5 GHz antenna from the same area of Wakulla soil shown in Figure 3. Vertical scale units are cm. Point "A" denotes the location of the metal calibration disk.

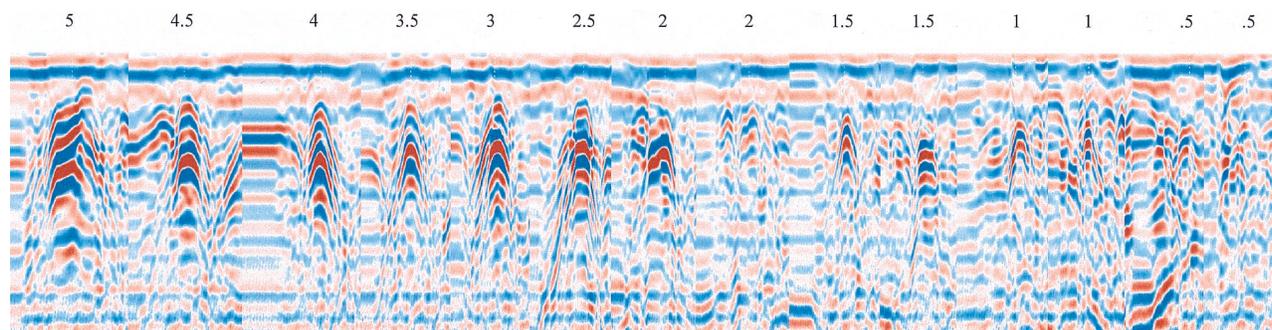


Figure 5. Composite radar profile of a loblolly pine root buried in a 15-cm-deep trench. Root diameter (cm) is shown above each reflection. All radar passes were made perpendicular to the root in order to image a radial "slice."

60 cm. The estimated velocity of propagation was 0.1176 m ns^{-1} . Numerous point reflectors were detected within the upper 30 cm of the soil profile. These point reflectors represented both rock fragments and roots. The radar profiles produced with the 1.5 GHz antenna were of modest interpretative value. High amplitude, low-frequency background noise produced horizontal bands that partially masked reflections from point anomalies, many of which were likely roots. Even after signal processing, the profile was ambiguous.

The 400 MHz antenna provided a profiling depth of about 1 m, with more contrast and less ambiguous images of large ($> 3.7\text{-cm}$ diameter) roots. The estimated velocity of propagation was 0.1005 m ns^{-1} . Large roots were correctly interpreted and observed in four of six pits at the estimated depths. Roots with diameters of 10, 7.4, 7.0 and 3.7 cm were distinguished. However, in the other two pits, coarse rock fragments were observed at depths that, in the field, were interpreted to contain roots. Although some larger roots (3.7 to 10 cm in diameter) were detected with the 400 MHz antenna, smaller roots were not detected.

The utility of GPR to estimate root size and biomass and to map tree root systems

In the sandy, excessively drained soils at the Georgia and Carolina Sandhills MLRA, GPR successfully estimated root diameter of the loblolly pine root at both the 15 and 30 cm depths. A composite radar profile created from 14 perpendicular scans across the test trench is presented for the 15 cm depth in Figure 5. The center of the scan, where the root should be, is marked with a white dotted vertical line. The reflected parabola near the centerline is the root. Areas of high amplitude reflection minus the false multiple reflections were closely correlated with root diameter (Figures 6A and 6B). The relationship was highly significant at a depth of 15 cm, but declined with increasing depth. The upper parts of the Lakeland and Wakulla soil profiles are similar. They are comprised primarily of coarse sand, which is ideally suited to GPR. Cottonwood roots as small as 0.5 cm in diameter were detectable with GPR. However, high amplitude reflections did not correlate well with root diameter (Figure 7). Comparing Figures 6A and 6B to Figure 7, it is apparent that the correlation between tree root diameter and areas of high amplitude reflection varied with soil depth and tree species.

Root biomass assessment For each of the 64 radar passes, high amplitude area and reflector tally were correlated to the observed root biomass directly below it. Both of the radar variables accounted for approximately one third of the variation in root biomass (Table 1). When the entire plot was scanned and data from the four passes that were conducted in the same direction were combined, the correlation improved markedly (Table 1). Combining the south to north and east to west data for each plot further improved the correlation. The composite of all passes in a plot gave the best correlation. High amplitude area and reflector tally are directly proportional to changes in root biomass (Figure 8).

Radar profiles were separated into depth classes of 0–20

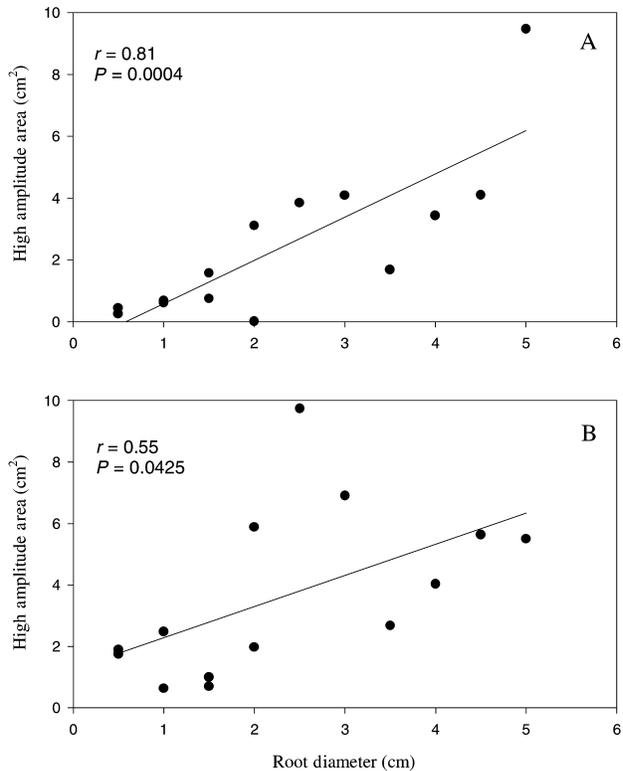


Figure 6. Correlation of areas of high amplitude reflection derived from radar profiles and loblolly pine root diameter at the Wakulla site at two depths: (A) 15 cm and (B) 30 cm.

and 20–40 cm and tested to determine if high amplitude area could distinguish root biomass by depth class. Correlation of high amplitude area to root biomass in the two depth classes was poor ($P > 0.1$). Tests were performed to see if any of the root size classes (0–2, 2–5 and > 5 mm diameter) were correlated with radar variables. We were unable to correlate mass of roots in a particular size class with any of the radar variables

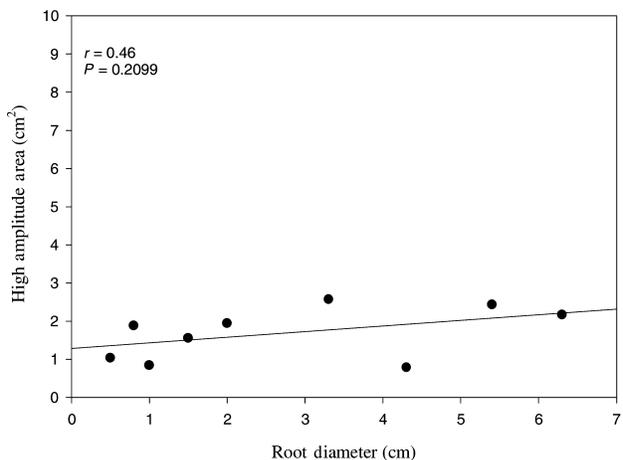


Figure 7. Correlation of high amplitude area (cm^2) and diameter of the cottonwood root buried in a 20-cm-deep trench at the Lakeland sand site.

Table 1. Comparison of data derived from each radar pass (reflector tally, high amplitude area) to root biomass harvested directly beneath each pass.

Radar pass	Reflector tally			High amplitude area		
	<i>n</i>	Correlation coefficient	<i>P</i> -Value	<i>n</i>	Correlation coefficient	<i>P</i> -Value
All data correlated to biomass beneath each radar pass	64	0.36	0.0001	64	0.34	0.0001
Four south to north radar passes in each plot combined and correlated to biomass	16	0.45	0.0795	16	0.57	0.0211
Four east to west radar passes in each plot combined and correlated to biomass	16	0.46	0.0718	16	0.48	0.0600
Composite of all eight radar passes in each plot correlated to biomass	16	0.49	0.0535	16	0.55	0.0274

($P > 0.1$). The best correlation was obtained using total root biomass, undifferentiated by size class.

Using the complete randomized block design (four replications) at SETRES, we sampled to determine if there were differences in root biomass after 7 years of fertilizer treatment.

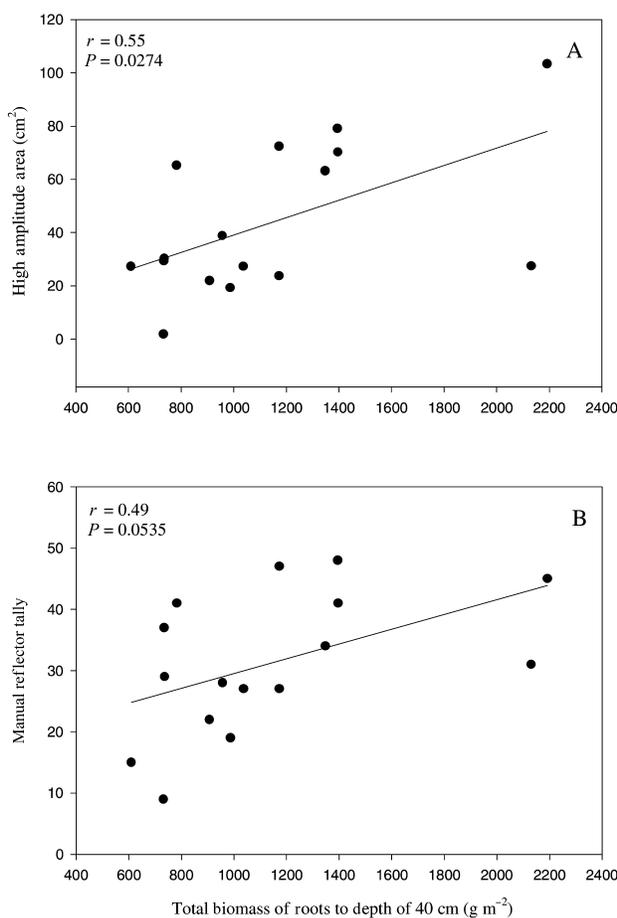


Figure 8. Correlation of total root biomass with (A) high amplitude area and (B) reflector tally in each plot at the SETRES replicated forest nutrition study.

Root biomass, high amplitude area and reflector tally totals for each of the 16, 1 × 1-m subplots sampled are presented in Table 2. Both high amplitude area and reflector tally closely followed the trend observed in root biomass. However, because of the high variability in root biomass, the statistical significance of the fertilizer treatment on root biomass was weak ($P = 0.0749$; Table 3). Using reflector tally as an index of root biomass indicated a statistically significant difference ($P = 0.0152$), whereas using high amplitude area gave a P -value closer to that of the actual root biomass ($P = 0.1061$) and was not significant.

Discussion

The successful application of GPR is site-specific. In some areas, conductive soil conditions limited the profiling depth and the applicability of GPR. The maximum observation depth is, to a large degree, determined by soil conductivity. Soils with high electrical conductivity rapidly dissipate electromagnetic energy and restrict observation depth. The principal factors influencing conductivity of soils to electromagnetic radiation are degree of water saturation, amount and type of salts in solution, and the amount and type of clay. In addition, detection of roots is affected by: (1) the electromagnetic gradient existing between a root and the soil; (2) the size, shape, and orientation of a root; (3) the presence of scattering bodies within the soil; and (4) antenna frequency.

The results of the buried root test are the least ambiguous and provide the best evidence of the value of GPR for sizing roots. The correlation between the area of high amplitude reflection that meets threshold luminescence and actual root diameter is quite good at shallow depths for loblolly pine, but declines with increasing soil depth. However, this applies under ideal circumstances: only one root was present, the radar scan was perpendicular to the root, and the soil was sandy and amenable to GPR. Under typical field conditions, results can be confounded when there are many interconnected or adjacent roots that mask or change the area of the parabola. Orientation of the root and the shape of the reflective surface are also important. Scans made parallel to the buried roots were

Table 2. Root biomass, high amplitude area and reflector tally totals (tally total of eight radar passes) from each of the 16, 1 × 1-m subplots scanned with GPR and then harvested to a depth of 40 cm.

Variable	Treatment	Block 1	Block 2	Block 3	Block 4	Mean (± SE)	Percent difference between treatments
Root biomass (g m ⁻² to depth of 40 cm)	Control	783.2 1395.0	1036.7 610.1	957.4 908.1	987.0 733.1	926.3 (83.9)	31.9
	Fertilized	1172.8 2131.3	1396.4 736.9	735.0 1172.9	2192.3 1347.7	1360.7 (195.4)	
High amplitude area (cm ²)	Control	65.24 79.11	27.21 27.27	38.85 21.95	19.17 1.86	35.08 (8.97)	33.1
	Fertilized	23.67 27.42	70.28 30.28	29.38 72.41	103.37 63.21	52.50 (10.27)	
Reflector tally	Control	41 48	27 15	28 22	19 9	26.13 (4.67)	28.3
	Fertilized	27 31	41 29	37 47	45 34	36.38 (2.63)	

less useful for estimating size. They appear as long, unbroken, parallel bands on radar profiles. Roots with a domed shape or tapered surface may shed the electromagnetic energy, whereas those with a flattened or cupped surface may give exaggerated reflections. It is unlikely that roots with unknown orientation could be sized with any accuracy.

Because little research has been carried out using GPR to investigate roots, the contrast in dielectric properties between a root and the surrounding soil matrix is largely unknown. In electrically resistive sandy soils (e.g., Lakeland and Wakulla), both loblolly pine and eastern cottonwood roots were detectable with the 1.5 GHz antenna. Assuming that roots have a high water content, the contrast between a root and the surrounding soil matrix is assumed to be greater under drier soil conditions. Increases in soil moisture likely decrease the electromagnetic gradient between roots and soil. Reflected signals are weakened, making the detection of subsurface interfaces more difficult. The sandy, excessively drained Lakeland and Wakulla soils were ideal for root investigations with GPR. However, roots were indistinguishable in moist or saturated

areas of the loamy, somewhat poorly drained Lynchburg soil.

The observation depth of GPR increases as the clay content decreases or the proportion of low activity clays increases. Daniels et al. (1988) noted a reduction in observation depths from about 5 m (with a 1 GHz antenna) in sandy soils to less than 2 m (with a 100 MHz antenna) in clayey soils. Soils at the Southern Piedmont sites (Georgeville and Appling) were clayey, but because of their mineralogy were still penetrable with radar. However, in the upper part of these soils, roots with diameters of less than 3.7 cm were not discernable.

The ability of GPR to detect individual roots depends on root size, depth and spacing. Hruska et al. (1999) found an error of 1 to 2 cm between radar-interpreted and excavated measurements of coarse tree roots. By using higher frequency (greater than 450 MHz) antennae, these authors were able to resolve roots that were less than 1 cm in diameter. Large roots reflect more energy and are easier to detect than small roots. In our study, most small roots (< 0.5 cm diameter) were not directly detectable with GPR in the field. Small, shallow roots will be overlooked, unless located directly beneath the aperture of the radar antenna. In addition, the reflective power of any object buried in the soil decreases at a rate proportional to the fourth power of the distance to the object (Bevan and Kenyon 1975). Therefore, small, isolated, deeply buried roots are not discernable with GPR, although clumps of small closely spaced roots can produce a single large reflection similar to that of a larger root. This makes profiling or quantifying the biomass of taproots or clustered masses of roots difficult. The presence of large overlapping roots along a vertical plane makes interpretation complex. This study did not attempt to estimate taproot biomass, which would likely require the development of new or enhanced GPR methods.

There are no means to distinguish dead and live roots with GPR. It is much more likely that only live roots will produce high amplitude reflections. When roots die and begin to decay they rapidly take on characteristics of the adjacent soils and become less detectable with GPR. Even large decaying tap-

Table 3. Analysis of variance for root biomass and two radar-derived variables (high amplitude area and reflector tally) that estimate root biomass.

Variable	Source	df	F-Value	P > F
Root biomass	Block	3	1.19	0.3740
	Fertilization	1	4.19	0.0749
	Block × Fertilization	3	0.83	0.5125
High amplitude area	Block	3	0.26	0.8542
	Fertilization	1	3.32	0.1061
	Block × Fertilization	3	6.57	0.0150
Reflector tally	Block	3	1.99	0.1946
	Fertilization	1	9.47	0.0152
	Block × Fertilization	3	7.18	0.0117

roots, easily seen when excavated, do not provide enough contrast with the surrounding soil to be detected.

Clutter can be introduced by reflections from objects other than roots. Reflections from roots are difficult to distinguish from those produced by rock fragments, concretions, animal burrows, cultural debris, or some stratified or segmented soil layers. These scattering bodies produce hyperbolic reflections that can cause destructive interference among several closely spaced features, making roots difficult or impossible to identify.

Our attempt to use GPR to quantify treatment differences in root biomass took place in nearly ideal conditions: SETRES has sandy soils with few rock fragments, and fertilizer treatments have resulted in large differences in above- and below-ground biomass (Albaugh et al. 1998). Even so, the correlation between both high amplitude areas and reflector tallies with root biomass was quite remarkable. The overlapping grid-sampling pattern gave the highest correlation to actual root biomass. Because the orientation of the roots can influence the size of the reflection in the radar profile, the sum total of all scans in a grid is most appropriate. Most roots are scanned from one direction, and that value is added to another 90° scan to give the best composite data for that plot. The high amplitude area analysis technique was the least subjective method. It would be valuable, if feasible, to use GPR to separate biomass by size or depth class; however, we were unable to do this. The major drawback of using high amplitude area is that reflections travel down the profile, "invading" depth intervals from above, thus masking roots below. If reflection area is used, and advanced signal processing techniques are not, the entire length of each parabolic reflection must be used; it cannot be sectioned by profile depth.

Ground-penetrating radar could be useful for measuring increases in root biomass on an annual basis. This would be particularly beneficial in studies where trees are newly established, initial root biomass is low (available rooting substrate is high), the trees respond to experimental manipulations, and root biomass is noninvasively measured over time. Because roots < 0.5 cm in diameter cannot be detected in the field, we doubt that seasonal fluxes in fine root biomass could be measured.

When assessing the potential use of GPR, a major consideration is signal attenuation at the desired antenna operating frequency (Daniels et al. 1988). Because signal attenuation increases with frequency, low-frequency antennae must be used in high-loss media to increase observation depth. The maximum observation depth decreases rapidly with increasing antenna frequency. High-frequency antennae (> 400 MHz) can provide well-resolved images of shallow features in soils with low conductivity. In soils with high conductivity, signal attenuation becomes prohibitive (Daniels et al. 1988). In these soils, low-frequency antennae increase observation depth. However, as lower frequencies are used to achieve greater observation depth, resolution is diminished and smaller features are more likely to be overlooked. High resolution is vital for the detection of small roots.

Although Wakulla and Lakeland soils have similar properties, the cottonwood root in an area of Lakeland soil could not be accurately sized. Because the Wakulla and Lakeland soils had similar dielectric properties (dielectric permittivity of 7.8 and 7.9, respectively), the difference in resolution is likely related to species-specific root properties. Loblolly pine has been shown to have 21% higher specific gravity (G) than cottonwood (Panshin and de Zeeuw 1980). The higher G likely provides better dielectric contrast between the root and the soil matrix. Specific gravity may therefore be useful for predicting whether tree roots can be detected and accurately sized with GPR. In this study, loblolly pine roots were detectable, and it is likely that trees with roots of equal or greater G would also give satisfactory reflections. Hruska et al. (1999) reported greater success with root imaging by GPR than that achieved in this study; this may be related to their use of an oak species which likely has a higher G than that of loblolly pine or eastern cottonwood.

Conclusions

Soil with high electrical resistivity was the most amenable to root detection with GPR. The 1.5 GHz antenna gave the best resolution and was able to detect roots as small as 0.5 cm in diameter. The high clay contents and more electrically conductive properties of Appling and Georgeville soils limited penetration depth. Pine roots could be sized accurately (0.5 to 6.5 cm in diameter), but only when the orientation of the roots was known. The ability to delineate root size declined with profile depth. The cottonwood root could not be sized using GPR, possibly because of the low G of roots of this species.

Ground-penetrating radar was useful in assessing total root biomass at SETRES, but did not allow delineation of biomass by root size class. With suitable soil conditions (well drained to excessively drained, sandy soils with low conductivity, and absence of scattering bodies), GPR can be a valuable tool for noninvasive root biomass estimation and may prove useful for the nondestructive measurement of root biomass growth over time. It is probable that tighter grid spacing (i.e., 5 cm) of radar passes may yield even better correlations with root biomass.

Ground-penetrating radar did not appear useful for mapping roots over diverse terrain. Radar antennae need to maintain contact with the ground while being pulled at a fairly constant speed. This was difficult where undergrowth, logs, raised beds and logging slash impeded smooth advance of the antenna.

Tight clusters of roots often gave one large parabolic reflection, which prevented individual roots being distinguished. This is the greatest impediment to mapping complete root systems with radar. The use of more advanced data processing techniques, such as horizontal and vertical band-pass filtering and migration, may help improve the discrimination of some closely spaced roots and facilitate *in situ* imaging of tree root structure. Ground-penetrating radar can provide valuable data in small intensively studied plots, provided that the proper antenna is used. With current technology, and under appropriate conditions, GPR can be particularly useful for augmenting traditional and time-consuming root harvesting.

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