Forest Biology Research Cooperative

Feasibility of Using Ground-penetrating Radar to Quantify Root Mass in Florida's Intensively Managed Pine Plantations

Collecting data with the GPR Antenna

Exposed loblolly pine root system

FBRC Report #38
2005

UNIVERSITY OF FLORIDA
Institute of Food and Agricultural Sciences
School of Forest Resources and Conservation

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Cover: Upper right: John Butnor and Daniel McInnis use GRP to scan a transect at the Sanderson, FL PPINES trial on December 6th, 2004. Lower left: A loblolly pine root system from the same treatment that has been excavated using an air knife (in background). Photos: Brian Roth

Forest Biology
Research Cooperative

FBRC Report #38 - 2005

Feasibility of using ground-penetrating radar to quantify root mass in Florida's intensively managed pine plantations

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Background

Tree root systems are commonly evaluated via labor intensive, destructive, time-consuming excavations. 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 civil engineering for non-destructive testing of concrete as well as road and bridge surfaces. This technology is ideal for these applications since the electrical properties of concrete and rebar (steel) are very different. Under amenable conditions (i.e. electrically resistive, sandy soils) tree roots are detectable and can be quantified. Ground penetrating radar has been used to resolve roots and buried organic debris, assess root size, map root distribution, and estimate root biomass (Butnor et al., 2001). Being noninvasive and nondestructive, GPR allows repeated measurements that facilitate the study of root system development. Root biomass studies provide insight into the effectiveness of various irrigation and fertilizer amendments and are an indicator of tree health.

Roots, as small as 0.5 cm in diameter, have been detected at depths of less than 30 cm with a 1.5 GHz antenna in well drained, coarse-textured soils (Butnor et al., 2001). However, without 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. Butnor and others (2001) found GPR to be ineffective in soils with high clay or water contents, having large number of coarse fragments, or in most unimproved, forested terrains (presence of herbaceous vegetation, fallen trees limbs, and irregular soil surfaces). With advanced image processing, high amplitude areas and reflector tally were directly proportional to the actual root biomass. Butnor and others (2003) correlated GPR based estimates of root biomass within the upper 30 cm of soil profiles with harvested root samples. They found a highly significant ($r = 0.86$, $p < 0.0001$) relationship between actual biomass in cores and GPR estimates in a loblolly pine (*Pinus taeda* L.) plantation in southern Georgia. Substantial improvements in root biomass estimations with GPR were made possible with advanced digital signal processing techniques.

There has been considerable interest in mapping tree root systems to understand root architecture and soil volume utilization (Hruska et al. 1999, Cermak et al. 2000, Stokes et al. 2002). Compared with simple transects for biomass, three-dimensional data sets are tedious to collect and process for interpretation. As long as the grid line spacing is kept small (2 – 5 cm between scans) larger roots that are continuous across several two-dimensional profiles are distinguishable. Reconstructing the location of roots is straightforward, but successfully modeling size, shape and root volume is not. For most forest survey projects, root biomass transects yield sufficient information. Three-dimensional root mapping is useful when detailed root location information is required for a small area provided there is sufficient time to collect and process the data.

This report outlines work conducted at the PPINES site in Sanderson, FL and the IMPAC site near Gatornationals Speedway, FL (2003-2005)

The objectives of this research are:

1. Test the feasibility of using GPR to quantify root mass and root distribution in Florida pine plantations.

2. Use GPR compare root mass across cultural treatments, pine species, spacing and genetic families at PPINES in Sanderson, Florida and the IMPAC site.

3. Make recommendations for future research with GPR in Florida's pine plantations.

Materials and Methods

Equipment

The Subsurface Interface Radar (SIR) System-2000, manufactured by Geophysical Survey Systems, Inc. (North Salem, NH) was used in this study. The SIR System-2000 consists of a digital control unit (DC-2000) with keypad, LCD VGA screen, and connector panel. A custom designed sampling rig which steadied the high frequency antenna (model 5100,1.5 GHz antenna) and incorporated a survey wheel to meter electromagnetic pulses was used (Figure 1). After system calibration (Butnor et al. 2001 & 2003), measures are made by slowly drawing the survey rig along a measurement transect while ensuring that the antenna remains in contact with the soil surface. The resulting scan is a two-dimensional profile (transect length by depth) where electromagnetic anomalies are located.

Figure 1. SIR 2000 Ground-penetrating radar system used with a forest survey rig, compromised of a high-frequency GPR antenna mounted on a stabilization board (1.5 GHz) and a survey wheel.

Sites and sampling designs

IMPAC 2003

The IMPAC site was surveyed on Feb. 10th, 2003. The coarse sandy soils would usually be considered ideal for GPR evaluation, but there had been heavy rains for several days prior to this work. Soil moisture was high for this site, but the depth to the water table at IMPAC was greater than 1 meter at the time of sampling. Since the antenna needs to maintain contact with the soil surface, only the complete weed control plots were surveyed. Understory vegetation in the control plots was far too dense to properly couple the antenna to the soil. This only allowed for comparisons between pine species (loblolly and slash pine) and fertilizer amendments. A total of 12 plots were measured (Figure 2; 3 replicates each of a 2 x 2 x 2 species by fertilizer x weed control design).

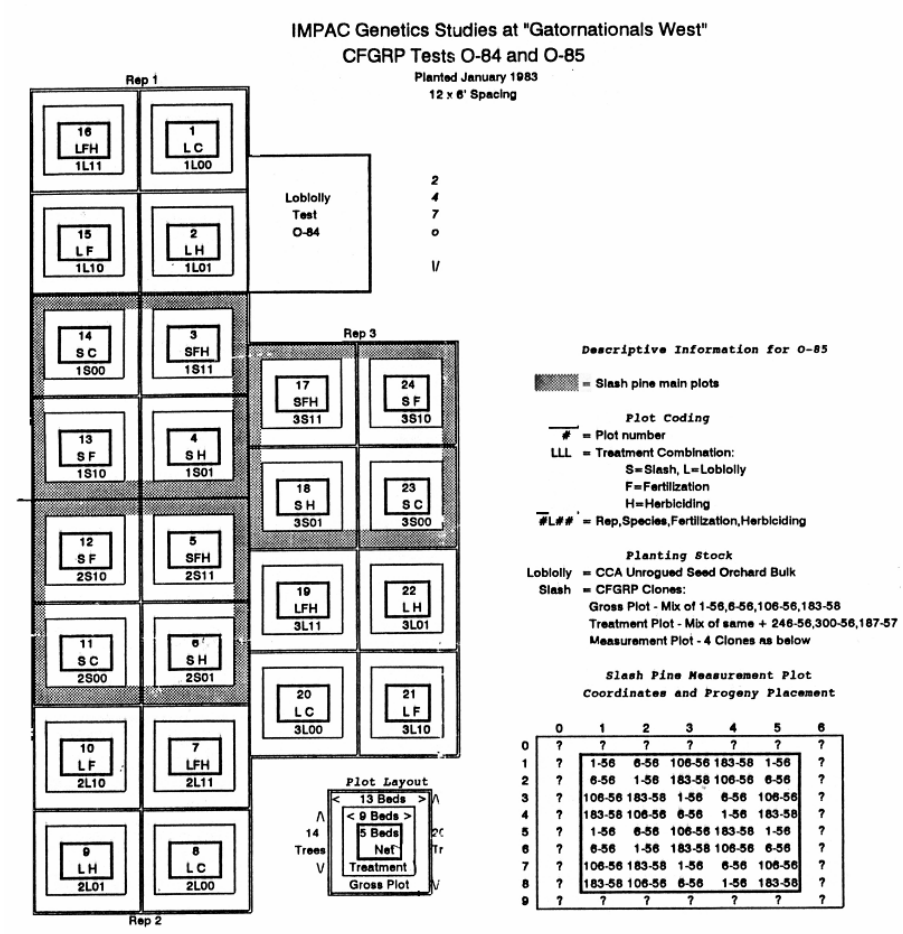

Figure 2. Experimental layout at the IMPAC trail near Gainesville, FL.

Within each plot, 2 adjacent (~10 m) transects running perpendicular to the beds were located within the plot (transects with large debris, wells, or soil pits were not chosen). The transects were surveyed (one adjacent to trees and one half the distance between trees. The transect closest to trees were cored to obtain validation data. Soil sampling points were located next to the interior three trees (3) and on the inter-beds between these trees (2) for a total of 5 samples per plot (60 total).

PPINES 2003

The Sanderson site was surveyed beginning Feb. 11th, 2003. There were heavy rains in the days preceding the GPR measurements. The water table at Sanderson during sampling varied between 0 and 20 cm below the surface of the inter-beds. Transects two meters long were established centered on and perpendicular to the beds. On half of these transects, validation soil cores were taken systematically after scanning with GPR, from which a validation data set of actual root biomass was developed (Figure 3).

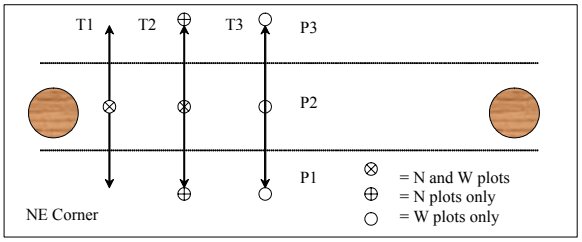

Figure 3. Schematic layout of survey and sampling protocol for a single position.

Four replicate blocks were surveyed. Within each block there are two densities of trees (N=1200 tpa and W=540 tpa) and up to eight family block comparisons. We selected two families, based on contrasts in previous data (L4 = 7-56, a fast grower; L6=a poor grower). In an effort to use larger trees with more defined lateral roots, only the high culture was surveyed. Within each family plot, two sub-sampling locations were chosen at random. In the low density plots (W), three transects (T1-T3) were surveyed; in the high density plots (N) two transects were surveyed (Figure 3). The first transect (T1) began perpendicular to the bed as close to the tree trunk as possible with the starting point either at the furthest North or East point a fixed distance from the center of the bed (i.e. 4.5 feet). T2 was 2 feet from the trunk (half the distance between trees on the narrow spacing) on both densities. The wide spaced plots will have a third transect (T3), which was half the distance between trees (4.5'). Sample cores were collected at 4 locations on the low density plots and from 5 locations on the high density plots. These will be positioned at both ends and the middle of the transect. To limit the total number of cores and increase the number of cores collected at the extreme data ranges the positions were predetermined as follows and is dependant on density: Transect 1(all densities) = center of bed position, T2 (N) = center and ends, T2(W) = center only, T3 (only occurs in W)= all three locations. Positions (P) within each transect will be numbered P1-P3. A 6 inch diameter soil core will be extracted at each position to a depth of 30 cm and all live pine roots >=2mm diameter washed, oven dried and weighed to nearest 1/10th gram.

PPINES 2004 and 2005

In December 2004, additional GPR measurements were made at the Sanderson PPINES site in conjunction with a planned root harvest by the FBRC. Earlier results indicated that the core verification technique used in 2003 was not sufficiently accurate to achieve a strong correlation between root mass and GPR-based estimates, as found on other sites in the southeast. In an effort to increase accuracy, we decided to scan a 20 by 100 cm section of (36) 1 by 1 m pits which were scheduled to cleared with an air knife and subsequently harvested by hand. An extensive sampling regime of (288) 10 m transects was implemented; 6 transects per each unique experimental combination within narrow spacing ; 3 blocks, 2 culture (high, low), 8 families (7 families and 1 mixed plot). Transects were positioned perpendicular to the beds, within each plot, three were run near the base of the trees, three transects were equidistant from tree. We began scanning in low culture and found the leaf litter to be sparse; it did not seem to interfere with the quality of the GPR data, so we collected radar data with the litter left intact. However when we moved to the high culture plots, we found leaf litter depth ranged from 5 to 20 cm. The trees had recently dropped a large cohort of needles. For continuity, we scanned through the leaf litter then raked a small subset to bare soil and re-measured it, in order to determine if the litter had effects on the data. This was a very intensive survey were 2.9 km of transect data (equivalent to 19,140 15 cm soil cores) was collected in the span of 1 week.

Results

IMPAC 2003

Despite high moisture content of soil, GPR was able to detect roots at the IMPAC site, though signal attenuation may have limited detection to larger roots. Examples of minimally processed data are presented in Figure 4.

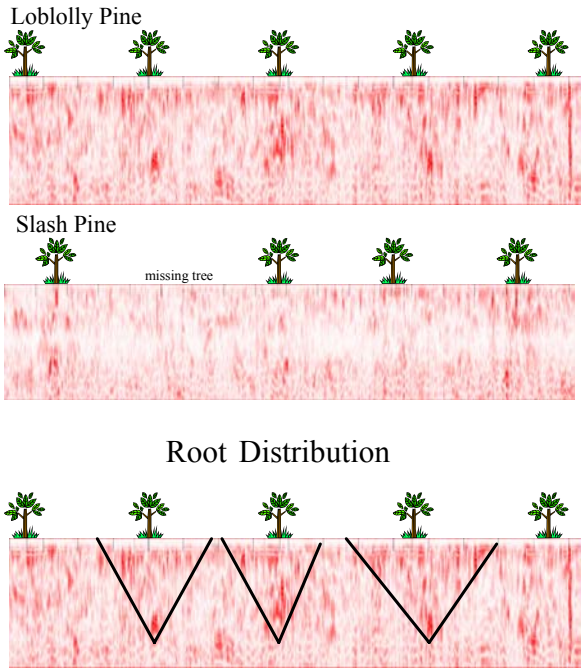

Figure 4. Examples of data collected at the IMPAC site, the tree locations are denoted by the small "tree" graphic. The upper two scans demonstrate differences between species, while the bottom scan illustrates root distribution (0-50 cm depth scale) along a transect.

As expected, more roots were detected as the scan approached the base of each tree. A total of sixty 15 cm soil cores were used to calibrate the GPR data. The correlation of GPR data with root mass collected from each core was poor (Figure 5A), however when the average values of GPR index and root mass in each species/fertilization combination were correlated across all blocks the R^2 value improved markedly (Figure 5 B). On other sites in the southeast, the relationship between estimated mass and actual mass is described by a linear equation with an R^2 value ranging from 0.45 to 0.70. There are many possible explanations for this phenomenon; the soils were very wet at the time of sampling causing signal attenuation, core locations may not have been marked precisely enough at the time of the survey or similar problems coring exactly in the correct position may have occurred. Any errors in core location may have a greater impact on individual scan/core comparisons, but when the larger treatments are considered the inter-treatment difference may outweigh the lack of spatial precision.

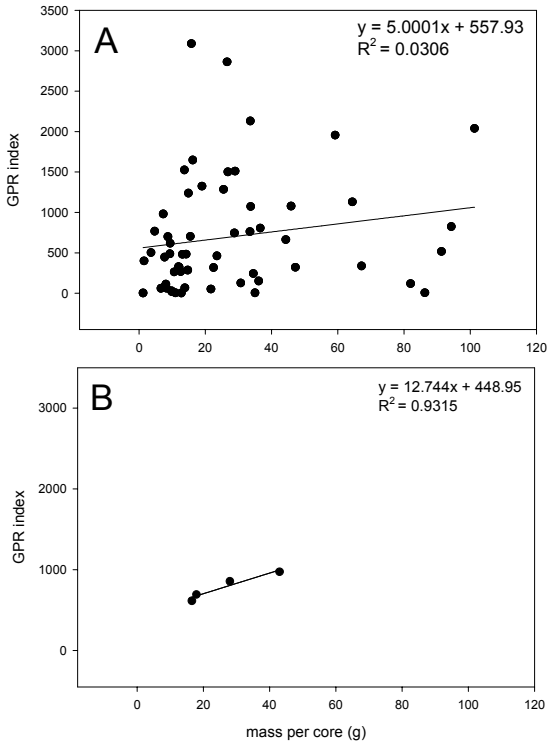

Figure 5. The correlation of GPR and individual root cores was rather poor (A), when the average values of GPR index and root mass were correlated across all blocks (B) the R^2 value improved markedly.

While we have reservations about this calibration, the equation in Figure 5B was used to scale the data and determine the difference in root mass between species and fertilizer treatments (Table 1).

Table 1. Relative differences in root mass between 20 year-old loblolly and slash pine grown with and without fertilizer amendments. The data have been normalized by the loblolly plus fertilizer treatment which had the greatest root mass estimates.

Species/Fertilizer combination	**Root mass relative to Loblolly plus fertilizer**
Slash pine plus fertilizer	0.64
Slash pine no fertilizer	0.59
Loblolly pine plus fertilizer	1
Loblolly pine no fertilizer	0.80

ANOVA Results		
Treatment	***F Value***	***P value***
Fertilization	7.18	0.0366
Species	38.98	0.0008
Fertilization * Species	2.78	0.1464

In less than four hours of sampling, 240 meters of transect lines were surveyed non-destructively, yielding the data equivalent to 1600 soil cores. Fertilization significantly increased root biomass in both loblolly (20 %) and slash pine (7%) plots (P = 0.036). Marked differences in root biomass between species were also observed, with loblolly having more lateral root biomass than slash pine. (Table1).

Table 2. Comparison of root mass collected from soil cores and estimated with GPR (using the equation in Figure 6B).

Family / Spacing	Average mass per core (g) ± s.e.	GPR mass estimate per core (g) ± s.e.
Family 4 / Narrow Spacing	24 ± 7	32 ± 7
Family 6 / Narrow Spacing	46 ± 12	39 ± 11
Family 4 / Wide Spacing	36 ± 9	19 ± 6
Family 6 / Wide Spacing	28 ± 11	26 ± 6

PPINES 2003

The correlation coefficient between soil cores and GPR data at PPINES was lower than what is usually seen in the Southeast when all of the cores were considered individually (Figure 6).

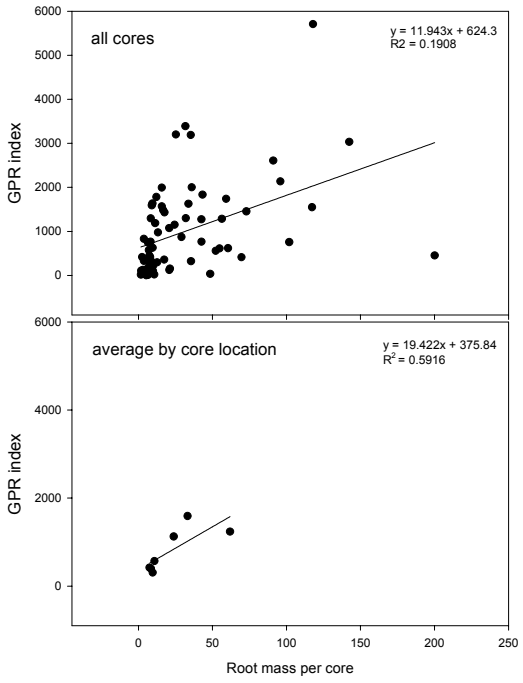

Figure 6. The correlation coefficient of GPR data and root mass individual root cores (all cores) was small at the Sanderson PPINES site, when the average values of GPR index and root mass were correlated for each core position (Figure 3) the R^2 value improved.

When data were averaged by core position (Figure 3) the correlation improved in a manner similar to what was reported at the IMPAC site.

GPR estimates of root mass were not as accurate as we would have preferred, but GPR was able to detect spatial differences in root mass distribution. Cores collected in the inter-row (furthest point from any tree) had the lowest root mass, this pattern was also followed by the GPR based estimates of root mass (Figure 7). While this observation seemed promising, we were unable to detect any root mass differences between family or spacing experimental combinations (Table 2). We hoped to use what we had learned in this sampling campaign to plan a more comprehensive survey which would include all families as well as high and low culture.

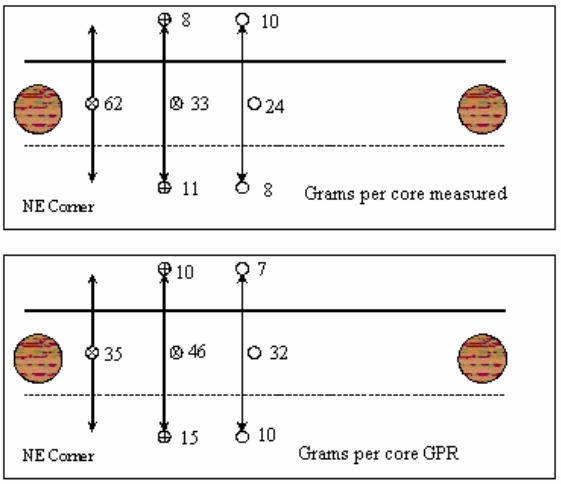

Figure 7. Compare actual root mass collected from soil cores and estimates from GPR for each core position across all families/spacing.

PPINES 2004

At the time of sampling, we believed there was a problem accurately matching the footprint of the radar antenna to soil cores and new methods of verification were necessary. In December 2004 we implemented a new scanning protocol for GPR verification using a subset of 1 by 1 m soil pits. When the mass of roots collected from each soil pit sub-sample (20 by 100 cm area) was compared to GPR data there was no correlation. We were surprised by this finding and searched for an explanation. There were no serious accounting errors associated with the belowground harvest, though it was noted that many dead roots and organic debris were lost when the pits were cleared with the air knife. At other sites in the southeast

dead roots were found to be undetectable or at least readily oxidized and absent from the system in any large quantity. At this point there was no way to determine what was lost and no way to scale our extensive survey of all families in both high and low culture.

PPINES 2005

In January 2005, we revisited PPINES to determine what had gone wrong with our previous verification effort and attempt to "rescue" the extensive GPR survey which was conducted in December 2004. We established 4 transects perpendicular to the beds in high culture and another 4 in low culture. Each transect had 3 verification points on the bed and 2 in the inter-bed area. Once transects were scanned, extreme caution was used to extract the cores in the correct location. The cores were screened and the biomass was separated into live roots and dead organic debris. The roots were almost exclusively pine, while the dead organic debris were comprised of decaying palmetto roots, residual slash and dead roots. From the 40 cores, more than half of the biomass was classified as dead organic debris. A strong positive relationship was observed between live and dead material (combined) and the GPR data (Figure 8). However, if we tried to separate out live roots the amount of variation in root mass explained by GPR was greatly diminished (R^2 =0.26). There was also no relationship between live roots and dead organic debris in a given core. It is not possible to separate out live and dead material at the Sanderson site and the high proportion of buried organic debris limits further limits the utility of the technique to detect live roots.

Approximately 10% of the survey was measured with litter in place and again with litter removed to quantify the effects of litter on root resolution. Scanning through the leaf litter served to defocus the GPR antenna and degraded the ability to detect roots (Figure 9). If litter depth was uniform across all treatments the de-focusing effect could have been mitigated. However, since the experimental manipulations of culture and family resulted in differential litter depth, the differences in root mass could not be assessed.

We re-measured several of the transects measured in 2004 at the time of the 2005 coring, to quantify the moisture change on the GPR data and employ the new calibrations to utilize the 1000's of meters of plot data collected in 2004. At the time of the sample we were not aware of the problems with litter depth (above). Twelve transects that went past 48 trees were re-measured, representing 4% of the complete survey. When transects were compared point to point (with and without litter) with data collected in 2004, there was no correlation. This may have been due to the precise nature of high frequency antennas; data was collected every 5 mm so it may be impossible to get a re-measure in exactly the same spot. When whole transects were compared (12 x 10 m) with regression analysis there was again no correlation. The transects were in 2 families in the high culture treatment, 6 transects were combined in each family. A 35% difference was observed in one family and only a 20% difference was noted in the in the other due to changes in soil moisture. The ability to resolve subtle differences in root mass between families was compromised with this data. The effects of litter, were very different in 2005, than in 2004 making modeling more of a guessing game than a mathematical process. Hence, hence there is no statistically valid method to link the newly collected cores with the data from 2004. This emphasizes that verification surveys need to be conducted at the time of surveying and must include every unique experimental design combination.

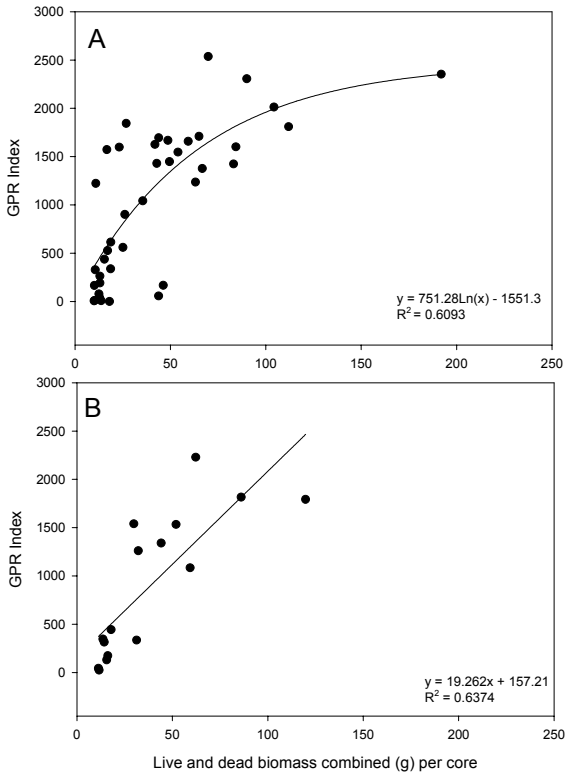

Figure 8. Correlation between GPR data and a combination of both live and dead biomass. Inset A includes all data from the 40 cores sampled at Sanderson PPINES in 2005, Inset B reduces the 5 cores collected in each transect to 2 classifications (bed and inter-bed) resulting in 16 data points. If inset A were fitted with a linear equation the R^2 would equal 0.50.

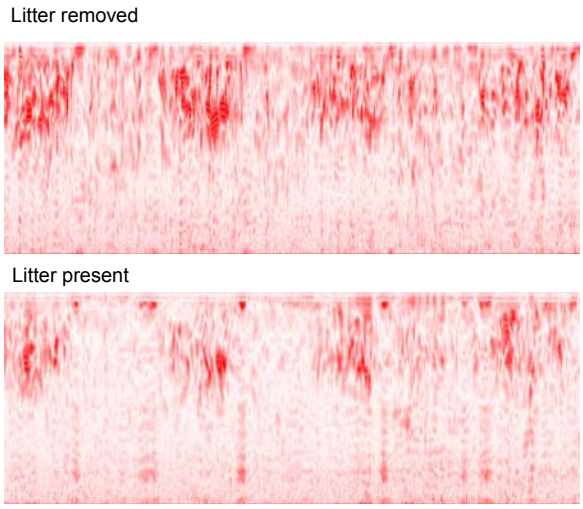

Figure 9. In high culture, the presence of a thick litter layer served to de-focus the antenna degrade the ability to detect roots.

Future of GPR in Florida pine plantations

The GPR work performed at Sanderson provided an excellent framework for improving the use of GPR to measure root mass in forest systems. Our sampling in December 2004 was designed to cover all families of narrow spaced trees in both high and low culture. Considering the poor correlation of GPR with soil cores collected in 2003, we thought it would be better to sample a 20 cm wide "slice" of each 1 m x m pit cleared of soil with the air knife and sub-sampled prior to the removal of the whole pit. This new method of ground-truthing was designed to precisely link GPR data collection and root sampling. This method should have worked, however there were several problems: 1) the air-knife destroyed or dispersed much of the dead organic/root matter, 2) Unlike other sites, buried slash, palmetto rhizomes, dead roots and rodent tunnels are detectable with GPR. 3) Dead roots and other non-pine biomass accounts for about 50% of belowground biomass on this site five years from harvest. The combination of the GPR detecting undesired targets and the loss of many of these targets during the root blasting, yielded gpr:root mass correlations that were unacceptable < 0.1 R^2.

At PPINES, GPR was detecting both live and dead biomass and they could not be separated. Analysis of the cores revealed that there is slightly more dead material than living lateral roots on this site. GPR has been very successful in estimating root mass at SETRES in the North Carolina Sandhills (Marston, NC) and the Upper Coastal Plain near Bainbridge, GA. However these sites have very little residual buried coarse woody debris. The site near Bainbridge was in agriculture for decades before being converted to a 1st rotation experimental pine plantation. This emphasizes that the user cannot control what the GPR detects. It is simple to separate point anomalies from continuous features like hardpans, bed rock or buried utilities, metal, etc., however the contrast between roots and rocks, mineral inclusions, buried organic matter is a site feature which cannot be controlled.

There are two methods of using GPR to detect roots. We employed a method that uses amplitude or the strength of the reflected signal to estimate mass. It is affected by soil and litter moisture conditions, hence the only reliable way to convert GPR data to mass is to have a small scale destructive sample that covers all of the potential confounding factors (bed vs. inter-row density, bed vs. inter-row moisture content, litter thickness and level of compaction, litter moisture, near surface water table etc.) encountered at the time of sampling. This method can measure roots in any size class, angle, orientation etc. There is another method which employs reflector geometry to estimate root size regardless of depth (Barton and Montagu 2004). The problem is it cannot be used under field conditions at present, since roots need to be traversed at 90 degrees, have a level orientation, not be near any other roots that can cause clutter/interference. These restrictions prohibit using the analysis under typical forest conditions, but it may be used in the future if the technique continues to evolve.

GPR can be a useful research tool in Florida pine plantations, though site conditions must be amenable to measure specific desirable targets and separate them from background clutter. Through the GPR studies at PPINES and IMPAC we learned the following:

- Scanning over litter, especially in treatments that can affect litter depth should be avoided.
- Sites with high, dynamic water tables and are difficult to re-measure.
- GPR calibrations can be successful using 6" cores, but sites differ in the type of targets that resolved.
- Detailed site surveys should be conducted to determine if non-target reflectors (slash, rocks, buried organic matter, rodent tunnels, surface discontinuities) will degrade the potential to quantify live tree roots.

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