Emerging Technologies for Measuring Tree Root Biomass in the Context of Global Greenhouse Gas Emissions Reductions Programs

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List of Abbreviations

CDM	Clean Development Mechanism
CO_2	Carbon dioxide
CoP	Conference of Parties
CVES	Continuous vertical electrical sounding
EM	Electromagnetic
ERT	Electrical resistivity tomography
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse gas
GPR	Ground penetrating radar
IPCC	International Panel of Climate Change
JI	Joint Implementation
KP	Kyoto Protocol, also the Protocol
LEP	Lateral electrical profiling
MUCEP	Multi-depth continuous electrical profiling
NPP	Net primary productivity
PACEP	Pulled array continuous electrical profiling
QELRO	Quantified emission limitation and reduction commitment
REDD+	Reducing Emissions from Deforestation and forest Degradation
RMD	Dry root mass density
R/S	Root-to-shoot ratio
SRM	Soil root matrix
UNFCCC	United Nations Framework Convention on Climate Change

Abstract

Greenhouse gas emission reduction programs fundamentally rely on accurate carbon dioxide data. A large part of annual emission inventories that countries undertake involve assessing carbon stocks in forests and agricultural lands. Subsurface carbon quantification in these landscapes has primarily been roughly estimated on especially coarse data when dealing with large and cumbersome tree root systems. Root biomass makes up a portion of the subsurface carbon and is difficult, labor intensive, and costly to measure. The present research seeks to answer the question: What new methods offer promise for measuring tree root carbon via biomass, and how may they be applied in the context of national greenhouse gas inventories? Two very promising geophysical methods have emerged over other novel root measurement technologies. Ground penetrating radar and electrical resistivity tomography are better suited for use in national greenhouse gas inventories than electrical impedance and capacitance methods. Use of ground penetrating radar (GPR) and/or electrical resistivity tomography (ERT) enable large tracts of land to be surveyed under appropriate conditions, allowing for the acquisition of more expansive data resources on which to develop more representative allometric models. Ground penetrating radar detects coarse roots well in dry soil. Electrical resistivity tomography does best in detecting roots in moist soils, but is especially limited by electrode configuration (Mancuso 2012). Integration of these two technologies into a baseline protocol based on site-specific characteristics, especially soil moisture and plants species heterogeneity, may

increase temporal efficiency of root biomass measurements for use in national greenhouse gas inventories.

Chapter 1

Necessity of improving measurement of root carbon content

1.1: Background on root carbon

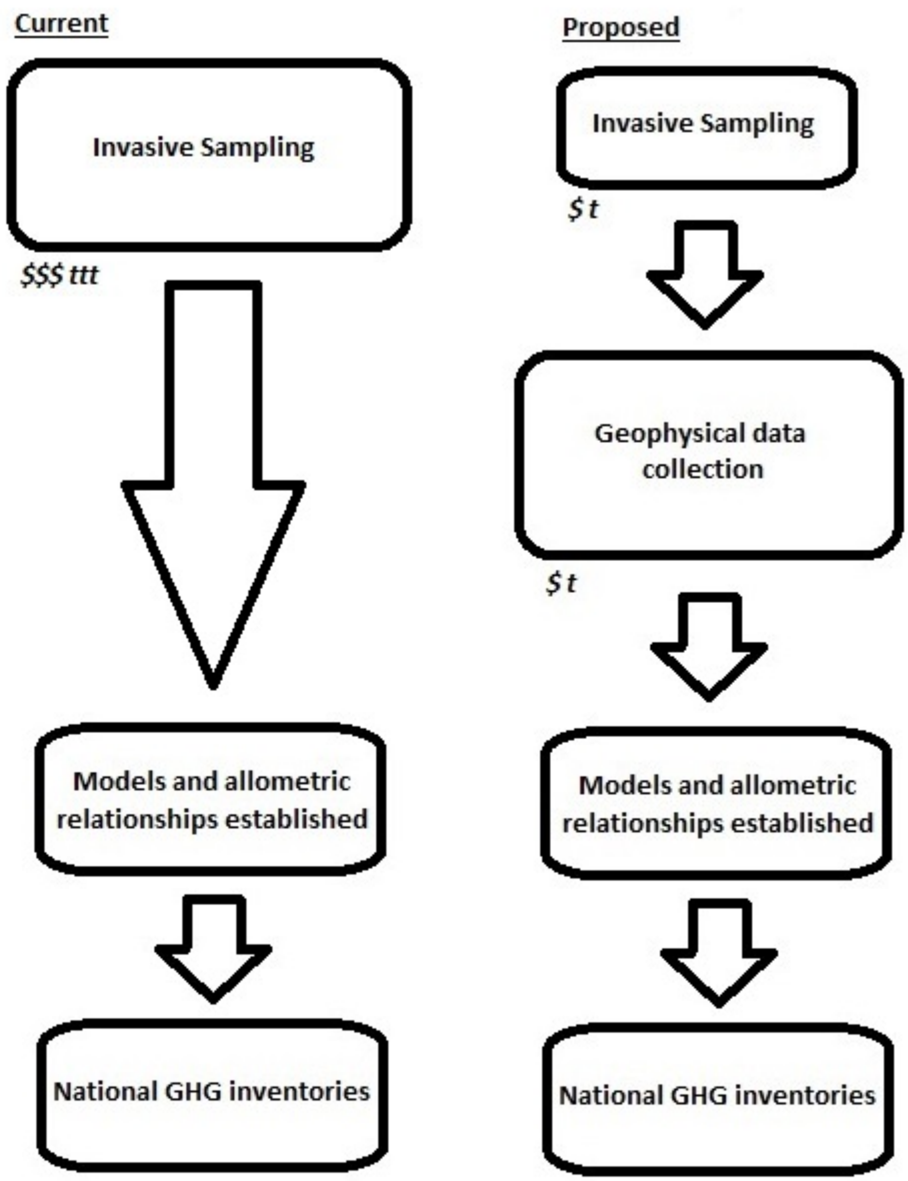
For the purpose of this thesis roots are simply the belowground portions of living plant tissue. Roots are essential to plant life in a variety of ways. They supply nutrients and water from the soil, anchor plants firmly in place, and stabilize the soil surrounding plants against erosion. Most importantly to this research, roots store carbon. Plants are autotrophs: They produce their own food from light energy, oxygen, and carbon dioxide (CO_2) as well as nutrients from the soil (Campbell 2005). Since their only carbon input comes from atmospheric CO_2, any carbon-containing compound in root tissue was ultimately once an atmospheric greenhouse gas. Greenhouse gases (GHGs) are natural and anthropogenic atmospheric gases which absorb and re-emit infrared radiation (United Nations 1992). Root growth represents a CO_2 sink, a process that remove CO_2 from the atmosphere (United Nations 1992). Root systems, therefore, represent CO_2 reservoirs, components of the climate system where CO_2 is stored (United Nations 1992).

Roots are complex systems that present scientists and policy-makers issues because they are so difficult to measure and model accurately without massive labor investments. Root complexity can be astounding. For example, Dittmer (1937) excavated and mapped one single adult rye plant. Its roots contained 13,815,672 branches, had a surface area of 237 m^2, a length of 622 km, and a root hair length of 11,000 km (Mancuso 2012). The roots and root hairs, end to end, were long enough to run the entire length of Africa from the Mediterranean Sea to the southernmost tip of South Africa. In the light of this finding, the complexity of root systems is unquestionable and the difficulty in their quantification understandable. Methods to quantify forest carbon stocks, especially the root portion, have been subject to high degrees of uncertainty and discrepancies due to imperfect and often inconsistent methods (Qureshi *et al.* 2012). Measuring forest carbon stock is important because deforestation, behind fuel combustion, is the second largest source of CO_2 to the atmosphere (UN Environmental Programme and UN Climate Change Secretariat 2002). The focus in this research is on tree roots as they are the more difficult, thus interesting, part of the tree to measure and estimate (Qureshi *et al*. 2012). The first chapter discusses the international political necessity for an expanded knowledge of tree root biomass and carbon content. The second chapter expands upon the current non-geophysical and emerging geophysical methods to estimate tree root biomass and carbon content. Finally, the third chapter shows how each of the emerging geophysical techniques may or may not be useful in the context of national greenhouse gas inventories.

1.2: Public policy contexts for measurement of tree root carbon

The historical international political response to climate change will be examined, namely the United Nations Framework Convention on Climate Change and its implications on the ground. The public policies that will be discussed in this section call for national greenhouse gas inventories. The way by which these inventories are obtained is the focus of this thesis. Figure 1-1 shows a workflow diagram of both the current process leading to such inventories (left) and the process proposed in this thesis (right). Cost of data collection (time and money) in the workflow diagram is based on statements by Butnor *et al.* (2001, 2003, 2008).

Figure 1-1 Current and proposed workflow diagrams for national GHG inventories. A positive correlation between cost and time is assumed. Cost of data collection is represented by "*$*", where *$$$*>*$$*>*$*. Time required for data collection techniques (invasive vs. geophysical) is represented by "*t*", where *ttt*>*tt*>*t.* The relative area of the top three boxes represents the relative magnitudes of the data collection effort (cost and time).



1.2.1: The United Nations Framework Convention on Climate Change

To understand the framework of public policies around the world out of which current carbon inventory policies have developed one must begin with an understanding of the United Nations Framework Convention on Climate Change, hereafter referred to as the UNFCCC or the Convention (United Nations 2014a). The UNFCCC is an international treaty adopted by 195 countries since its conception in 1992 (United Nations 2014b). Each country that has adopted this treaty is hereafter known as a party to the Convention. Representatives of a varying subset of the parties regularly meet to discuss and revise the Convention. Each group of such representative is known as a Conference of Parties (CoP, United Nations 1992). The goal of this treaty is to consider what could be done to limit average global temperature increases and the resulting climate change and initiate action to do so (United Nations 2014a). The parties to the Convention concluded that a large part of what they could do was to reduce net emissions of greenhouse gases (GHGs) that were not already controlled by the earlier Montreal Protocol (United Nations 1992). The Convention states that such a level of reduction of net GHG emissions would need to be collectively or individually equal to 1990 levels (United Nations 1992). This chapter will focus on policy as it relates to the most abundant clearly anthropogenic GHG not controlled by the Montreal Protocol, carbon dioxide (UN Environmental Programme and UN Climate Change Secretariat 2002). In 1995, CO_2 made up over 80% of total anthropogenic GHG emissions from developed countries

(UN Environmental Programme and UN Climate Change Secretariat 2002). This thesis focuses on a terrestrial CO_2 sink: tree roots.

The language of the UNFCCC states the importance of terrestrial sinks and reservoirs of GHGs from the very start. The Convention further recognizes that addressing climate change will be most effective if actions are based on relevant and continuously re-evaluated scientific, technical and economic considerations (United Nations 1992). Article 4 of the UNFCCC outlines the commitments each party to the treaty shall make. The Convention calls for the development and publication of national anthropogenic GHG inventories: tabulations of human-caused GHG emissions into and removals from the atmosphere. In order to support the development of these inventories, the Convention calls for parties to the Convention to cooperatively engage in scientific and technical research in addition to the development of data archives related to the climate system (United Nations 1992). The present research calls for the further development and application of technologies capable of contributing to such data archives with improved subsurface tree root biomass estimations for use in national GHG inventories.

The Convention further states that calculations of emissions and removals of GHGs should take into account the best available scientific knowledge of the effective capacity of sinks (United Nations 1992). The methodologies used for these calculations are to be agreed upon and regularly evaluated by the CoP (United Nations 1992). In addition to regular CoP meetings, a subsidiary body for scientific and technological advice was also established by the Convention for reasons such as identifying innovative, efficient, and cutting edge technologies and know-how

(United Nations 1992). The subsidiary body also provides advice on relevant international research and capacity building in developing countries (United Nations 1992). This subsidiary body is, therefore, tasked with identifying ways to integrate novel research and technology into the methodologies used to attain compliance with the UNFCCC. Any new changes to existing methodologies need to go through this subsidiary body. The Convention was just the beginning of the UN's international political response to climate change. Each one of these ongoing evaluative meetings represents a chance to change the prevailing methodologies in favor of less labor-intensive ones. This research seeks to assess the utility of several novel non-invasive geophysical techniques to quantify tree root carbon via root biomass quantification.

1.2.2: The Kyoto Protocol

Within a few short years it became evident that the emissions reductions provisions in the UNFCCC were too weak. Despite stabilization in a few countries, global emissions were still on the rise. An answer was urgently needed to the question about what to do when the Convention target date was met in 2000. In 1997, the Kyoto Protocol (KP or "the Protocol") to the UNFCCC was adopted to strengthen the global response to climate change by including new and stronger commitments than those found in the UNFCCC initially (United Nations 2014a). The Protocol responded to the issue of rising continued emissions through targeting developed countries to lead the way (UN Environmental Programme and UN

Climate Change Secretariat 2002). Currently there are 195 parties to the UNFCCC and 192 to the Kyoto Protocol. The United States has signed but not ratified the Protocol, and Canada withdrew its ratification of the Protocol in 2012 (United Nations 2014a, 2014b). The Protocol sets legally binding targets and timetables for reduction in these countries' emissions (UN Environmental Programme and UN Climate Change Secretariat 2002). By nature of being legally binding, the Protocol increases the need for improved labor efficiency in estimating national GHG inventories. The geophysical methods discussed in this thesis may improve labor efficiency for part of these inventories: tree root biomass estimation. The Protocol not only made targets legally binding, but also affected different emissions targets.

Whereas the Convention obligated developed countries to reduce emissions once, the protocol took it one step further to obligate them to reduce their emissions by at least 5% collectively by the end of the first commitment period from 2008 to 2012 (UN Environmental Programme and UN Climate Change Secretariat 2002). Subsequent commitment periods entail steeper reductions. The Protocol additionally allowed for targets to be met through the enhancement of natural carbon sinks such as growing forests (UN Environmental Programme and UN Climate Change Secretariat 2002). Since the parties to the Protocol are legally bound to their emissions targets, measurement of emissions and reductions needed to be credible and verifiable. This need for credibility sets the stage for improving GHG estimations. Improving the data with which carbon reservoirs are estimated would increase credibility for these measurements. This thesis seeks to do so through the inclusion of geophysical techniques in tree root biomass estimation.

The Protocol does not stop by simply addressing developed countries. It recognizes our globalized world and encourages intergovernmental cooperation and coordination, especially in the form of facilitated technology transfer and cooperating on scientific and technical research. Targets, however, are assigned individually to each country or economic union of countries (namely, the European Union). Despite the individual targets, the Protocol allows for credit to be given for developed countries investing in cheaper emission cuts in developing countries through several mechanisms. These developing countries may offer many avenues for emissions reductions. Quantifying the emissions reductions in these developing countries through measuring actively growing tree root carbon reservoirs would be most relevant presently.

One such mechanism, known as Joint Implementation (JI), allows for credit for the financing of emissions reduction projects in developed countries. Another, the Clean Development Mechanism (CDM), allows for credit towards financing emissions reduction or emission avoidance programs in developing countries. Since developing countries do not have emissions targets, the CDM effectively raises the overall emissions cap. For this reason, the methodologies used to verify credits under JI and the CDM should be as accurate as possible and highly replicable (IPCC 2006a). An increase in the representativeness of the data on which these credits are based should help to increase accuracy. Using novel geophysical techniques to more efficiently collect data on tree root biomass would allow for more representative data.

The Protocol specifically allows for part of emissions targets to be met by increasing forest absorption of CO_2 from the atmosphere (UN Environmental Programme and UN Climate Change Secretariat 2002). All of the major carbon pools in forests of parties to the Protocol are therefore significant politically. This thesis seeks to evaluate novel methodologies for estimating tree root biomass for future application in GHG inventory reporting.

1.2.3: Reducing Emissions from Deforestation and Forest Degradation

This program, Reducing Emissions from Deforestation and Forest Degradation, is typically referred to as REDD+. The plus indicates the later addition of activities seeking sustainable management of forests and the conservation of and enhancement of forest carbon stocks (UN-REDD Programme Secretariat 2013). Since the Kyoto Protocol went into effect, developed country signatories of the treaty have been legally bound to quantified emission limitation and reduction commitments (QELROs). In 2008 the UN launched another program under the UNFCCC to help mitigate GHG emissions in developing countries around the world. The REDD+ program seeks its objective through a rewards-based system of positive incentives, as opposed to just punitive systems, which impose harsh fines for noncompliance (UN-REDD Programme Secretariat 2013). This program brings the attention of the developing world to enhancing carbon reservoirs through enhancing their forests. Novel methods which allow for the more extensive sampling of tree root extent, ergo carbon reserves, should be desirable by the developing countries participating in such programs.

The REDD+ program consists of three phases in order to decrease barriers to entry into the program. In the first phase, REDD+ Readiness, a country develops and defines its own national REDD+ strategy. This strategy includes plans for national forest inventories and national-scale GHG inventories of forest emissions and removals (UN-REDD Programme Secretariat 2013). Phase two, REDD+ Readiness part two, is the demonstration phase of the methods selected in phase 1. Forest inventories should be established and operating during this phase. The goals of this phase is to assure that the methods and plans selected in phase 1 actually produce their desired results and to continue in capacity building for full implementation of each nation's REDD+ plan, policies, and measures (UN-REDD Programme Secretariat 2013). Phase three is the final phase, "National Implementation." Once entered into this phase, a country's national monitoring system should extend all the way to the country's borders so that the outcomes of policies and measures may be determined for individual regions as well as the country as a whole (UN-REDD Programme Secretariat 2013). Perhaps most importantly, Phase 3 marks the entrance into force of monitoring and reporting for GHG inventories. This entrance into force allows for the availability of tree root data for both domestic (potentially biased) and international (non-biased) professionals to analyze the effectiveness of different policies and measures (UN-REDD Programme Secretariat 2013). By this third phase data concerning tree root carbon content becomes available for analysis. Quickly replicating portions of these massive data reserves in the field with geophysical and geoelectrical methods may allow for excellent validation of these emerging technologies for tree root biomass measurement.

1.2.4: The European Union's Emissions Trading System

The Europe Union (EU) has obligations under the Kyoto Protocol which led to the creation of the first international cap-and-trade system to limit GHG emissions (Cooper 2010). This cap-and-trade-system, the EU Emissions Trading System (ETS), is now largest and longest running international emissions cap-and-trade system (United Nations 2014c). The system limits emissions from high-emitting industry sectors with a cap which is reduced each year. Companies can buy and sell emission allowances as needed in a free market system similar to a stock market. This approach allows for the flexibility of the free market to drive down emissions reduction costs (European Union 2013). If companies do not use all of their emissions credits, they may save them for the following year instead of selling them. Additionally, limited emissions credits from international emissions reduction projects are available for purchase. If a company fails to surrender adequate emission allowances for its emissions that year, heavy fines are imposed (United Nations 2014c). This regulatory structure of the ETS allows for the flexibility of a free-market system and forces a price on emissions, bringing entire sectors of the European economy into alignment with the EU goal of reducing anthropogenic GHG emissions (United Nations 2014c).

The ETS covers roughly 45% of EU GHG emissions, focusing on the major centralized contributors since they may be measured with the highest degree of accuracy (United Nations 2014c). Unfortunately, the EU had expressed reservations (as of 2010) about any credits arising from projects involving forestry and land-use changes (Cooper 2010). Currently no REDD+ programs may be used to meet emissions allowances under the ETS. Despite this stringency, the EU has allowed for the use of JI and the CDM from the Kyoto Protocol in meeting emissions caps (European Commission 2014). Though unlikely, the EU may eventually allow forestry and REDD+ programs into the ETS once improvements in forestry data representativeness have been made. The geophysical and geoelectrical data collection methods discussed in this thesis may allow for such increased representativeness.

1.2.5: The United Nations International Panel on Climate Change

The United Nations Intergovernmental Panel on Climate Change (IPCC) determines the methodologies behind all of the UNFCCC GHG emissions and removals programs (IPCC 2003). In this way, the IPCC decisions on methodologies impact the Convention, the Kyoto Protocol, the Joint Implementation mechanism, the Clean Development Mechanism, REDD+, and the ETS**.** The IPCC recommended in 2003 that regional forest biomass carbon be estimated with allometric relationships using measured forest volumes from forest inventory data (IPCC 2003).

The IPCC outlines three approaches in estimating forest carbon stocks (IPCC 2006a). These approaches are referred to as tiers. Tier 1 methods are the easiest to use, yet they rely on the most spatially coarse data (IPCC 2006b). For Tier 2 methods important emission and stock change factors are specific to each country or region, spatial and temporal resolution is higher, and activity data is disaggregated. These differences allow Tier 2 methods to more accurately estimate greenhouse gas inventories than Tier 1 methods (IPCC 2006b). Neither Tier 1 nor Tier 2 inventories will be relevant to this research, however, since belowground carbon dynamics are not considered under them (IPCC 2006b).

Tier 3 methods, on the other hand, account for belowground biomass. The high-resolution data that drives Tier 3 models is also disaggregated to multiple data points within a country (IPCC 2006b). Tier 3 measurement protocols and models are tailored to each country's specific circumstances, allowing for more accurate and precise estimates than with lower tiers (IPCC 2006b). Generally Tier 3 methods rely on some combination of climatic factors, regular and comprehensive field sampling, GIS-based monitoring, and disaggregated livestock census data (IPCC 2006b). Using regular and comprehensive field sampling along with GIS-based monitoring allows for the integration of data that may be used to locate potential sites for the application of geophysical and geoelectrical tree root measurement methods. Such data includes as stand age, production, soil, land-use, and management activity data (IPCC 2006b). Tier 3 methods clearly provide the best estimates of greenhouse gas inventories. The labor and data intensity required by this method, however, preclude its use where resources are less available. Improving Tier 3 forest carbon estimations would have a ripple effect down the tiers as better data would be available to calibrate the larger scale regional models on which the lower tiers rely. This improvement may be attained in part through application of the emerging geophysical and geoelectrical techniques discussed in this thesis to the measurement of tree root biomass for use in greenhouse gas inventories at all tiers.

This research is restricted from funding for field data collection. Without financial support the hypothesis that *large scale application of geophysical and geoelectrical techniques will allow for cost-effective improvements in the accuracy of forest inventory data for tree roots* cannot be properly tested. In light of this limitation, the final two chapters of this thesis will explain the theoretical basis of two promising geophysical and geoelectrical methods (Chapter 2) and assess their relevant applications to national GHG inventories (Chapter 3).

Chapter 2

Theoretical basis for methods available to measure tree roots

2.1: Measuring tree roots

The aim of the present research is to assess the strengths, weaknesses, and integrative opportunities of two newly emerged non-invasive root measurement techniques for their applicability in measuring belowground tree root carbon content for GHG inventories. This chapter lays the theoretical foundation for the function of these two techniques: ground penetrating radar (section 2.3) and electrical resistivity tomography (section 2.4). First, necessary background information tying tree root metrics to GHG inventories will be discussed (section 2.1) along with a brief overview of common invasive techniques used in measuring tree roots (section 2.2).

2.1.1: Tree root biomass and carbon

In the context of greenhouse gas inventories, biomass measurements may be used to estimate carbon content, which in turn converts easily into tonnes of CO_2 removed from the atmosphere. The conversion between tree root biomass and carbon content is a simple manner of multiplication by a species-specific biomass carbon density. Thus, the conversion from biomass to CO_2 removals from the atmosphere follows Equation 2-1, where R_{CO_2} is the CO_2 removed from the atmosphere represented in the biomass measured (tonnes), B_M is the measured biomass (tonnes), D_C is the carbon density of the species measured ($\frac{tonnes\ carbon}{tonnes\ biomass}$), and 44/12 is the ratio of the molecular mass of CO_2 to that of C. Values for D_C are widely available in the scientific literature or may be obtained destructively.

Equation 2-1: $R_{CO_2} = B_M * D_C * (44/12)$

Biomass estimations may be used along with knowledge of carbon density to estimate tree root carbon content. Therefore, the ability to determine root biomass allows for the easy determination of the amount of carbon stored in the roots of interest with simple carbon density data. Since the UN programs described in Chapter 1 are structured to consider carbon storage as equivalent to emissions reductions (except in the ETS), there is an abundance of international demand for fast and accurate carbon storage estimations for the dozens of national greenhouse gas inventories produced under UNFCCC obligations. Since growing trees store carbon as they accrue biomass, they are often used in such inventories as emissions offsets. The widespread availability of root biomass data is, therefore, crucial to the long-term success of carbon emission reduction programs such as the UN REDD+ (UN-REDD Programme Secretariat 2013).

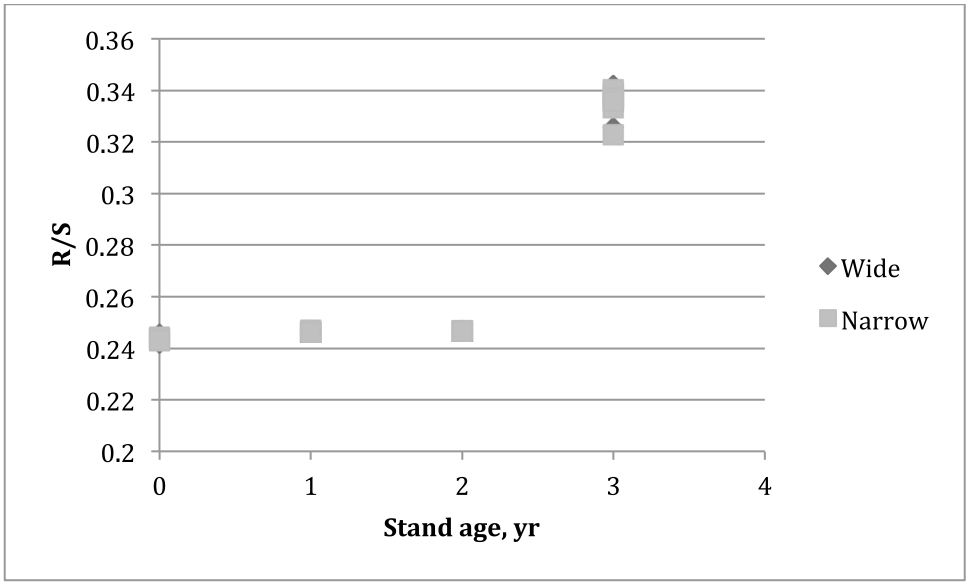
Geophysical techniques show promise in the realm of refining allometric models used in national GHG inventories. Accounting for species and site-specific factors in allometric models may be achieved by geophysical techniques after first calibrating geophysical measurements with destructive sampling. These factors include such properties as root-to-shoot ratios, fine-to-coarse root ratios, and root depth distributions. Each of these factors will be covered in its own subsection.

2.1.2: Root-to-shoot ratios

Applying allometric relationships such as root-to-shoot ratios (R/S), collected in extensive data tables, are an important way much of national GHG inventories are tabulated (IPCC 2006b). Geophysical measurements, once calibrated, may allow for a much more robust database on which to base these R/S ratios, in theory allowing for more accurate GHG inventories. R/S ratios vary extensively based on factors such as stand development, climate, and forest type (Luo *et al.* 2012).

Stand development can have a significant impact on R/S ratios. Interpreting data from Aspinwall *et al*. (2011) showed that R/S ratios varied markedly even in the first few years of a juvenile loblolly pine (*P. taeda*) stand (Figure 2-1). Between years 2 and 3, the R/S ratio jumped by about 37%. Different spacing treatments did not affect R/S ratios noticeably, likely due to the fact that the stand was so early in development.

Figure 2-1: *P. taeda* juvenile R/S ratios as a function of stand age plotted. Data extracted from Aspinwall *et al.* (2011) based on measurements from 160 different trees.



Although the trend shown by the data points in Figure 2-1 would predict a positive correlation between R/S and stand age past age 2, Wang *et al.* (2008) have concluded a negative one exists when expanding the time scale in the temperate and boreal forests of northeast China. Wang *et al.* (2008) also found that proxies for stand age such as shoot biomass, height, and volume showed the same trend.

Climate also has a large role in influencing R/S ratios. In dry climates (mean annual precipitation less than 1000 mm), Schenck and Jackson (2002b) found that tree R/S ratios decreased with increasing potential evapotranspiration. This finding goes against the conventional wisdom that root allocation (R/S ratio) increases with decreasing water supply. On the other hand, Wang *et al.* (2008) found that in the temperate and boreal forests of northeast China R/S ratios indeed increase with decreasing water supply.

Forest type influences R/S ratios as well. Wang *et al*. (2008) found that R/S ratios differed significantly between tree taxa (broadleaf vs. coniferous forests) and more significantly between forest origins (natural vs. planted/plantation). Luo *et al.* (2012) found similar results with greater R/S ratios for broadleaf versus coniferous forests and greater R/S ratios for natural versus planted forests.

Overall, many factors can influence R/S ratios. This variability underscores the importance of good site-specific data for biomass estimations. Using well-calibrated geophysical measurements to broaden the foundation of data on which national GHG inventories rely may help to efficiently account for the above factors and many more.

2.1.3: Fine-to-coarse root ratios

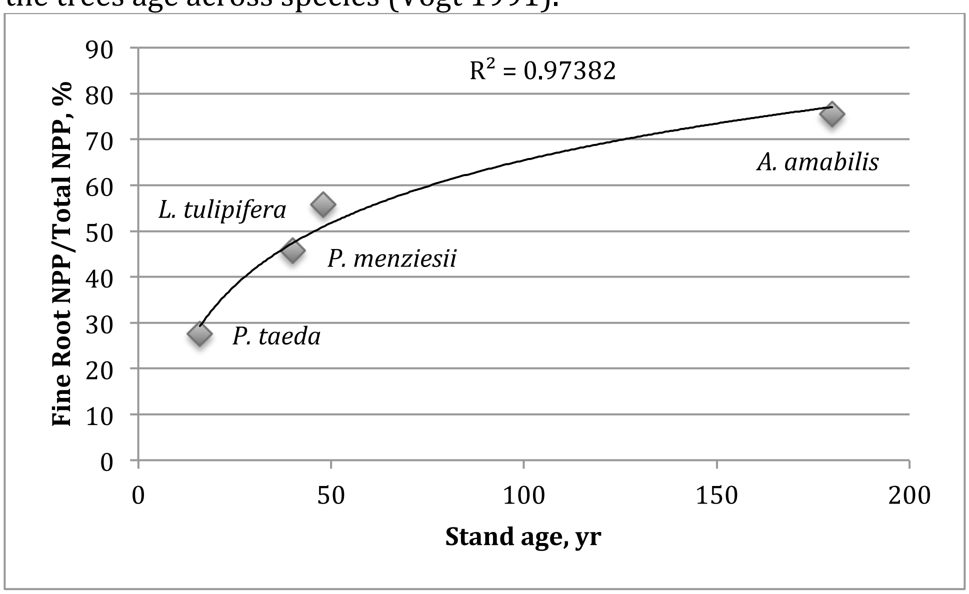
Fine roots are an important component of the biomass in tree root systems. When pine, fir, spruce, and hardwoods have been considered, fine roots have made up as little as 2% of a plant's living belowground biomass or as much as 17% of it (Vogt 1991). Fine roots can be even more significant when annual measures such as net primary productivity (NPP) are considered. Table 2-1, adapted from Vogt (1991), shows several pieces of data relating to the relative abundance of fine roots.

Table 2-1: This table shows data on biomass and productivity for four different tree species at four different sites. The data was taken directly from Vogt (1991, Table 13).

	P. taeda	*P. menziesii*	*A. amabilis*	*L. tulipifera*
Stand age, yr	16	40	180	48
Fine root NPP/ fine root biomass, %	23	67	77	118
Belowground: NPP/biomass, %	51	5	9	24
Fine root NPP/total NPP, %	27.6	45.7	75.5	55.8

Interpreting this data (Vogt 1991) shows that fine root biomass can more than double from year to year (*L. tulipifera* fine root NPP/fine root biomass = 118%). This data (Vogt 1991) also shows that fine roots may account for anywhere from roughly 25% (27.6%) to 75% (75.5%) of total NPP for a tree. This trend appears to correlate positively with stand age for this data: A tree's fine root NPP makes up an increasingly large portion of that tree's total NPP as the tree ages. This relationship is shown in Figure 2-2.

Figure 2-2: Fine root NPP makes up an increasing proportion of total tree NPP as the trees age across species (Vogt 1991).



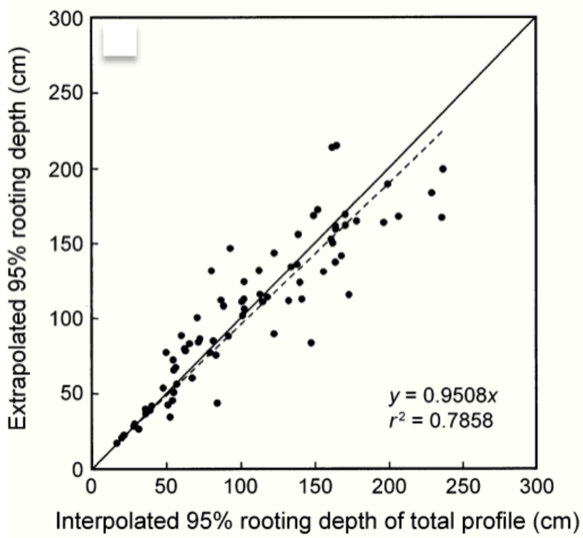
This trend is sensible, as its woody biomass would be expected to make up a decreasing proportion of its NPP as that tree ages and reaches mature dimensions. Other data not shown here from Vogt (1991, Table 13) indicate a similar increasing importance of belowground NPP versus aboveground NPP. Other studies (Gower *et al*. 1996), however, show no correlation between measured NPP of fine roots and total root carbon allocation across species, but a strong one within species. Total root carbon allocation includes fungal mycorrhizae in addition to fine and coarse root production, respiration, and exudates (Gower *et al*. 1996). These varying findings underscore the importance of determining coarse versus fine root relationships for measuring root biomass. Currently the IPCC suggests that fine roots of less than 2mm diameter be excluded from national GHG inventories because they often cannot be distinguished empirically from soil organic matter or litter (IPCC 2006b).

2.1.4: Root depth distributions

Root depth distributions are an important factor when estimating forest carbon stocks. Since the depth of investigation often falls short of the maximum rooting depth, even with cutting edge geophysical techniques (Mancuso 2012), understanding how a root biomass changes with depth under specific site conditions is a necessity to providing accurate biomass estimations for national GHG inventories.

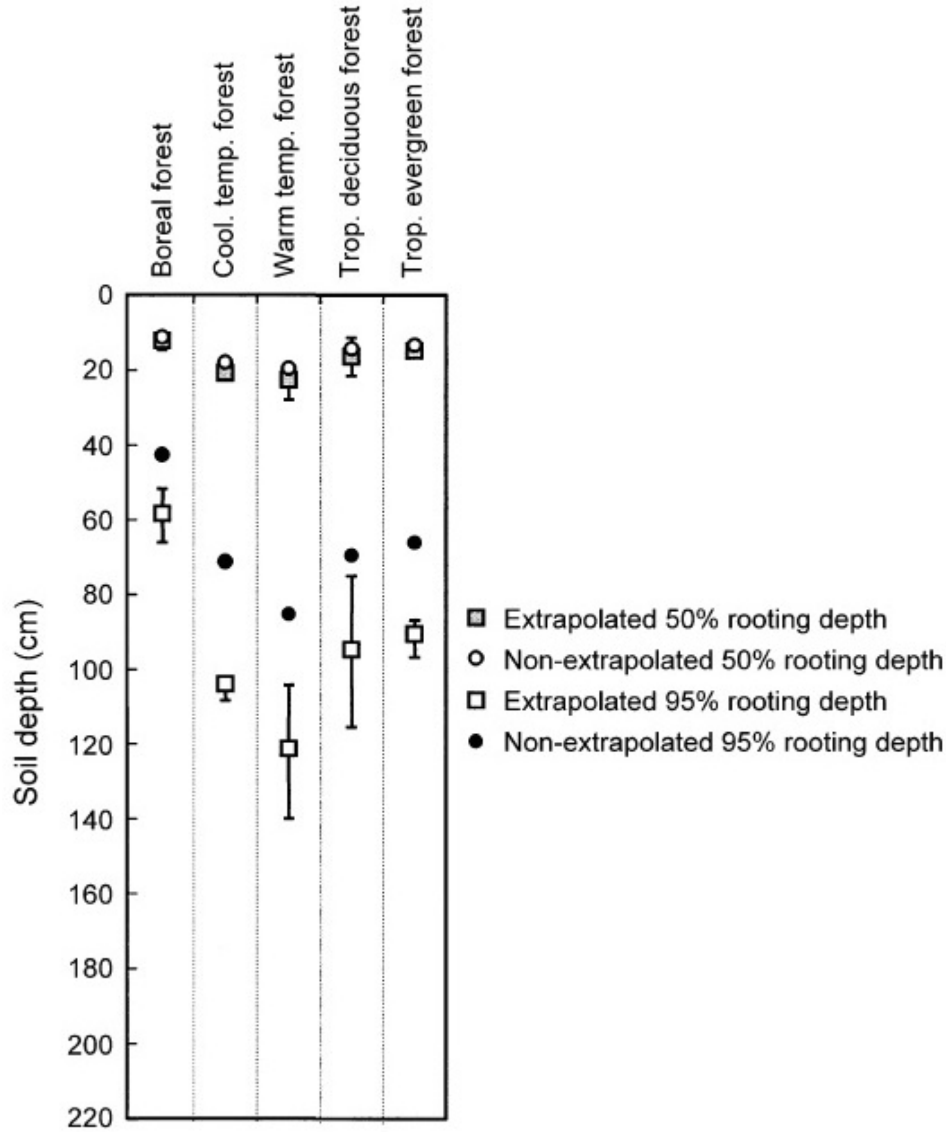
Schenck and Jackson (2002b.) investigated a global dataset of measurements for over 1300 plants. They found a mean tree rooting depth of about 3m (geometric) to 6m (arithmetic), but an astonishing range from less than 1m to 58m! This phenomenal range highlights the need to understand the change in biomass with rooting depth. Geophysical techniques such as GPR have been shown to only function well to about 30 cm depth (at a common frequency of 1.5GHz, Butnor *et al*. 2003), and destructive root measurements for calibrations do not reach these depths (Butnor *et al*. 2005). A study using 475 root profiles from 209 geographic locations found that over 90% of all root profiles had at least half of their roots in the upper 30cm of soil (Schenck and Jackson 2002a). This finding implies that shallow measurements may be of utility when estimating root biomass so long as biomass extrapolations accurately reflect samples taken at depth. Figure 2-3 shows a comparison of extrapolated 95% rooting depth from measurements in the upper 1m of soil versus interpolated 95% rooting depth from root samples taken in intervals down to the maximum rooting depth (Schenck and Jackson 2002a). The results show a significant correlation ($r=0.7806$, $P<0.00001$, $df=75$) interpolated 95% rooting depth and 95% rooting depth extrapolated from measurements in the upper 1m of the SRM.

Figure 2-3: Extrapolated 95% rooting depth (cm) versus Interpolated 95% rooting depth of total profile (cm). Uses 76 completely sampled profiles to reduce percent error of mean rooting depth below 5% (Schenck and Jackson 2002a).



Another way to parse the data is to distinguish between the validity of extrapolating 95% rooting depths versus 50% rooting depths. In order to assess tree root biomass, the depth is irrelevant except as it applies to biomass concentration. Since the zone from the soil surface to the 50% rooting depth contains 50% of the biomass, measuring root biomass to the 50% rooting depth and extrapolating should allow for accurate root biomass estimations. Figure 2-4 shows the accuracy of extrapolated versus non-extrapolated (i.e., measured at discrete depth intervals) 50% and 95% rooting depths.

Figure 2-4: Extrapolated and non-extrapolated rooting depths (50% and 95%) by biome. Error bars show 95% confidence intervals. This figure was edited from Schenck and Jackson (2002a) to remove extraneous information.



Since all of the extrapolated 50% rooting depth 95% confidence intervals contain the non-extrapolated 50% rooting depth values, one may conclude that measuring to the 50% rooting depth is an acceptably accurate method for determining total tree root biomass. The issue is, therefore, ascertaining the 50% rooting depth in the first place. Ascertaining the 50% rooting depth can be done by either searching the scientific literature or taking one's own measurements at various depths. Generally these measurements must go down to the 95% rooting depth, and the data gaps between measurements must be interpolated to calculate the 50% rooting depth. This second method yields what is referred to above as the “non-extrapolated” or “interpolated” 50% rooting depth. Once the 50% rooting depth has been established, a measurement protocol must be established using techniques appropriate for the site and measurement depth at hand.

2.2: Common invasive tree root measuring techniques

Several different techniques exist with the aim of ascertaining belowground root biomass and structure within the soil root matrix (SRM). Data sampling may be done in several manners. The most prominent historical techniques are invasive and destructive. Invasive data sampling entails disturbing the root zone in order to take data samples. Invasive sampling may be either destructive or non-destructive.

Destructive methods include trenching, coring, root profiling, and using in-growth cores. These methods are typically quite expensive in terms of time, money, and resources, thus difficult to replicate extensively in both spatial and temporal terms. Destructive methods do have several benefits, however. They allow for the measurement of nearly all of the roots in a sample, of large sample densities to great depths, and of seasonal variation. Coring even allows for increased sampling intensity spatially and temporally (Keith 2000).

Invasive non-destructive sampling involves the use of root windows, mini-rhizotrons, stable isotopes, and respiration. These methods tend to be relatively inexpensive and easily replicated spatially and temporally. They also allow for the estimation of root productivity and phenology. They are not perfect, however. In order to estimate biomass, they require careful calibration that can be costly. Additionally, they do not allow for either the distinction between plant species or measurements of more than a few meters in depth. Perhaps the biggest problems with root windows and mini-rhizotrons in particular is their ability to bias the data by providing a different root environment - one with drastically increased light exposure and preferential pathways for water penetration (Mancuso 2012).

There are several non-invasive techniques for root detection and quantification: labeling methods such as radio and stable isotope techniques, sap flow approaches, and geophysical and geoelectrical techniques. Geophysical and geoelectrical techniques include ground penetrating radar (GPR), electrical resistivity tomography (ERT), the electrical capacitance method, electrical impedance tomography, and seismic refraction tomography (Hagrey 2007). The present research focuses on one geophysical technique, GPR, and one geoelectrical technique, ERT. These two techniques show the most promise for measuring tree roots for national GHG inventories. The present chapter provides a theoretical basis for these technologies. Chapter 3 includes information about the relative strengths, weaknesses, and future potential of these technologies. With the further development of these geophysical and geoelectrical technologies, invasive and destructive sampling for root quantification may one day only be necessary in small-scale calibration procedures.

2.3 Emerging geophysical and geoelectrical techniques

These emerging geophysical and geoelectrical techniques, namely GPR (Hruška *et al*. 1999) and ERT (Amato *et al*. 2008), have been developed as non-invasive, non-destructive, and easily scalable alternatives to current techniques. Data analysis, measurement protocols, and sampling techniques have improved dramatically for these techniques since their conception for measuring tree roots (Butnor *et al*. 2008, Cui *et al*. 2010, Amato *et al*. 2008). These techniques may minimize the need for the current invasive and destructive techniques of tree root measurement after the establishment of species and site-specific calibrations have been made.

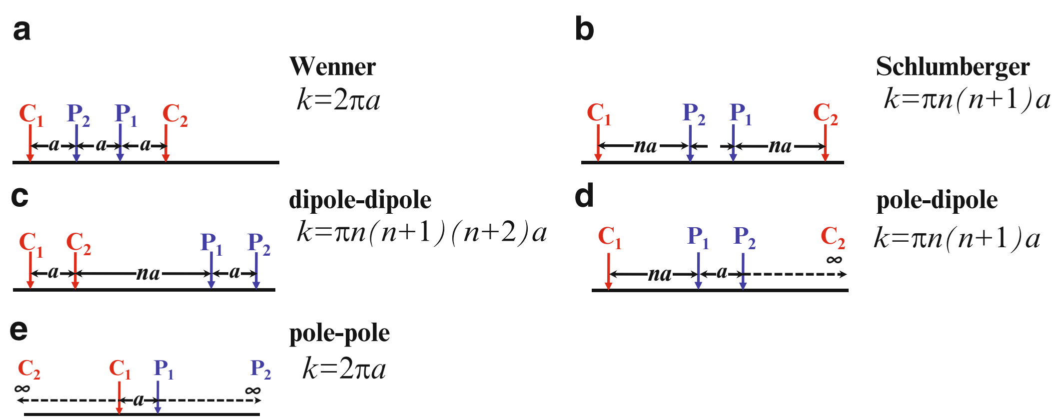
2.3.1 Electrical resistivity tomography

Electrical resistivity tomography (ERT) is capable of detecting roots in the unsaturated zone. ERT uses direct current and any multiple of four (4n) electrodes inserted into the earth. To simplify the setup conceptually, a 4-electrode system (n=1) is described here (Amato *et al*. 2008). The current is applied between two of the electrodes at a time, the current electrodes. The remaining two electrodes are the potential electrodes, and they measure the resulting potential difference, the voltage. This voltage information (ΔU, volts), the measurement of the current applied (I, amperes), and a geometric factor related to the chosen electrode configuration (k) are used to calculate the resulting apparent electrical resistivity (ρ_a, Ωm) according to Equation 2-2 (Hagrey 2007 and Amato *et al*. 2008).

Equation 2-2: $\rho_a = k\,(\frac{\Delta U}{I})$

The apparent resistivity is measured as opposed to the true resistivity due to the inevitable heterogeneity of real world subsurface measurements. True resistivity measurements necessitate a homogeneous subsurface. The true resistivity is independent of electrode configuration, but the apparent resistivity is not. This dependence on electrode configuration necessitates the aforementioned geometric factor *k*. The most common five arrays are shown in Figure 2-5 along with their associated *k* values (Mancuso 2012).

Figure 2-5: The various 2D electrode arrays commonly used for ERT. "C" electrodes are current generating electrodes, and "P" electrodes measure potential differences. Different values for "k" are shown for different arrays based on the electrode configuration. The "a-spacing" or "α-spacing" is the inter-electrode spacing (Mancuso 2012, Figure 10.5).



These different configurations each provide their own strengths and weaknesses (Table 2-2).

Table 2-2: This table is taken directly from *Measuring Roots* (Mancuso 2012). Pertinent characteristics are rated for the five most common 2D arrays. The variables α, n, and k are the same as those presented in Figure 2-5.

Parameter	Wenner	Schlum-berger	Dipole–dipole	Pole–dipole	Pole–pole
Sensitivity for lateral structures	***	***	**	***	**
Sensitivity for vertical structures	*	**	****	**	**
lateral data coverage (data density)	*	**	***	***	****
Lateral resolution (decrease with depth)	**	***	****	***	*
Depth of investigation (DOI)	**	***	*	***	****
Signal strength, directly proportional to $1/k$ or to →	**** (1/ɑ)	*** ($1/n^2$)	* ($1/n^3$)	*** ($1/n^2$)	*** (1/ɑ)
Suitability for multichannel acquisition	*	**	****	****	**

The parameter quality is classified form least (*) to highest (****), k = geometry factor

For the Wenner Array, Figure 2-5a and Table 2-2 column 2, the a-spacing is increased continuously by the same increment to sound for deeper and deeper structures. This unsurpassed sensitivity of this configuration for resolving vertical changes and superior signal strength make it very useful for resolving lateral structures in field surveys with high background noise (Mancuso 2012). For the Schlumberger array (Figure 2-5b and Table 2-2 column 3) application involves placing the two potential electrodes very close together and gradually increasing a-spacing between the current electrodes by integer multiples of a. This array has a focused pattern of sensitivity beneath the center of the array, making it a good choice for vertical sounding. The dipole-dipole array (Figure 2-5c and Table 2-2 column 4) is applied by keeping the a-spacing small initially and increasing the spacing between the pair of potential electrodes and current electrodes by integer multiples of *a*, up to no more than 6*a* due to low signal strength. Low signal strength limits the depth of investigation. This array is very good at mapping vertical structures, thus very good for use in multichannel measurements. The pole-dipole array (Figure 2-5d and Table 2-2 column 5) uses an asymmetric setup with the potential electrodes placed a distance *a* apart and one current electrode on each side of this pair. One current electrode is far away, and the other is a distance *a* away, increased incrementally by an integer *n* multiple of *a*. The good horizontal coverage of this array makes it an effective choice for areas of difficult accessibility. The asymmetric nature of this array, however, necessitates additional reverse measurements in order to prevent skewed data. The final array covered is the pole-pole array (Figure 2-5e and Table 2-2 column 6). This array uses a tightly spaced current and potential electrode with like adjacent electrodes farther away. The pole-pole array has the poorest resolution, but the small electrode spacing and great horizontal coverage and depth of investigation make it a great candidate for multichannel 3D systems (Mancuso 2012).

The 1D arrays are those that make the assumption that the subsurface is homogeneous. These arrays must be applied in 2D when measuring roots within soil, which is by definition a heterogeneous system (Mancuso 2012). Two-dimensional systems consist primarily of two methods: lateral electrical profiling (LEP) and continuous vertical electrical sounding (CVES). LEP, as suggested by its name, describes a lateral cross section of the soil-root matrix at a constant depth. Hardware and software advances currently allow lateral mapping of large areas with this technique, up to 10 hectares per day in open fields. For these highly efficient LEP surveys, mobile platforms are used such as Multi-Depth Continuous Electrical Profiling (MUCEP) and Pulled Array Continuous Electrical Profiling (PACEP). MUCEP uses a tractor to pull four axles connected to pairs of electrode wheels (Mancuso 2012). This system is too bulky for use in forest measurement. PACEP uses a linear array of electrodes which each alternate between acting as current and potential electrodes. This configuration allows for measurement in tight spaces, such as in a tree plantation. At any given time, one pair of electrodes acts as the current electrodes and the remaining pairs as the potential electrodes. The variable spacing between the potential electrode pairs allows for measurement at multiple depths (Mancuso 2012). The primary alternative to a LEP 2D survey is a CVES 2D survey. This system uses a string of electrodes. The a-spacing between electrodes is adjusted by choice of electrode pairs, requiring most electrodes to be used at different times as both current and potential electrodes. For an example using the Wenner Array with N electrodes, one may chose an initial minimal spacing, using a numerical designation of electrode 1 for the first electrode and electrode N for the last electrode in the array. Electrodes 1 through 4 would initially be designated as $1C_1$, $2P_1$, $3P_2$, and $4C_2$. Next would be $2C_1$, $3P_1$, $4P_2$, $5C_2$, and so on until $(N-3)C_1$, $(N-2)P_1$, $(N-1)P_2$, and $(N)C_2$. Next the spacing would be doubled: $1C_1$, $3P_1$, $5P_2$, $7C_2$, and the pattern repeats. This pattern results in a total of $[(N-1)(N-2)]/6$ data points, forming an inverted triangular cross section of data points with the deepest measurement consisting of a single point (Mancuso 2012).

2.3.2 Ground penetrating radar

Hruška *et al*. (1999) first used ground penetrating radar (GPR) in 1999 as a non-invasive, non-destructive, less labor intensive, and more replicable alternative to traditional root excavation. After 14 years of data processing refinements and under suitable site conditions, GPR estimates both coarse root diameter and biomass within acceptable error limits (Guo *et al*. 2013).

Subsurface root detection using GPR relies on detecting changes dielectric permittivity in the shallow subsurface. Dielectric permittivity is a measurement of the resistance encountered when forming an electromagnetic (EM) field in a substrate. A simple conceptual view of this experimental setup is shown (Figure 2-6; Hruška *et al*. 1999). A GPR system typically consists of at least two antennae, a transmitting antenna and a receiving antenna, a control unit/computer, and a monitor. The transmitting antenna emits an EM wave at a specific frequency within the radar spectrum into the ground. When this wave encounters a substrate with different EM properties than those of the adjacent substrate, mainly a different dielectric permittivity, a fraction of the energy is reflected back to the surface. The receiving antenna detects the intensity and return time of this reflected energy at a specific frequency (Guo *et al*. 2013). The raw GPR data corresponds to relevant root size and location (Figure 2-7).

Figure 2-6: This figure, taken from Hruška *et al*. (1999), shows a simple conceptual view of a GPR setup in the field.

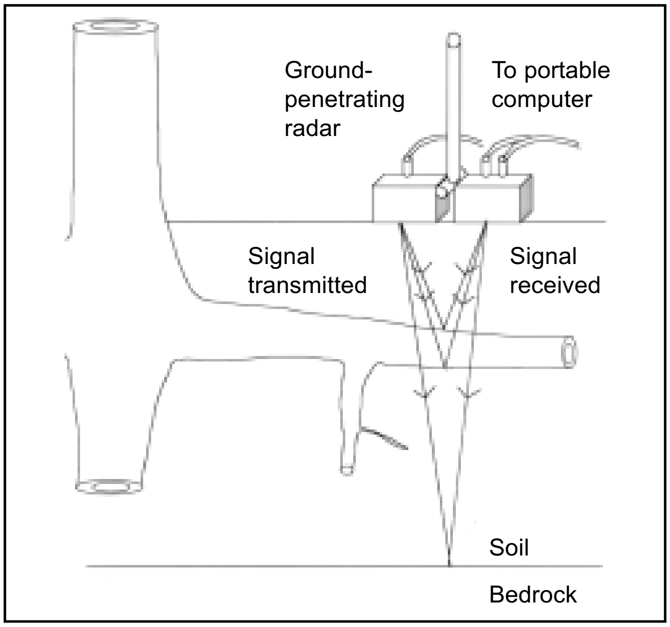
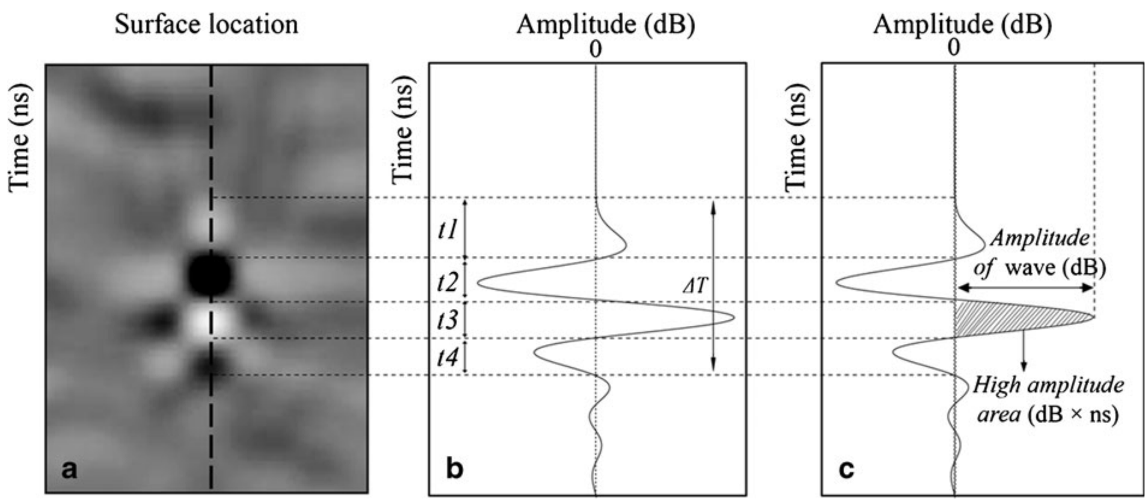


Figure 2-7: Raw GPR raster data represents the measured amplitude (dB) and reflection time (t, ns) of the reflected radar waves. From amplitude and time one may judge the size and depth of the root reflectors, and lateral spacing (left to right moving of the vertical dotted line) gives a third dimension to the data (Guo *et al*. 2013).

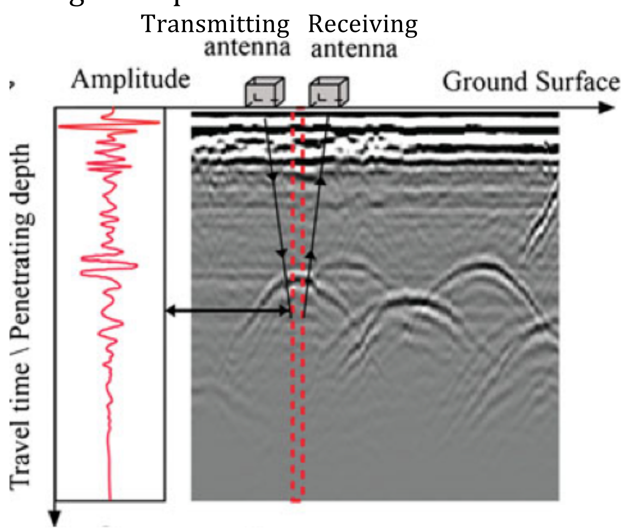


These reflections continue until a depth is reached where the energy has been effectively attenuated, meaning the reflected energy remaining becomes too small in magnitude to detect over the background noise (Guo *et al*. 2013). This attenuation results in penetration depth limitations specific to the antenna frequency used as well as the electrical conductivity and attenuation of the soils. Electrical conductivity is a measure of the ability of a substrate to conduct EM energy. Attenuation is a measure of the loss of intensity of a flux through a substrate. Decreased penetration depths are associated with higher frequencies, higher σ, and much higher α. Penetration depths can range anywhere from upwards of 15m to a mere few centimeters depending on these three parameters (Mancuso 2012). Given knowledge of the frequency of the EM wave and several properties of the substrate (soil) such as magnetic permeability (μ) and dielectric permittivity (ε) an EM pulse velocity (V) can be calculated according to Equation 2-3 (Guo *et al*. 2013).

Equation 2-3: $V = \frac{1}{\sqrt{\mu\varepsilon}}$

A depth to the point of reflection may be calculated using this velocity and the associated time measurements collected by the receiving antenna. The data that this measurement produces, with the travel time or penetrating depth on the (vertical) z-axis and waveform amplitude of the return signal on the x'-axis, is referred to as an A-scan (Figure 2-8, Guo *et al*. 2013). Since the A-scan alone does not indicate the x-y arrangement of roots, the GPR technique relies also on moving the two antennae along a horizontal trajectory at a fixed speed determined by the researcher (Mancuso 2012). This technique produces a B-scan, a scan in the x and z dimensions. In this manner, an x dimension can be accounted for in each pass, and data from successive parallel passes incrementally produce a y dimension. Amplitude data, the bases of biomass estimates, are obtained coincidentally. In other words, aggregated closely spaced parallel B-scans produce a three-dimensional signal of the root structure and include amplitude data. Detection of coarse roots is strongest when the roots of interest are perpendicular to the GPR unit trajectory. Roots show up as apices of hyperbolas on the parallel B-scans (Figure 2-8). These roots may be mapped roughly using aggregated parallel B-scans scans (Guo *et al*. 2013).

Figure 2-8: The resulting A scan (left) from a single point GPR scan. The 2D section (right), known as the B scan, is the result of moving the antennae and transmitter along a line path on the surface while scanning (Guo *et al*. 2013).



2.4: Conclusions on geophysical methods

Ground penetrating radar and electrical resistivity tomography offer a promising glimpse into the future of subsurface root measurement. Though each of these technologies presents limitations, their integration results in a surprisingly robust tool kit for measuring root and root systems in the SRM in a cost-effective manner. Integrating these techniques would allow for measurements across many soil conditions. Water content of the SRM is a factor that necessitates measurement protocol decisions. GPR falls short in detecting roots in wet soils, and ERT tends to do well. These two techniques use continuous data collection, which allows for efficient sweeps of large tracts of land. Using these techniques for tree root measurement would therefore be easily scalable due to the efficiency with which data is collected relative to merely applying invasive and destructive techniques. This tradeoff implies that areas of extremely wet soil or extremely dry soil will not allow simultaneous use of both techniques. For assessment of tree root biomass using ERT, limited equipment configurations such as PACEP, which fits easily between gaps in flora, would be necessitated (Mancuso 2012).

Overall, successful non-invasive root measurement stems from a thorough understanding of each technique's strengths and weaknesses as well as supporting research regarding allometric ratios and site-specific conditions. These techniques have grown by leaps and bounds over the last decade with respect to root measurement. The integration of GPR with ERT for the purpose of measuring root biomass is a very promising up and coming area of research. These two techniques will likely replace the majority of current invasive and destructive techniques of digging and measuring under amenable site conditions. Future research should be aimed at establishing more species-specific allometric relationships and at refining data analysis procedures, measurement protocols, and sampling techniques. With the further development of these and others in the suite of geophysical technologies currently available, invasive and destructive techniques of root detection and quantification may only be necessary in small-scale calibration procedures in the years to come.

Chapter 3

Opportunities for improving national greenhouse gas inventories through the application of emerging geophysical and geoelectrical techniques

3.1: Introduction

The utility of each method for measuring tree root biomass for application in national GHG inventories will be assessed as available peer-reviewed research allows. The flow chart presented in Figure 1-1 shows the logical basis for including non-invasive geophysical data collection to augment destructive sampling (Butnor *et al*. 2001) in assessing tree root carbon content.

3.2: Ground penetrating radar

Ground penetrating radar (GPR) data is analyzed to produce a numerical index with which to compare destructively sampled biomass measurements. Many factors can influence results of correlation analysis between GPR indices and tree root biomass. These factors, presented in Table 3-1, may be broadly grouped into three categories: site selection factors, experimental design factors, and data post-processing factors. The following subsections address these broadly grouped factors in turn.

Table 3-1: Factors influencing correlation between GPR indices and tree root biomass along with the ideal state of each factor. Broadly based on the information presented in Butnor *et al*. 2001, 2003, 2005, and 2008.

Broadly grouped factors	Specific factors	Ideal
Site selection	Tree species	Homogenous
	Stand age	Homogenous
	Undesirables in SRM (dead roots, organic matter, air pockets)	Not present/minimal
	Soil conditions (texture, moisture, drainage)	Sandy, dry, well-drained
	Surface litter/debris	Free of surface debris
	Root depth distribution	Concentrated in upper 30cm (for 1.5GHz)
Experimental Design	GPR frequency	1.5 GHz typically
	Choice of plot layout	Account for SRM variability
	Cores vs. pits	Inconclusive
Post-collection processing	Background removal	Yes, perform one.
	Horizontal distance normalization	Yes, perform one.
	Hilbert transformation	Yes, perform one.
	Kirchoff migration	Yes, perform one.
	GPR index: Pixel intensity or hyperbolic area?	Pixel intensity
	Correlate GPR index to individual core samples or average over multiple samples?	Average

3.2.1: Site selection

GPR site selection is perhaps the most important step in obtaining quality data. Without the proper site for GPR measurements, no amount of rigor in experimental design and post-collection data processing will be able to produce meaningful correlations between GPR indices and tree root biomass. GPR necessitates a resistive soil medium (i.e., sandy, dry, and well-drained) in order to discriminate soil from more conductive roots (Butnor *et al*. 2003). Undesirable soil elements such as dead organic matter (old roots) and air pockets (animal tunnels) also degrade data quality (Butnor *et al*. 2005). For obvious reasons tree monocultures of homogenous age structure allow for quicker calibration procedures and for GPR measurements to make larger-scale estimates. Furthermore, surface contact between the soil and the GPR unit was shown to be important by Butnor *et al*. (2005). Thick litter layers had the effect of de-focusing the antenna and reducing the ability to detect roots (Butnor *et al*. 2005). Raking away the surface litter before measurement mitigates these ill effects (Butnor *et al*. 2005). Root depth distribution, as discussed in section 2.1.4, should be shallow enough to allow for quality GPR data to the 50% rooting depth. The effective penetration depth of GPR depends on frequencies and soil conditions and is discussed in the next subsection. A detailed site survey should be conducted to ensure GPR's effectiveness before any experimental data is gathered (Butnor *et al*. 2008).

3.2.2: Experimental design

The choice of GPR frequency is the first consideration when designing an experiment. Low frequencies cited in the literature are typically either 500MHz or 900MHz (Cui *et al*. 2012, Mancuso 2012). The advantages of lower frequencies include improved data quality under varied soil moisture conditions, and increased penetration depth up to 2m (Cui *et al*. 2012). Unfortunately, however, signal frequency correlates negatively with minimum root size detection (Mancuso 2012). Higher frequencies such as 2GHz (Cui *et al*. 2012) or 1.5 GHz (the most commonly used, Butnor *et al*. 2001, 2003, 2005, 2008, Stover *et al*. 2007) detect finer roots down to 0.5cm but require more uniformly low soil moisture and penetrate less deeply (Cui *et al*. 2012). For example, Butnor *et al*. (2003) found that a 1.5GHz frequency allows for the best root discrimination, but good data was only obtainable down to 30cm depth.

Choice of plot layout will vary according to soil conditions and 50% rooting depth as discussed above. If the 50% rooting depth necessitates low frequency measurements, plots with higher and more variable moisture content may be chosen than those using higher frequency measurements (Cui *et al*. 2012). The core versus pit issue will be discussed in the following sub-section.

3.2.3: Post collection processing

Post collection processing is applied to radar data in order to reduce clutter and minimize the effects of multiple hyperbolic reflections (Butnor *et al*. 2003). Several post-collection processing steps are nearly universally agreed upon for assessing tree root biomass with GPR: background removal, horizontal distance normalization, Hilbert transformation, and Kirchoff migration (Butnor *et al*. 2001, 2003, 2005, 2008, Stover *et al*. 2007, Cui *et al*. 2012, and Mancuso 2012). Each will be briefly discussed.

Background removal removes parallel bands that represent unwanted plane reflectors such as soil layers as opposed to the desirable hyperbolic reflectors such as roots (Butnor *et al*. 2008). Horizontal distance normalization is a step that converts the GPR scan from units of time versus intensity into units of distance versus intensity based on the GPR unit's trajectory and speed (Butnor *et al*. 2001). The geometry of the path a radar signal travels can create extra hyperbolas from a single point reflector and skew perceived root location. Kirchoff migrations remove this effect from the data (Butnor *et al*. 2008). Hilbert transformations allow for subtle discontinuities to be detected by creating a mathematical relationship capable of obtaining signal phase data from intensity values (Butnor *et al*. 2008). Typically after these steps, the amplitude of the signal is converted into a pixelated grey-scale image, and an intensity threshold is applied to focus on detectable root sizes (Butnor *et al*. 2008). Hyperbolic area is not typically used in place of pixel intensity since it requires tighter grid spacing in order to for the radar wave to detect roots near the requisite 90 degrees (Butnor *et al*. 2005).

In order to address statistical post collection processing choices, correlation coefficients between GPR and coarse root biomass data are presented for temperate *Pinus taeda* plantations (Figures 3-1 and 3-2).

Figure 3-1: *Pinus taeda* r^2 values between coarse root biomass (from individual core samples) and GPR indices (extracted from a larger scan for each core location). Data is plotted by data publication year with a linear regression. Data from Guo *et al*. 2013 concerning Butnor *et al*. 2001, 2003, 2005, 2008, and Samuelson *et al*. 2008.

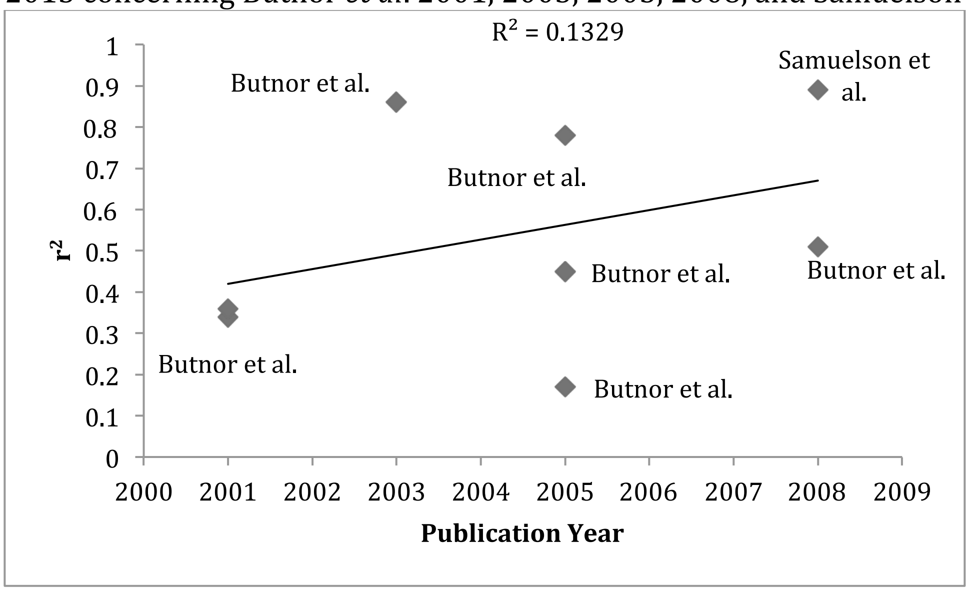
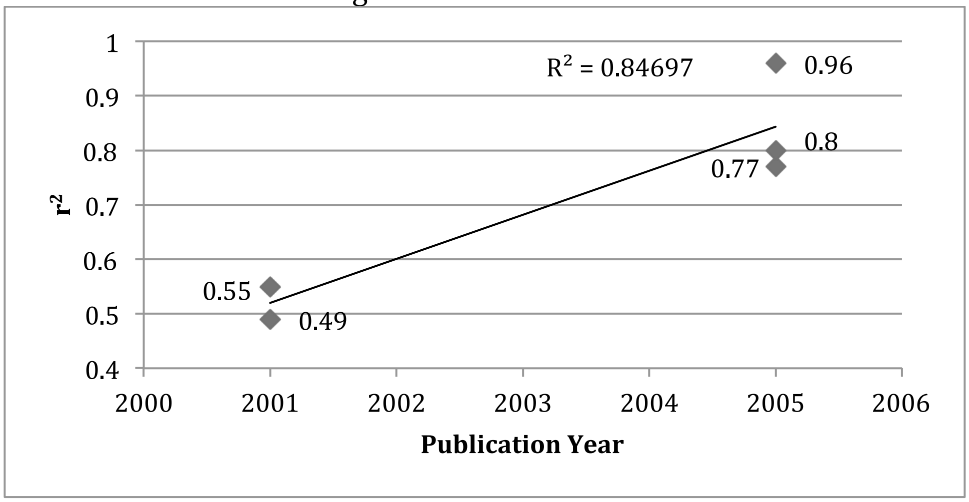


Figure 3-2: *Pinus taeda* r^2 between coarse root biomass (averaged from core samples by plot) and GPR indices (extracted from larger scan by plot and averaged). Values for r^2 are plotted by data publication year with a linear regression. Data from Guo *et al*. 2013 concerning Butnor *et al*. 2001 and 2005.



These figures suggest that GPR measurements have been improving in accuracy since their conception in 1999 with regard to tree root biomass estimation. Although the trend is not statistically significant when individual measurements are used (Figure 3-1, P=0.375, r=0.3646, df=7), the trend strengthens considerably in significance when plot averages for GPR measurements and biomass measurements are compared (Figure 3-2, P=0.0797, r=0.9203, df=4). This finding implicates a problem with accurately determining which portion of the GPR data corresponds precisely to each soil core as discussed by Butnor *et al*. (2005). Butnor *et al*. (2005) found similar results within their 2005 study reporting an improvement from P=0.181 (r=0.1749, df=59) to P=0.169 (r=0.9651, df=3) when grouped averages were used rather than individual core measurements. Butnor *et al*. (2005) assumed the poor correlation of GPR index with individual core measurements was due to inaccuracies in the horizontal distance normalization. As such, they tried a pit (20cm by 100cm by 30cm) instead of a core (15cm diameter by 30cm), increasing the volume of the sample by a factor of roughly 11. They were not able to find good data from scaling up the sample, thus the core versus pit issue remains inconclusive. The air knife used to remove the soil from the pits likely removed much of the root and dead organic matter, and wet soil conditions decreased root reflectivity (Butnor *et al*. 2005).

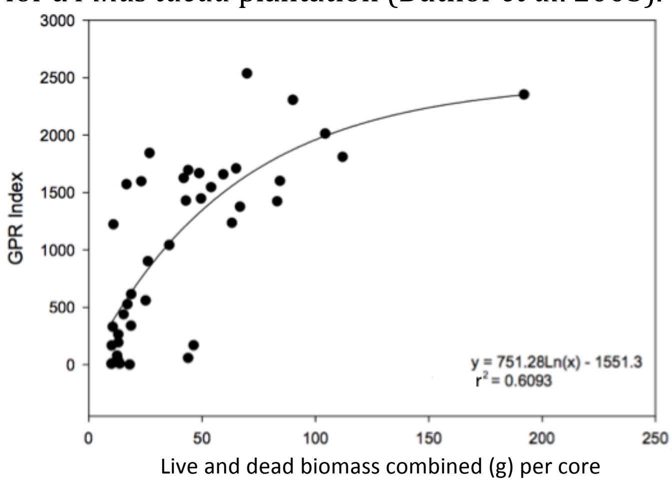
Figures 3-1 and 3-2 fail to explain why this improvement has taken place. The soil conditions for Butnor *et al*. (2005) were highly variable in moisture and the SRM was high in undesirables (dead roots and air pockets). Without a detailed site survey, which would have suggested choosing a different site or using a lower GPR frequency to allow for the moisture variability, Butnor *et al*. (2005) ran into unexpectedly poor results (Figure 3-1) relative to their previous study (Butnor *et al*. 2003) at a more suitable site. The averaging by plot done for Figure 3-2 decreases the impact of individual core variability, thus returning more significant r values.

3.2.4: Ground penetrating radar conclusions

The effectiveness of GPR under such whole plot monoculture conditions makes GPR an appealing candidate for use in GHG inventories. GPR appears to more accurately estimate biomass when averaged over a larger land area than at the individual tree scale. This result may likely be due to the fact that GPR theory (Guo *et al*. 2013) suggests that the technique is incapable of distinguishing between the intermingled root systems that occur with closely neighboring trees. Results from

Butnor *et al*. (2005) indicate a much stronger relationship (Figure 3-3, $P<0.00001$, $r=0.7806$, $df=39$) between GPR index and root biomass measurements when taken at the individual core level than those from several studies represented in Figure 3-1 ($P=0.375$). This result is likely due to the fact that dead biomass is included in Figure 3-3, giving empirical evidence of GPR's known inability to discriminate between live and dead biomass with similar magnetic permeability (see section 2.3.2). GPR performs much better in pine plantations with less dead belowground biomass (Butnor *et al*. 2005).

Figure 3-3: GPR indices plotted versus individual core total (live + dead) biomass for a *Pinus taeda* plantation (Butnor *et al*. 2005).



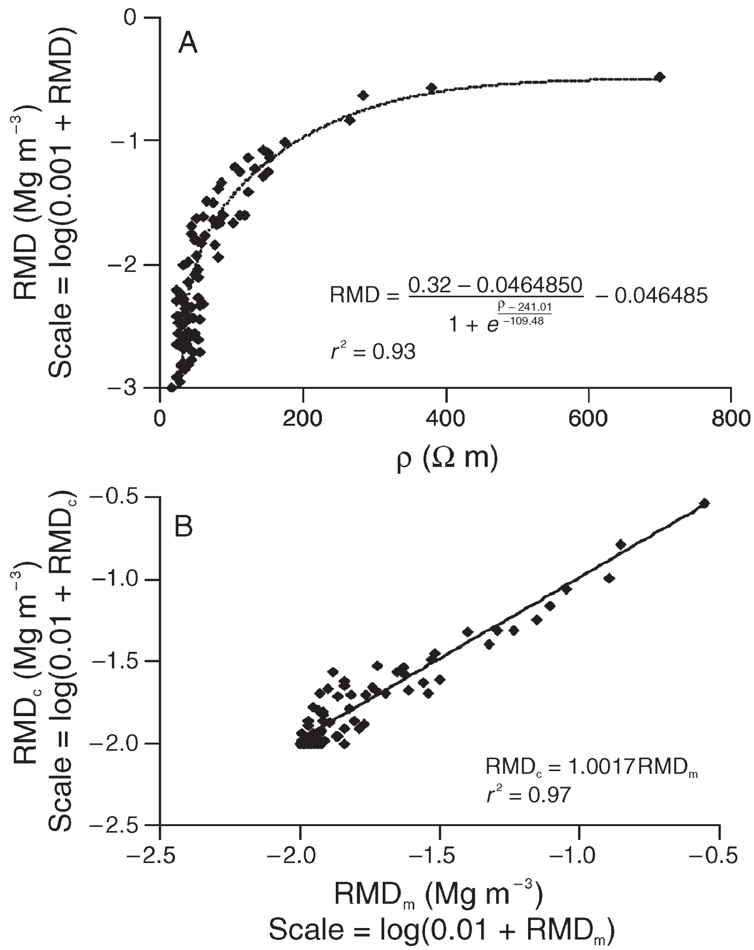
Several physical limitations exist when using this GPR. First, this technique only works well under certain conditions. Well-drained and electrically resistive soils allow for the best data. Also, the technique tends to discriminate towards detecting coarser roots. Second and as a corollary, choosing a particular radar frequency involves a detection trade-off. Higher frequencies detect finer roots as well as coarse ones but only penetrate to a shallow depth. Lower frequencies can detect coarse roots at a greater depth but lack the resolution to detect finer roots.

For these first two reasons, use of multiple GPR frequencies, complementary techniques, and/or allometric relationships between coarse and fine roots for a given species in a given environment would be helpful to maximize root detection using GPR. Third, data processing steps, thus root detections, vary from study to study despite the baseline protocol established by Stover *et al*. (2007). This problem becomes especially apparent when scientists attempt to use GPR data to model 3D root systems. Unified data processing software for distinguishing root reflectors and aggregating parallel scans into 3D maps would greatly improve the quality of the GPR root research field (Guo *et al*. 2013). The unification of this hypothetical software would allow for effective comparisons between studies. Additionally, making this software open-access and crowd-sourced would allow for an inclusive and continually evolving program to perpetuate and accelerate the progress being made with data processing using this technique. Fourth, this technique currently relies on statistical relationships between physical root characteristics and GPR data. Development of conceptual mathematic models linking the root characteristics to the signal intensity would increase the accuracy of this method (Guo *et al*. 2013). Fifth and most importantly, this technique has shortcomings that may not be entirely overcome by improvements such as those suggested in this section (Guo *et al*. 2013). For this reason, complementing the GPR technique with additional non-invasive techniques such as ERT will be essential to providing the most comprehensive picture of subsurface root systems.

3.3: Electrical resistivity tomography

Since ground penetrating radar cannot detect the vertically oriented taproot (Amato *et al*. 2008) and coarse roots below a frequency-dependent size threshold (Guo *et al*. 2012), ERT offers several advantages over GPR for tree root biomass measurement. Although *Pinus* data for ERT is not available in the scientific literature, electrical resistivity tomography has been shown to be highly successful in measuring soil dry root mass density (RMD) with other species. Since RMD is simply the mass of roots per unit volume of the SRM sample, conversion to root biomass for consistency with GPR discussion is straightforward. Regressing RMD measured to 1.1m against soil resistivity has revealed a highly significant logistic relationship confirmed with two separate datasets (n=97 and n=67; Amato *et al*. 2008). This finding shows that soil resistivity is quantitatively related to belowground tree root biomass (Amato *et al*. 2008). Figure 3-4 shows data produced using a 48-electrode Wenner array in an *Alnus glutinosa* stand in sandy loam soil (Amato *et al*. 2008).

Figure 3-4: Figure A shows RMD strongly correlates to soil resistivity. Figure B shows that destructively measured RMD values (RMD_m) strongly correlate with calculated ones based on soil resistivity (RMD_c; Amato *et al*. 2008).



Rossi *et al*. (2011) evaluated ERT for tree root measurement with a similar 48-electrode array in a mixed citrus and olive orchard (*Citrus sinensis L*. var. *navelina isa 315* and *Citrus limon L*. and *Olea europaea L.* var. *Coratina*). The stand age structure was homogenous (22 years old), and the soil was a loam. They also found strong correlations between RMD measurements and soil resistivity. The Pearson's correlation coefficient between coarse roots and resistivity was r=0.967 (P<0.01), and the value for all roots correlated with resistivity was r=0.963

($P<0.01$), both extremely significant values. The correlation was not significant, however, between resistivity and fine root biomass for both this dataset (citrus and olive, $r=0.027$, $P=0.887$) and Amato *et al*. 2008 (alder). Overall, ERT offers a promising compliment to GPR where conditions allow and alternative to GPR where conditions favor ERT.

Electrical resistivity tomography has several limitations as well. Distinct layers of different thicknesses within the soil root matrix (SRM) may produce an identical signal when the product of their thickness and resistivity is equal (Mancuso 2012). Due to this multiplicative nature of the signal, very thin layers must have extremely high or low resistivity values to be detected. Additionally, a layer within the SRM must be almost twice as thick as the layer above it in order to resolve its resistivity and thickness independently (Mancuso 2012). Highly conductive soils reduce current penetration due to a flow concentration in the upper soil horizon. Highly resistive soils also reduce current penetration (Mancuso 2012). Finally, problems arise when using techniques such as PACEP, which alternates individual electrode between usage as current electrodes and potential electrodes. Current electrodes may polarize, especially in saturated soils, as charges build up around them. These charged electrodes will skew data when they are subsequently used as potential electrodes if not given sufficient time, often minutes, to depolarize (Mancuso 2012).

3.4: Conclusion

Ground penetrating radar and electrical resistivity tomography have differing strengths and weaknesses with respect to tree root biomass measurement for national GHG inventories (Table 3-2).

Table 3-2: Strengths and weaknesses of GPR and ERT with respect to tree root measurement for national GHG inventories.

	GPR		ERT	
	Strength	**Weakness**	**Strength**	**Weakness**
Soil texture	Sandy	Clayey	Loamy	Sandy, Clayey
Soil moisture	Minimal	Wet, heterogeneous (for high frequencies)	Moderate, High AND low at different times	Saturated or dry without multiple measurements
Soil resistance	High resistance	Low resistance	Moderate resistance	High or low resistance
SRM contents	Detects live roots	Detects air gaps and intact dead roots	Detects all coarse roots	Fine roots with high resistivity can look like coarse roots with low resistivity
Root size	Coarse roots	Fine roots	Coarse roots	Fine roots
Root orientation	Horizontal	Vertical (tap root)	All	None
(Unique)	Plot averaged GPR index vs. biomass	Root size/depth detection tradeoff with frequency	Detects all coarse roots in upper 1m of SRM	Electrode polarization in saturated conditions
Scalability	Excellent		Excellent	

Neither of these techniques are ubiquitously useful, but together they make up a toolkit that could save a lot of time, therefore money, in assessing carbon stocks from the belowground portion of trees which otherwise are only dug up sparingly to calibrate allometric models. GPR has been shown to work best when averaged over large areas well-drained monocultures such as the sandy *Pinus* plantations which are common in the southeastern United States (Butnor *et al*. 2001, 2003, 2005). ERT works best under moderate moisture conditions (Amato *et al*. 2008) and when one is able to compare measurements from dry and wet conditions since roots cause a local increase in resistivity when the soil is moist (Zenone *et al*. 2008). Zenone *et al*. (2008) propose an integration of GPR with ERT when measuring root biomass since data from each technique, along with technical knowledge of the theory underpinning each technique, can help to create physics-based data filters to remove the excess of noise to which each of these methods may fall prey.

The labor-efficient scalability of GPR and ERT in addition to their individual strengths makes both techniques appealing candidates for use in UNFCCC and KP national GHG inventories for measuring tree root biomass. These novel techniques should have a place especially in REDD+ forest inventories in developing countries. Indeed any entity required to report forest root carbon stock changes may benefit from the strengths of GPR and ERT. The increase in speed and ease of deployment of measurements made using these techniques together should allow for more extensive allometric model calibrations due to the decreased cost density of data from these surface geophysical and geoelectrical methods. Since these allometric models provide the data foundation for a major part of Tier 3 national greenhouse gas inventories (IPCC 2006b) with respect to Land Use, Land Use Change, and Forestry activities as well as for REDD+ reporting, improving the ease of acquisition for the data upon which these models are based could greatly increase the representativeness of these models without sacrificing excessive resources as would be necessary in accomplishing the same goal with destructive techniques.

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