TRACKING TEMPORAL CHANGES OF MOISTURE CONTENT IN SOUTHERN YELLOW PINES USING TIME-DOMAIN REFLECTOMETERY

by

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(Under the Direction of Laurence R. Schimleck)

ABSTRACT

Moisture storage in living trees is fundamental to tree health and poorly understood due to the destructive nature of most sampling methods. Low cost systems that continuously monitor moisture content (MC) of standing trees are required. Time-domain reflectometry (TDR) was explored as an option to monitor moisture content (MC) of standing trees. TDR data was collected from 10 *Pinus elliottii* Engelm. (slash pine) and 10 *Pinus taeda* L. (loblolly pine) trees on the Lower Coastal Plain and 10 *P. taeda* from the Piedmont on a weekly basis for one year. Site specific calibrations were used to predict MC, but owing to a pronounced wound response it was not possible to accurately track changes in whole-tree MC with time. If calibrations more oriented toward living trees can be obtained I believe TDR could be used to monitor temporal changes in standing tree MC.

INDEX WORDS: Time-domain reflectometry, TDR, moisture content, dielectric constant, water usage

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DEDICATION

I dedicate this thesis to the people in my life who were instrumental in the accomplishment of this work. First I would like to thank my family. My father John Gerald White Jr. who gave me perspective when this work seemed insurmountable, my mother Carolyn White who is the yardstick by which I measure the world, and my brother John Gerald White III for whose council I seek when choices seem too immense to undertake alone. Secondly, I would like to thank my thesis committee without whom my future would be less prosperous. Thank you Dr. Schimleck, your foresight was the difference between a higher degree and uncertainty, thank you Dr. Coder, your enthusiasm fostered a dedication toward outreach in natural resources; and thank you Dr. Daniels whose encouragement to “know what’s knowable” will be an everlasting part of life. Lastly I want to thank my loving wife Sheri Lynn White who entered my life like a strong wind and set my sail toward adventure ever since. You are my whole world.

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CHAPTER 1

INTRODUCTION

Understanding how water is stored in wood is fundamental to our understanding of tree health and wood use. Many characteristics of wood are strongly related to moisture content (MC). Wood products physical dimensions, stability, resistance to fungal activity and weight is highly affected by MC. In living trees vitality and health are influenced by the plant’s ability to store and transport water. In forestry log transport costs are highly correlated to MC. A better appreciation of the MC of standing trees could assist in understanding how trees respond to stress and seasonal changes. Unfortunately there are limitations to our ability to accurately measure MC in standing trees without destructive sampling.

Despite the relative importance of MC to a wide variety of wood properties and tree health, options for field measurements of MC are extremely limited. These limitations are especially pronounced if the researcher wishes to collect MC data without serious injury to the tree. This makes long term monitoring of individual living trees difficult in most cases.

The two most common methods of determining moisture content in wood are the oven dry method and electronic resistance-based meters. The oven dry method is accurate but time consuming as a sample must have all water removed, which for a large sample can take greater than 24 hours. Typically this is done either by using a core, disk or wood shavings. Taking a disk allows for sampling at several heights but requires the tree be felled making it impossible to track changes in moisture content with time. By using a core or wood shavings trees can be revisited for multiple readings but several problems arise. First, the same location cannot be sampled twice. Second, the practice of collecting samples causes damage to the tree which may compromise its health by increasing the possibility of insect attack or introduction of disease. Third, small samples may not be representative of actual moisture content of the tree as water is often lost due to heat or pressure while removing the sample and small samples can dry out quickly once removed from the tree. Electronic resistance meters are less damaging but are only accurate between 6% and 30% MC, far below typical known MC of living pine species (Shmulsky and Jones 2011), and only give a measure of moisture content in the outer most rings of sapwood.

Moisture content of living trees has been evaluated in the past through destructive sampling. Patterson and Doruska (2005) examined 183 *Pinus taeda* L. trees in eight locations across the Southeastern United States. Sampling was done by felling 6 trees at each of eight locations and taking bolts at butt, mid-point, and at a three inch top. Their study investigated bulk density, specific gravity (SG) and MC changes over the course of one year. Their work indicated within a tree MC increases with increasing height and the average difference among all seasons between the butt and top of the tree was 51.7%. They also found specific gravity remained stable throughout the year but MC varied by season. Seasonal MC differences were modest with highest average MC (including all three height levels) in the Spring of 130.0% followed by the Fall at 121.0%, Summer at 120.6% and finally the Winter at 120.3%. Each height level showed different activity during the seasons, average butt MC was the same in Fall and Spring (101% and 102% respectively) and lower in Winter and Summer (95% and 97%). Mid-point averages for MC were the same for Fall, Winter, and Spring (120%, 124%, and 125% MC respectively) and lower in Summer (110%). The top by comparison was statistically not different in Spring and Summer (163% and 155%) and lowest in Fall and Winter (both at 142%).

The variability between height and season indicates a need to establish a specific place along the stem most representative of whole tree MC.

Differences in MC with height can be related to changes in SG within trees. SG tends to decrease with height in *P. taeda*. This decrease in SG means the lower density wood (which has thin cell walls and large lumens) is able to hold more water and therefore attain a higher MC. Regional changes in SG (Jordan *et al.* 2008), related to a longer growing season for the South Atlantic Coastal Plain and the Gulf Coastal Plain cause differences in the ratio of earlywood and latewood can also explain changes in MC between regions as a result of different SG.

Antony *et al.* (2012) examined MC variation with tree height with the aim of establishing the best location on the stem to estimate whole-tree MC. Their study also found MC increased with height (as was observed by Patterson and Doruska 2005) and established a sampling height of 25% total tree height gave the best representation of whole tree MC. Antony *et al.* (2012) examined over 400 *P. taeda* trees across the Southeastern United States using destructive sampling and showed MC changed not only with height but also with geography and diameter. Trees were sampled from six different physiographic regions across the native range of *P. taeda* and differences in average MC and SG were observed. Geographically most regions fell into two groups with the South Atlantic Coastal Plain and the Gulf Coastal Plain being statistically the same for both SG and MC as were the North Atlantic Coastal Plain, Upper Coastal Plain, and the Piedmont. The Hilly Coastal Plain displayed average SG similar to what was seen in the North Atlantic Coastal Plain group and MC similar to the South Atlantic Coastal Plain set. This study indicates whole-tree MC increases moving away from the coast toward the Piedmont within the range of *P. taeda* because of the change in SG.

Typically when properties of wood need to be evaluated within living trees, destructive sampling is utilized, by felling a small number of trees from a defined sampling area. Alternatively several methods potentially exist for estimation of moisture in standing trees. One approach which has shown promise is Gamma-ray attenuation (Edwards and Jarvis 1983) but it requires use of a radioactive source and heavily shielded equipment making its use impractical. Another option is computer tomography using ultrasound (Raschi *et al.* 1995), which has been used to create a density map of trees in cross-section and then infer moisture content from density data. Computer tomography shows promise in tracking MC over time but the equipment is cumbersome and requires extensive set-up for every reading making it impractical for use on more than one tree at a time. Nuclear magnetic resonance has also been used on wood with success (Merela *et al.* 2009), but the equipment necessary is far too large to monitor living trees in the forest. Another option is near infrared (NIR) spectroscopy; however this method only provides surface measurements of MC and probes for collecting NIR spectra are large and have to be inserted into the tree through holes bored for this purpose. These holes can become pathways for insects and disease, and because of the resinous defenses of pines the same location could not be accurately measured multiple times without re-drilling the hole.

The use of the time domain reflectometry (TDR) to track moisture content changes in trees and logs has been reported by several authors. While its application to wood is fairly recent it has several advantages over other methods for measuring the MC of standing trees including its relative portability, potential for limited damage while collecting readings, and it’s proven use in the fields of soil science and telecommunications. Soil scientists have been utilizing TDR for some time (Ledieu *et al.* 1986) to monitor soil moisture. While in the telecommunications field it has long been used to detect faults in cables. TDR works by sending an electromagnetic pulse through a substance (usually a wire) and measuring the time it takes for the pulse to reach a fault and return (Pettinelli *et al*. 2002). TDR measurements are based on the dielectric constant (k) of a given material; when the pulse enters a substance with a different k part of the pulse is reflected creating a waveform that can be read from an oscilloscope display (read as a distance to the point the pulse entered a medium having a different k, i.e. the apparent fault). This principle can be applied to wood. By reading a predetermined point on the waveform it is possible to determine an apparent length to compare with known wood moisture contents collected in a calibration study. Because the dielectric constant of water (k_{water} = 80) is much higher than that of wood (k_{wood} = 2) the apparent distance to the predetermined point on the waveform will decrease as the moisture content decreases and more of the pulse is reflected back to the TDR and not carried into the wood by the high k of the water . This method allows probes to be installed in trees and left for the entire experiment without damaging the wood (which can affect the rate of dehydration) while providing estimates over the entire moisture content range.

Typically this data is collected using two stainless steel probes, inserted into the wood at a predetermined depth and distance apart. The probe is attached to a coaxial cable that connects to the TDR. More recently probes have been built that allow the pin length to be changed as desired (Schimleck *et al.* 2011). The probes consist of the same stainless steel rods, brazed to the metal shielding and the copper center of coaxial cable, then embedded in a cast resin block. This gives the probes greater durability and weather resistance and reduces the risk of probes bending that could lead to inaccurate readings. These attributes make them better suited for work in the field where atmospheric moisture could cause unforeseen problems in metal rods exposed to the open air.

Ever since TDR technology was adapted for use in the measurement of soil MC it has been hypothesized that this same process could work in wood. Constantz and Murphy (1990) examined the feasibility of using TDR to estimate MC in wood. Their study utilized stainless steel rods inserted into a variety of tree species (*Quercus agrifolia* Nèe, *Quercus lobata* Nèe, *Eucalyptus* spp., *Sequoia sempervirens* (D. Don) Endl., *Pinus radiata* D. Don, and *Aesculus californica* (Spach) Nutt.) to test the feasibility of TDR for MC determinations. They determined equations established for MC in soils were not accurate where high levels of organic material were present and new equations had to be developed for organic substances like wood. Second, wood has a significant level of variability along the radial axis. For an estimation procedure to be meaningful it must take into account differences in sapwood and heartwood. It was also noted in their findings that this will fluctuate between species, individuals and height (Constantz and Murphy 1990).

Constantz and Murphy (1990) found that changes in volumetric MC could be observed in a variety of tree species using TDR and TDR may be a useful tool for tracking changes in moisture over time. They also discussed the relationship between temperature and k_{wood} and preformed an experiment to demonstrate the effect of temperature on k_{wood}. They found that above freezing TDR performed without a significant change in readings, but when the log or wood sample froze the change in k_{wood} was severe enough to nullify the ability of TDR to measure MC. They chose to use stainless steel rods attached to coaxial cable as probes for their samples but did not discuss the shape of the TDR curve or the point on the curve they recorded. Constantz and Murphy (1990) focused on the relationship between a measured dielectric constant (which may have been more easily collected with the equipment they utilized) and the volumetric moisture content of the wood. They theorized that species specific calibration curves would allow for more accurate predictions.

Holbrook *et al.* (1992) utilized TDR on arborescent palms and found it was superior to the oscillating circuit method (similar to TDR). The oscillating circuit method utilized a parallel-plate capacitor that sandwiched a portion of the stem. While they found the oscillating circuit method was not damaging to the material it was more sensitive to changes in temperature and was more difficult to calibrate.

Because of the difficulties proposed by Constantz and Murphy (1990) regarding variability of MC along the radial axis of a tree, Irvine and Grace (1997) investigated the possibility of using shorter probes to minimize variability. By utilizing shorter probes (20 mm instead of the traditional 50 mm), issues like heartwood could more easily avoided. Irvine and Grace (1997) compared rods of 50 mm and 20 mm length in *Pinus sylvestris* L. (Scots pine) in order to estimate volumetric MC, and found the shorter probes performed well and helped to minimize variability caused by heartwood. This study also utilized rods to collect TDR readings and compared k_{wood} to volumetric MC in much the same way as Constantz and Murphy (1990). Irvine and Grace (1997) also reported the occurrence of a tree wound response which had an effect on the MC in the vicinity of the rods during the initial weeks of installation.

Wullschlenger *et al.* (1996) utilized rods to examine the MC of four deciduous hardwoods (*Acer rubrum* L., *Quercus alba* L., *Quercus prunus* L., and *Nyssa sylvatica* Marsh.). This study aimed to develop a universal equation for use with all woods and incorporating the *P. sylvestris* data collected by Irvine and Grace (1997). Wullschlenger *et al.* (1996) found diameter class played a role in the relationship between k_{wood} and MC and also observed changes in k_{wood} observations during the initial weeks after installation, presumably due to a wound response of the tree. They concluded a single calibration curve of volumetric moisture and k_{wood} was possible despite the suggestion of Constantz and Murphy (1990) to the contrary.

TDR has also been investigated as an aid in the irrigation of *Citrus limon* L. (lemon trees) in Israel. Nadler *et al.* (2003) examined the relationship between soil TDR observations and tree stem TDR observations. They found averaging a large number of probe data to try and evaluate irrigation requirements was not a viable technique because of high variability in the sapwood of different individual trees. They also stated for a single tree, an irrigation program could be established based on temporal changes to stem MC. This was the first study to report variability in TDR readings owing to high temperatures in the cables and they devised an adjustment for this situation. They reported a change of 0.006 meters of cable length for every ˚C in a 4.9 meter cable.

TDR has also been utilized in live trees in the Mediterranean to estimate the volume of stored water (Hernandez-Santana and Martinez-Fernandez 2008). This study also suggests the necessity for individual calibration curves for each intended species. Researchers examined two species of Mediterranean oaks (*Quercus pyrenaica* L. and *Quercus rotundifolia* Lam.) to see if individual species predictions might be more accurate than the universal equation described by Wullschlenger *et al.* (1996). It was found that even between two similar species (white oaks), individual calibration curves were helpful.

More recently TDR has been used to monitor moisture content of logs in wet decks around the Southeastern United States in an effort to optimize water use where logs are stored (Schimleck *et al.* 2011). All earlier studies had used apparent dielectric content directly with volumetric moisture content (gH_2O/cm^3). While this worked for the their purposes it was not in a unit of measure common in forestry, Schimleck *et al.* (2011) chose to use the apparent length (meters) in association with a percent moisture content (on an oven dry basis). This is a far more common unit of measure and directly applicable to a wide variety of forestry activities.

The wet deck study (Schimleck *et al.* 2011) investigated the use of various length probes for their accuracy. Shorter probes allow the measurement of smaller diameter stems since the probes are typically inserted perpendicular to the bole. They tested probes of 75, 100, and 125mm and found while the length of the probe is directly proportional to its accuracy, probes as short as 75mm can be used; however, they are not as accurate as longer probes. Along with the verification of probe lengths they were able to identify stem diameter as an important covariate further added to the prediction accuracy of TDR for determining percent moisture content.

I plan to use TDR to monitor the moisture content in standing trees in the Lower Coastal Plain of Florida and the Piedmont of Georgia during each of the four seasons. I plan to evaluate both *Pinus elliottii* Engelm. (slash pine) and *P. taeda* (loblolly pine) in the Lower Coastal Plain and *P. taeda* in the Piedmont; these species represent the dominant plantation softwoods being grown in Georgia. TDR technology may allow us to develop a reliable baseline of how tree MC varies seasonally. Understanding MC trends in living trees may help with scheduling timber harvests to reduce fuel transportation costs, with irrigation scheduling, or with early warning for insects and diseases.

CHAPTER 2

CALIBRATION OF A TIME DOMAIN REFLECTOMETER TO ESTIMATE MOISTURE CONTENT OF SOUTHERN PINE SPECIES

Introduction

There are many reasons why moisture content (MC) is important to wood scientists, foresters, arborists, engineers, and anyone who utilizes wood or works with woody plants. The relationship between wood and water influences a wide variety of properties including weight, physical dimensions, tree health, and fungal resistance. Traditionally MC measurements have been performed in the laboratory on small pieces of wood removed from a tree or lumber. Existing methods for determining MC (that minimize the amount of damage to tissue) lack accuracy or are too cumbersome or dangerous to be effective for many applications (Edwards and Jarvis 1983, Raschi 1995, and Merela *et al.* 2009). An attractive option is time domain reflectometry (TDR) which has been investigated over the past two decades (Constantz and Murphy 1990, Holbrook *et al.* 1992, Wullschlenger *et al.* 1996, Irvine and Grace 1997, Nadler *et al.* 2003, and Schimleck *et al.* 2011) as a potential method to measure MC quickly without some of the obstacles that arise with other methods. A similar method utilizing TDR has been created for the measurement of soil moisture and is now a common tool for soil scientists (Ledieu *et al.* 1986).

Time domain reflectometery works by sending an electromagnetic pulse through a substance and measuring the interval between the sent and reflected signals. The movement of the pulse is based on the dielectric constant (k) of the substance. Materials with high k, i.e. water, allow this pulse to move smoothly while materials with low k reflect much of the signal to the

TDR device (Cerney 2009). This is useful for the measurement of MC because wood has a low k (k_{wood} = 2) while the k of water is much higher (k_{water} = 80), this means any measured change in a TDR signal in wood is due to an increase or decrease in water content and not a change to the wood.

Originally it was thought a calibration similar to the one established for soils (Ledieu *et al.* 1986) might also work for wood (Constantz and Murphy 1990) but it was found that high levels of organic material made using the same calibration impossible. Constantz and Murphy (1990) performed the first calibration with the assumption only one calibration curve for wood would be necessary. They measured two bolts from *Pinus radiata* D. Don (radiata pine) using a cable testing oscilloscope and two 130mm rods inserted into the bolts and allowed them to dry while readings were taken. They utilized the equations of Davis (1975) for calculating the volumetric water content of a porous material using a TDR to determine k and created a calibration based on the relationship between volumetric water content and k. This calibration was used successfully to show a change in volumetric water content of a *Juglans regia* L. (English walnut) tree after flood type irrigation. They also recognized accuracy could be improved if calibrations were species specific.

Every experiment regarding wood and TDR used a different calibration approach. Constantz and Murphy (1990) calibrated their study using two bolts from the same log of *P. radiata*, Irvine and Grace (1997) examined 20 cut blocks from a single *Pinus sylvestris* L. (Scots pine) tree. Wullschlenger *et al.* (1996) attempted a universal calibration with four hardwood species using 4 bolts from one log of each species. Holbrook *et al.* (1991) developed their calibration with an unknown number of blocks cut from a single stem of *Sabal palmetto* (Walt.) Lodd. (cabbage palm). More recently Hernandez-Santana and Martinez-Fernandez (2008) used 5 blocks cut from one *Quercus rotundifolia* Lam. (holly oak) tree and 4 blocks cut from a single *Quercus pyrenaica* L.(Pyrenean oak) tree for their calibration and finally Schimleck *et al.* (2011) used 29 *Pinus taeda* L. (loblolly pine) bolts cut from 10 individual trees. With the exception of Schimleck *et al.* (2011) who determined percent MC on a dry weight basis all of the studies examined volumetric water content (gH_2O/cm^3) and a calculated k.

Due to the relative immaturity of TDR research as it relates to wood moisture many issues require investigation. The need for species specific calibrations is the most prominent. Another important consideration is the influence of geographic location on wood MC caused by differences in specific gravity (SG). For instance, Antony *et al.* (2012) recently published evidence that MC within the geographic distribution of *P. taeda* increases moving away from the Atlantic and Gulf Coast's inland toward the Piedmont and SG decreases. Whether geographic variability in SG could have an effect on TDR predictions is unknown.

As the technique of estimating MC using TDR develops it is important we understand how geography and differences among species influence the k of wood. We also need to be cognizant of how these findings will be utilized in the field; therefore I believe it is critical we report results as percent MC (on a dry weight basis), as this is the standard MC unit in forestry and wood science. Considering these issues my goal for this study was to:

- Develop a species specific TDR calibration for the estimation of MC for *Pinus elliottii* Engelm. (slash pine) and *P. taeda*;
- Investigate the effects of the two species on TDR estimation of MC; and
- Investigate whether geography has an influence on the relationship between dielectric constant (k) and moisture content (MC) when estimating MC in *P. taeda*.

Materials and Methods

In order to predict moisture content (MC) using TDR data collected in the field a calibration was required. Bolts were collected from trees growing in the Piedmont of Georgia (a stand near the University of Georgia), and the Lower Coastal Plain near Yulee, Florida. Bolts were approximately 600mm in length with diameters between 90mm and 150mm. Bolts were collected for *P. elliottii* (21 bolts) and *P. taeda* (22 bolts) in Florida and for *P. taeda* (21 bolts) in the Piedmont. One bolt was collected from each tree at 25% tree height to best represent the average tree MC (Antony *et al.* 2012). Average diameter of the bolts was 104.7mm (Std. Error = 1.2mm) for *P. elliottii* and 111.9mm (Std. Error = 3.5mm) for *P. taeda*.

The 65 bolts were submerged in water until they were fully saturated (the point their weight no longer increased), to ensure the entire MC range of the samples could be observed. Before being soaked in water the bolt diameters were measured and all bark was removed. While the bolts were being collected they were visually inspected for heartwood. To my knowledge no samples were used that contained any visible heartwood; this was to reduce any variability from probes crossing the sapwood-heartwood transition.

While the bolts were soaking, probes were manufactured that were later inserted into the bolts. The literature indicated a distance of 25mm between two stainless steel rods was ideal (Constantz and Murphy 1990, Schimleck *et al.* 2011). The length of the rods was 100 mm, 30mm shorter than the rods used by Constantz and Murphy (1990) but success has been reported with rods as short as 75 mm (Irvine and Grace 1997 and Schimleck *et al.* 2011). Using shorter rods should minimize any variations caused by undetected heartwood.

Probes were constructed in the lab following the work of Schimleck *et al.* (2011). Approximately 600mm lengths of coaxial cable were cut. On one end of the cable a Bayonet

Neill–Concelman (BNC) connector was attached and the other end was stripped down to separate the inner copper wire and the woven metal shielding. Three mm stainless steel rods were cut to approximately 150mm in length and then bent to create a right angle at the 10mm point of the rod. An oxygen acetylene welding unit was used to braze the bent rods to the cable with one rod attached to the shielding and one rod attached to the inner copper wire. Copper crimping tubes were used to hold the pieces together and silver solder was used for the connection. The two rods with the coaxial cables attached were then placed into silicon molds and the molds filled with AeroMarine Casting Resin in blocks of approximately 40x70x30mm. After the resin had set the rods were cut to 100mm using bolt cutters. All probes were numbered for tracking as well as weighed and a reference length was measured. The reference measurement was taken using the TDR by attaching the BNC connecter on the probe to the TDR and shorting the probe rods with a metal blade. This provided an accurate probe length that would later be subtracted from all of the apparent length readings performed in the calibration phase and in the field.

When the bolts had reached a maximum MC they were removed from the tanks and probes were inserted in each. Probes were inserted by first drilling 3 mm diameter guide holes using a guide constructed for the purpose of this experiment. This ensured the probe rods entered the wood parallel to each other. Each bolt was then weighed, and a reading of apparent length was taken with the TDR. Apparent length was collected by identifying the inflection point on the TDR oscilloscope using the technique developed by Schimleck *et al.* (2011). Initially this process of weighing and taking TDR readings was done on a daily basis as the bolts rapidly lost moisture. As the bolts began to reach equilibrium the measurements were taken less frequently. After the bolts stopped losing weight to moisture loss they were oven dried at 102°C. After the samples were oven dried the weight of the probes was removed from all collected weights and the probe length was subtracted from all collected apparent lengths. The oven dry weights were used to establish a percent MC at every TDR reading.

After the data collection phase was complete an empirical model was developed with the help of the statistical consultant (Dr. Finto Antony) from the Wood Quality Consortium at the University of Georgia. A model was chosen that best fit the data from each data set, using NLIN and MODEL procedures within SAS 9.2. Models utilized collected TDR lengths along with stem diameter at the probe site to predict MC on a dry weight basis.

The calibrations are intended to be used to estimate the MC of standing trees in two geographic regions of the Southeastern United States. Because of the distance between sites it was necessary to use separate TDR units at each location. As a consequence separate calibrations were obtained for the different instruments. The Lower Coastal Plain calibration data, consisted of 43 bolts (21 *P. elliottii* and 22 *P. taeda*), was collected on a TV220 Cable Scout manufactured by Tempo Textron of Delaware. The Piedmont calibration based on 21 *P. taeda* bolts was collected on a 1502C metallic cable tester manufactured by Tektronix Inc. of Beaverton, Oregon. The Tektronix unit has been utilized in many previous studies that have used TDR to estimate MC (Irvine and Grace 1997, Hernandez-Santana and Martinez-Fernandez 2008, Schimleck *et al.* 2011) but is no longer available commercially. The UGA lab owned the Tektronix machine and purchased a new TV220 Cable Scout TDR for the coastal plain study. The Cable scout unit was chosen because it was compatible with the requirements of this experiment in that it has an oscilloscope display and is commercially available.

Results

Due to differences between the two TDR machines a single calibration could not be developed for both locations and individual calibrations were obtained.

Lower Coastal Plain Calibration

A plot showing the relationship between MC and apparent length for both *P. elliottii* and *P. taeda* from the Lower Coastal Plain is presented in Figure 2.1. The shape of the curve was very similar for both species.

Several candidate models were fitted to the data and a four parameter logistic model selected as the best. Though I used the same model to fit data from both species, I observed significant difference in parameters between species and therefore incorporated this difference into the model by adding species as an indicator variable. I have also observed a difference in curve shape with diameter of the bolts and diameter was added to the model as a covariate. The final model form (Equation 1) was;

$$y = b_0 + \left\{ \frac{b_1 - b_0}{1 + e^{\left(\frac{b_2 - x}{b_3}\right)}} \right\} + e \qquad [1]$$

Where, y is the observed moisture content; x is the apparent length; b_0, b_1, b_2 and b_3 are parameters to be estimated from the data and ε is the error term with $\varepsilon \sim N\left(0,\ \sigma^2\right)$. To take account of differences between species and diameter of the bolts, the parameter b_1 and b_2 are expressed as a function of species and diameter as:

$$b_1 = b_{11} + b_{12} I(\text{Species} = P.taeda)$$

$$b_2 = b_{21} + b_{22} D_{Bolt} + b_{23} D_{Bolt}^2$$

Where D_{Bolt} is the diameter of the bolt in cm.

Summary statistics and plots showing the predicted values and residuals for the Lower Coastal Plain samples are shown in Tables 2.1 and 2.2 and Figures 2.2, 2.3 and 2.4.

Piedmont Calibration

A plot showing data collected for the Piedmont calibration is presented in Figure 2.5. Several candidate models were fitted to the data with a Chapman-Richard growth model selected as the best candidate. The difference in curve shape with diameter was negligible primarily due to a narrow diameter range. However, I observed high variation in MC from bolt-to-bolt (based on mixed model results I observed large variability in the upper asymptote). In order to take account of the variability from bolt-to-bolt, I included bolt diameter in the model. I observed an increase in variability with increase in MC (Figure 2.5) and used a weighted least square with weight as the inverse of predicted moisture content in the model to get unbiased parameter estimates and standard error. The final model form (equation 2) is below and plots showing the predicted values and residuals are presented in Figures 2.6 and 2.7.

$$y = a(1-e^{-bx})^c + \varepsilon \qquad [2]$$

Where, y is the observed moisture content; x is the apparent length; a, b and c are parameters to be estimated from the data (Table 2.3) and ε is the error term with $\varepsilon \sim N\left(0,\ \sigma^2\right)$. To take account of difference due to diameter of the bolts, the parameter a in the model is expressed as:

$$a = a_{11} + a_{12}D_{Bolt} \qquad [3]$$

Where D_{Bolt} is the diameter of the bolt in cm.

Discussion

Calibrations for the prediction of moisture content from TDR readings of apparent length were developed for *P. elliottii* and *P. taeda* combined from the Lower Coastal Plain and *P. taeda* from the Piedmont. Based on earlier research I expected to have some differences between species and thought I might find differences in geographic regions as well. I found the two coastal plain species were remarkably similar and the difference between the coastal plain and Piedmont were difficult to ascertain due to the use of different TDR instruments.

Both TDR units performed well but had different waveforms. I found even though the TDR units provided different results for the same probes, the differences were linearly related and could be accounted for (Figure 2.8). The original calibration data is shown in Figure 2.9. Without adjusting the Piedmont data it appears the apparent length is significantly shorter with regard to MC than the data from the Lower Coastal Plain. Much of this difference is removed when I adjust the Piedmont data (collected with the Tektronix 5201C) to account for the differences in TDR measurements for trees from the Lower Coastal Plain (collected with the Cable scout TV220) as shown in Figure 2.10.

It should be noted the two TDR's used in this study function differently. Two main types of TDR's are produced, a step type (the Tektronix) and a pulse type (the Cable Scout). The pulse type of unit sends short individual bursts of a sine wave and then detects reflections using the intermittent time to calculate a distance to an event in the cable while a step device is constantly sending energy while listening for the returning signal. The lack of "blind spots" between outgoing waves gives the step device a much more accurate picture of what's happening in the cable (Cortez *et al.* 2009). The two devices can be understood by comparing the step device to Doppler radar creating a realistic image of what's happening and the pulse device as conventional radar where a single burst is sent and received giving an idea of a distance to an object.

Since both *P.* e*lliottii* and *P.taeda* share a calibration curve in the Lower Coastal Plain and given the similarities suggested in Figure 2.10 it is possible one calibration could be established for the Southeastern United States for both species. I am hesitant to create a calibration based on adjusted data, but believe one could be developed.

From the earliest TDR work it was suggested more specific calibration curves would be necessary for the accurate determination of MC in wood (Constantz and Murphy 1990) but it was unknown how specific the curves would need to be. Constantz and Murphy (1990) showed obvious differences between hardwoods and softwoods but whether every species would require an individual calibration curve was unclear. While TDR shows great promise, its ease of use would be lessened if it did require individual calibrations for every species. It is probable species with similar anatomy and fiber saturation points will behave similarly with regard to dielectric constant and therefore have similar calibration curves. My research, based on samples of two pine species from the Lower Coastal Plain is evidence this assumption has merit, as both *P. elliottii* and *P.taeda* share a calibration curve shape for that region. Whether this will also work for additional pine species growing in the same area is a logical next step for study. It may also prove useful to examine other large groups of species with similar wood structure to determine if calibration curves are similar enough to allow them to be grouped together; examples include the red and white oaks, hard and soft maples, and white and yellow pines. The organization of logical wood groups for calibrations could greatly improve the utility and functionality of TDR for determining MC in the future.

Assuming multi-species calibrations are feasible and species with similar wood can be grouped; there are still obstacles to be overcome. The consistent collection of data is an important consideration and will need to be addressed before MC can be reliably measured by those using TDR for research and industrial applications. Human variability is an obvious source of error and one that can be overcome by the use of data logging equipment (this equipment was not available for my research). I took every effort to minimize variability by having all data collected by the same individual but if the technique is widely used then it will be with data collected by others. I believe a method of data collection and analysis be used in the future, for example taking the derivative of a stored TDR waveform to identify the inflection point, would negate the need for human interpretation of an oscilloscope display. With a better data collection regime and proper calibration TDR shows great promise as a method for calculating MC information without resorting to destructive sampling.

TDR lacks the accuracy of traditional methods for measuring MC but it can be useful in a variety of situations. TDR could be utilized when the goal is to determine change over time; utility poles, structural support beams, boat docks or any number of construction applications where wood is left exposed to soil or weather. There is also a real possibility this technique could be adapted for situations where detecting a rapid change in MC would be sufficient to indicate some other related activity; for instance TDR probes may be able detect changes in living trees in response to insect infestations, fungal root infections, or drought (turning TDR into an early warning system for issues facing foresters and orchard managers). Many tree health issues that cause girdling would also cause a rapid decrease in MC shortly before manifestations of symptoms like wilting, color change, or leaf loss.

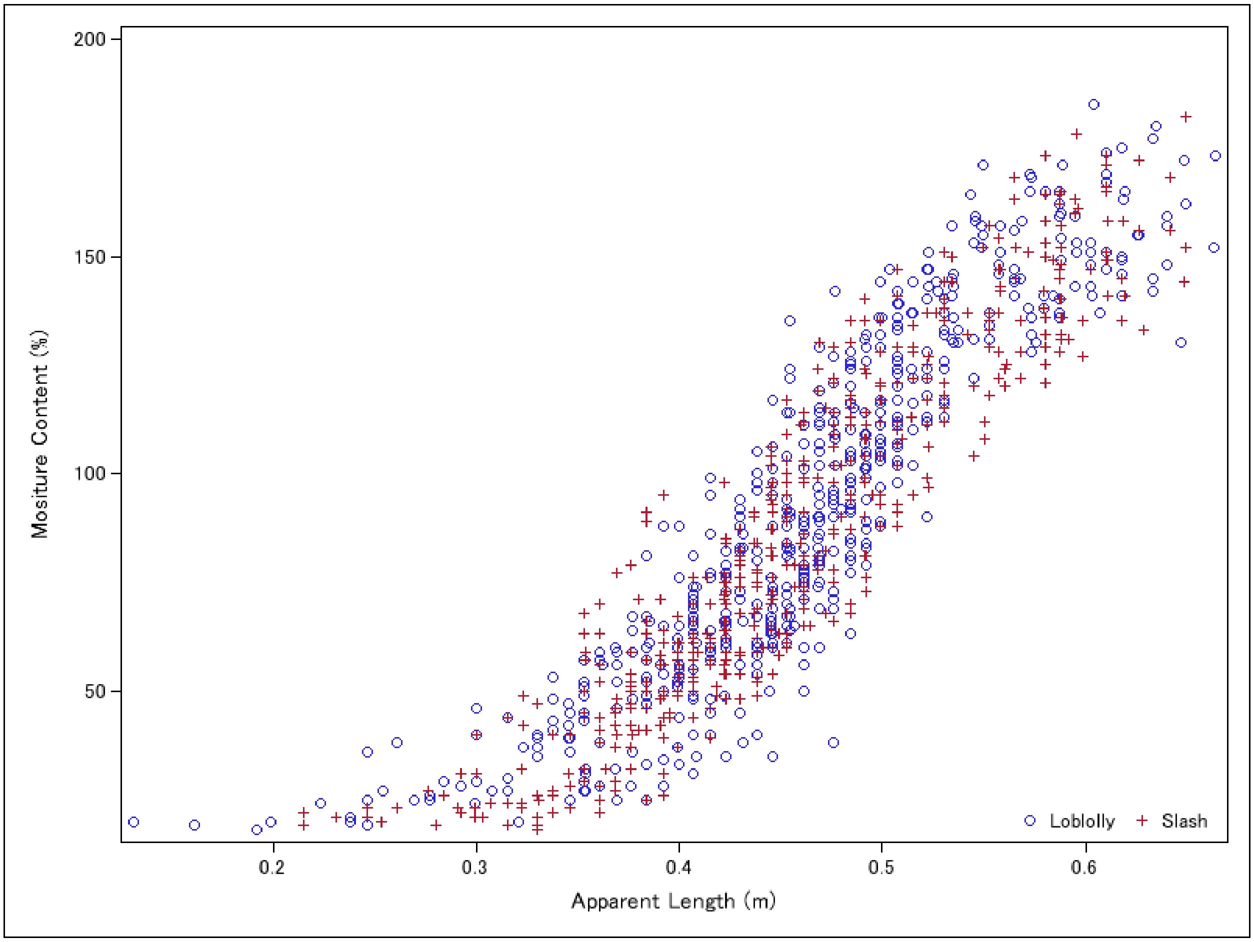

Figure 2.1. Relationship between MC and apparent length for *P. elliottii* (slash pine) and *P. taeda* (loblolly pine) from the Lower Coastal Plain. Measurements were collected with the TV220 TDR.

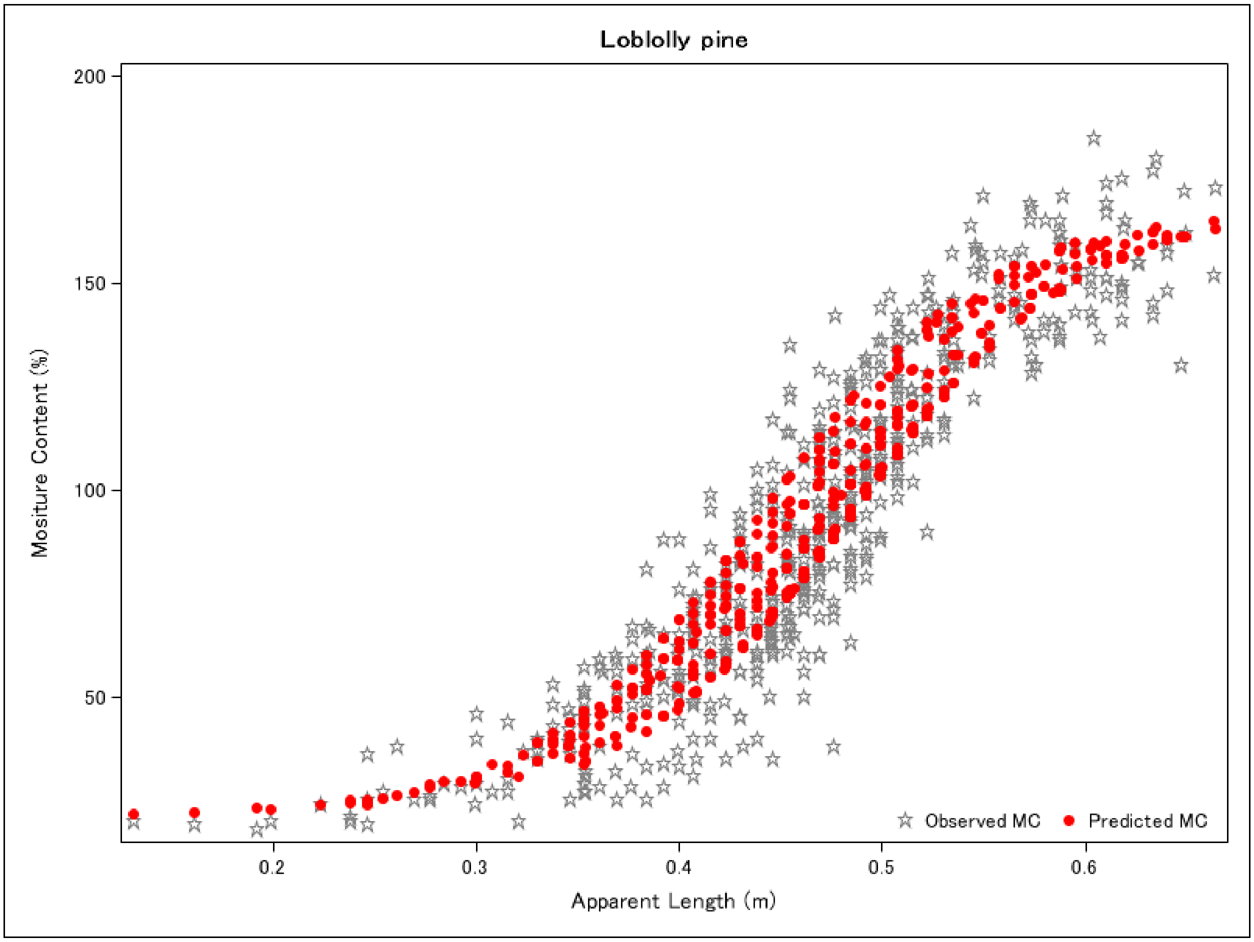

Figure 2.2. Comparison of predicted MC and observed MC for *P. taeda* (loblolly pine) from the Lower Coastal Plain.

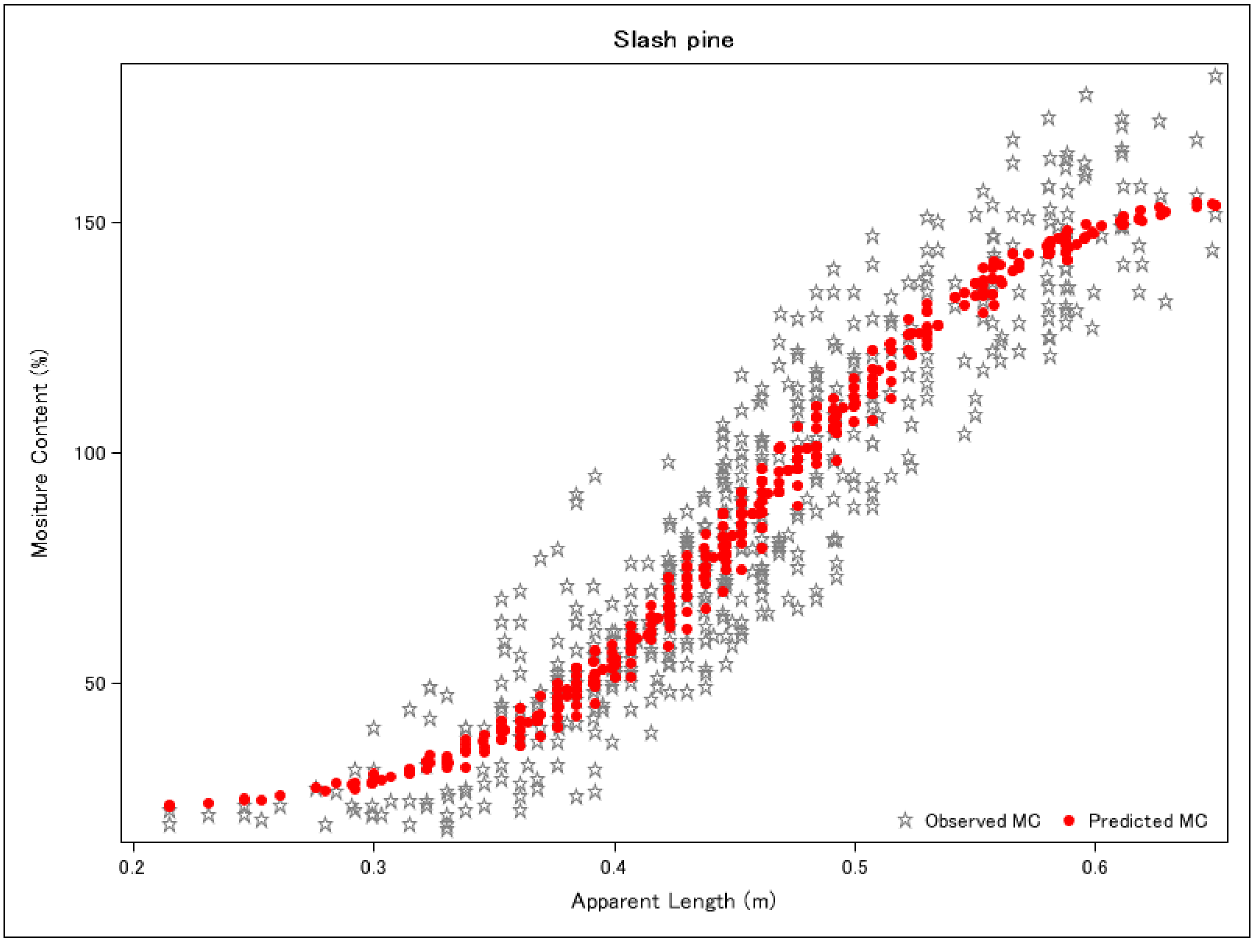

Figure 2.3. Comparison of predicted and observed MC for *P. elliottii* (slash pine) from the Lower Coastal Plain.

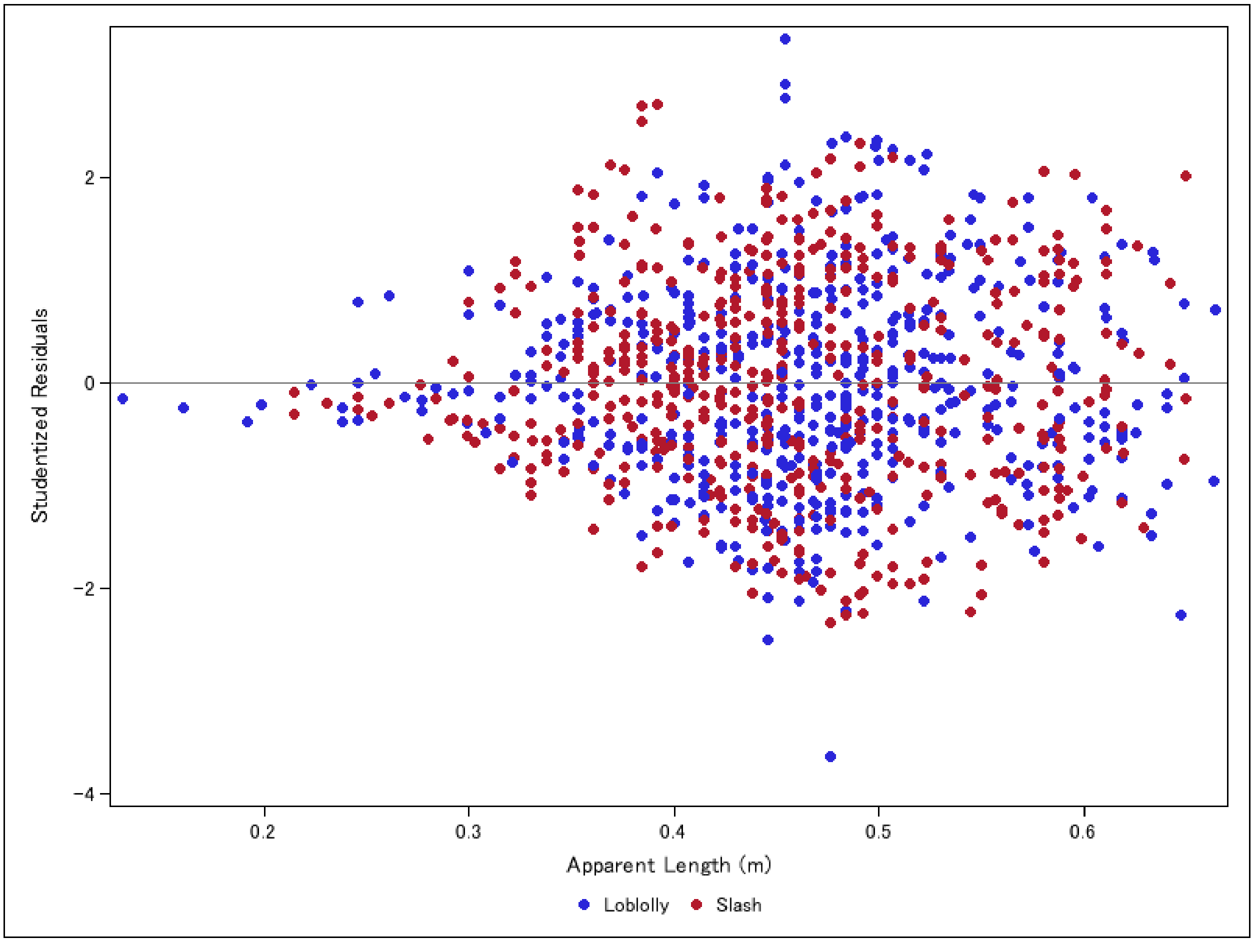

Figure 2.4. Residuals from the fitted model for *P. elliottii* (slash pine) and *P. taeda* (loblolly pine) from the Lower Coastal Plain.

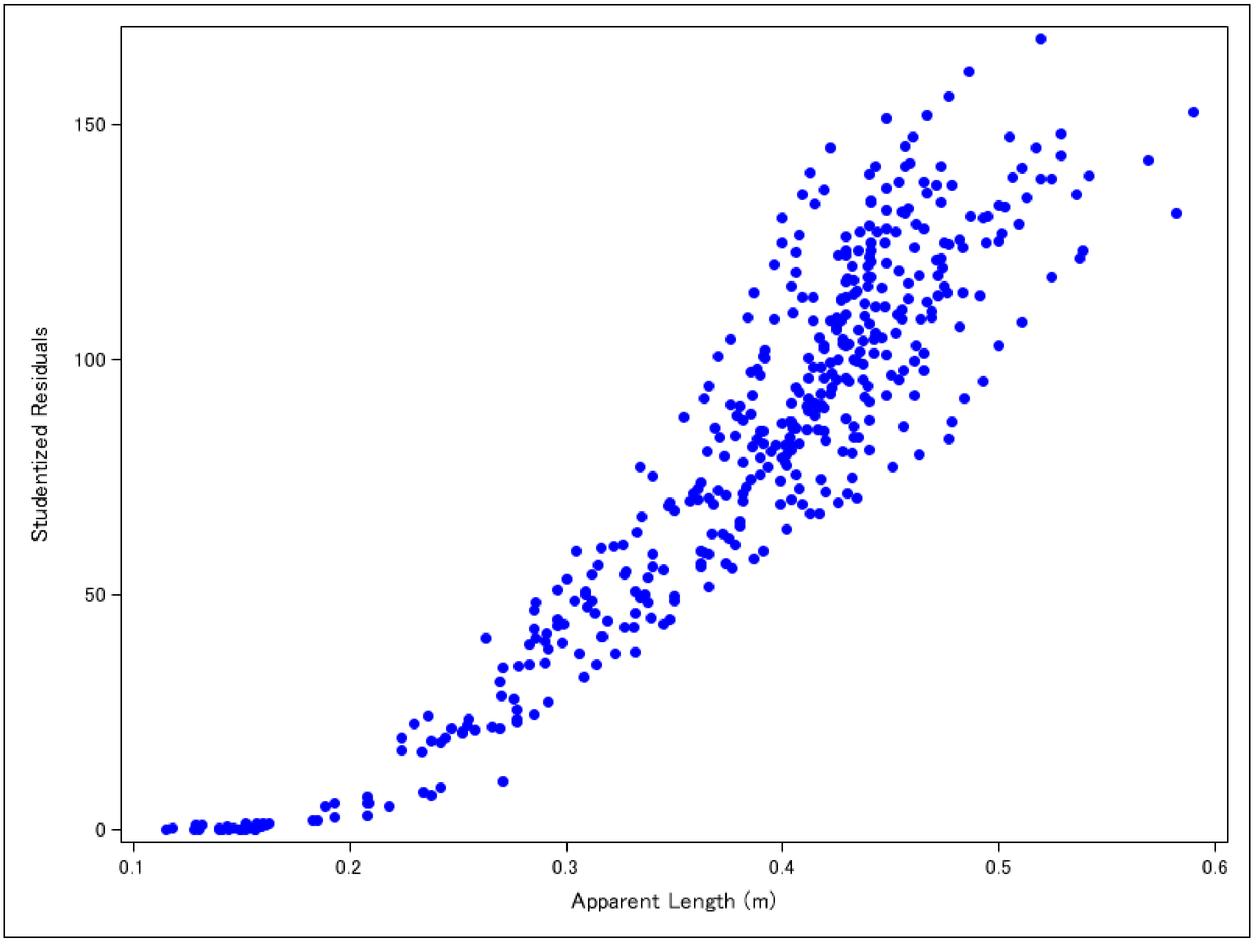

Figure 2.5. Relationship between MC and apparent length for *P. taeda* (loblolly pine) from the Piedmont. Measurements were collected with the Tektronix 1502C cable tester.

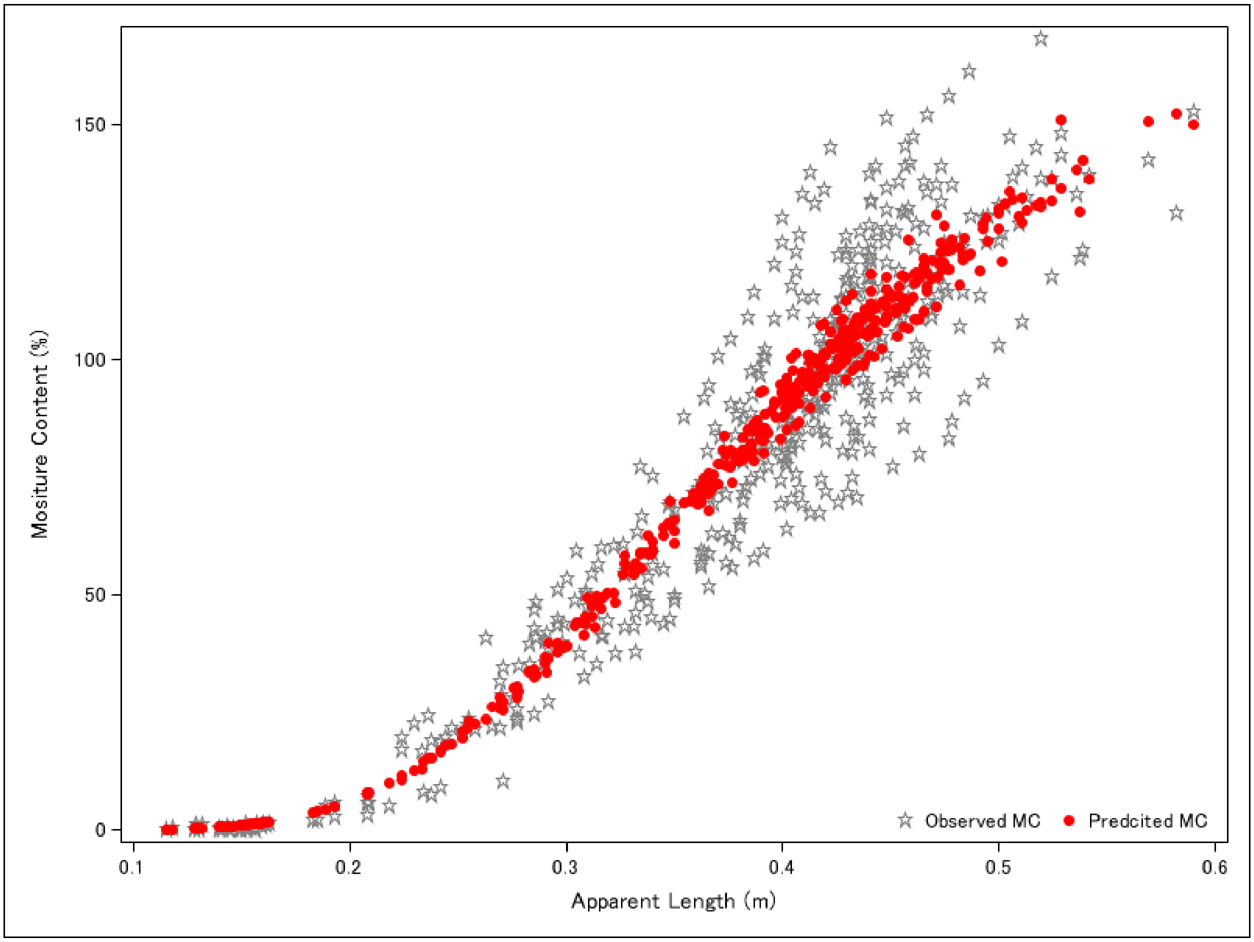

Figure 2.6. Comparison of predicted MC and observed MC for *P. taeda* (loblolly pine) in the Piedmont.

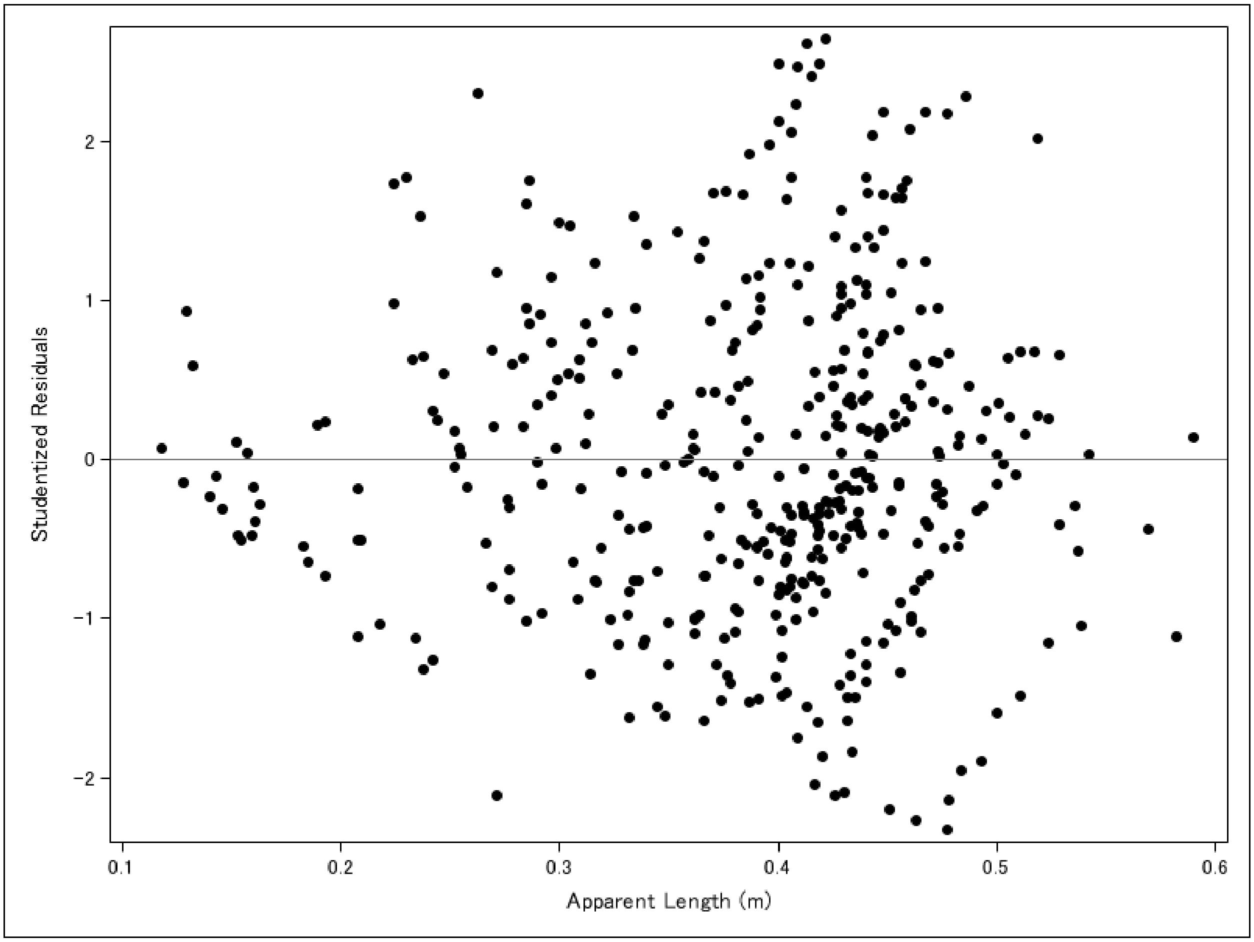

Figure 2.7. Residuals for the fitted model for *P. taeda* (loblolly pine) from the Piedmont.

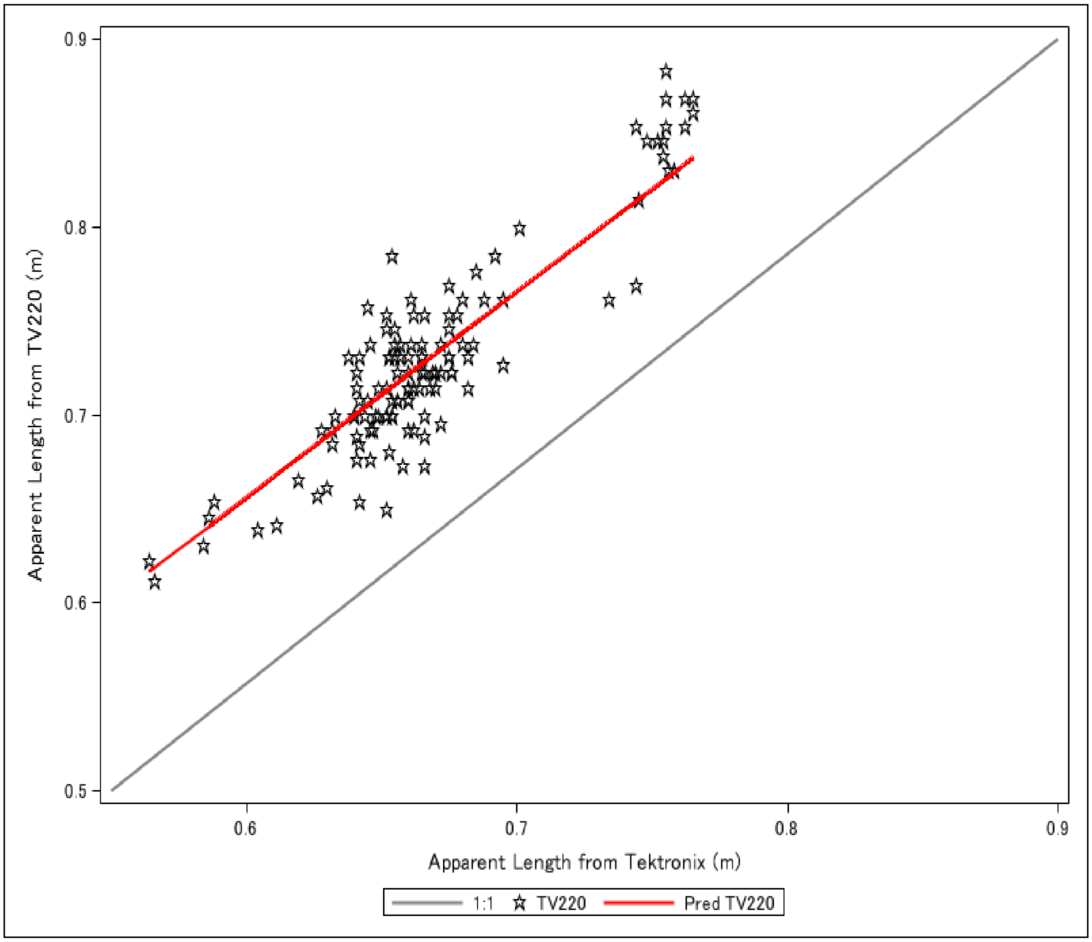

Figure 2.8. Reference length (m) for probes constructed for this research measured with the Tektronix 1502C and adjusted to the Cable Scout TV220 (the regression line for the conversion is shown).

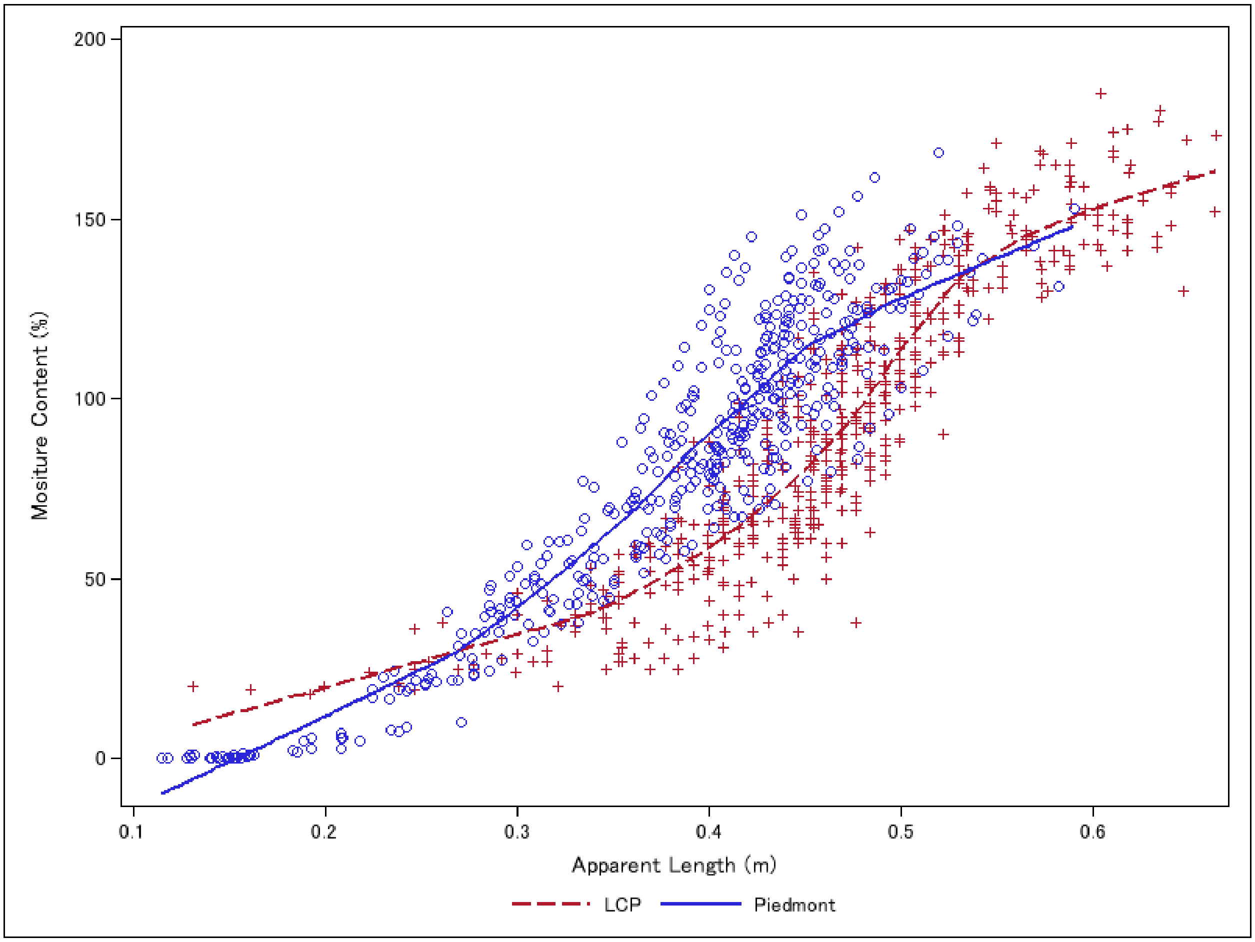

Figure 2.9. Data collected from both TDR machines without the linear regression applied to the Piedmont data.

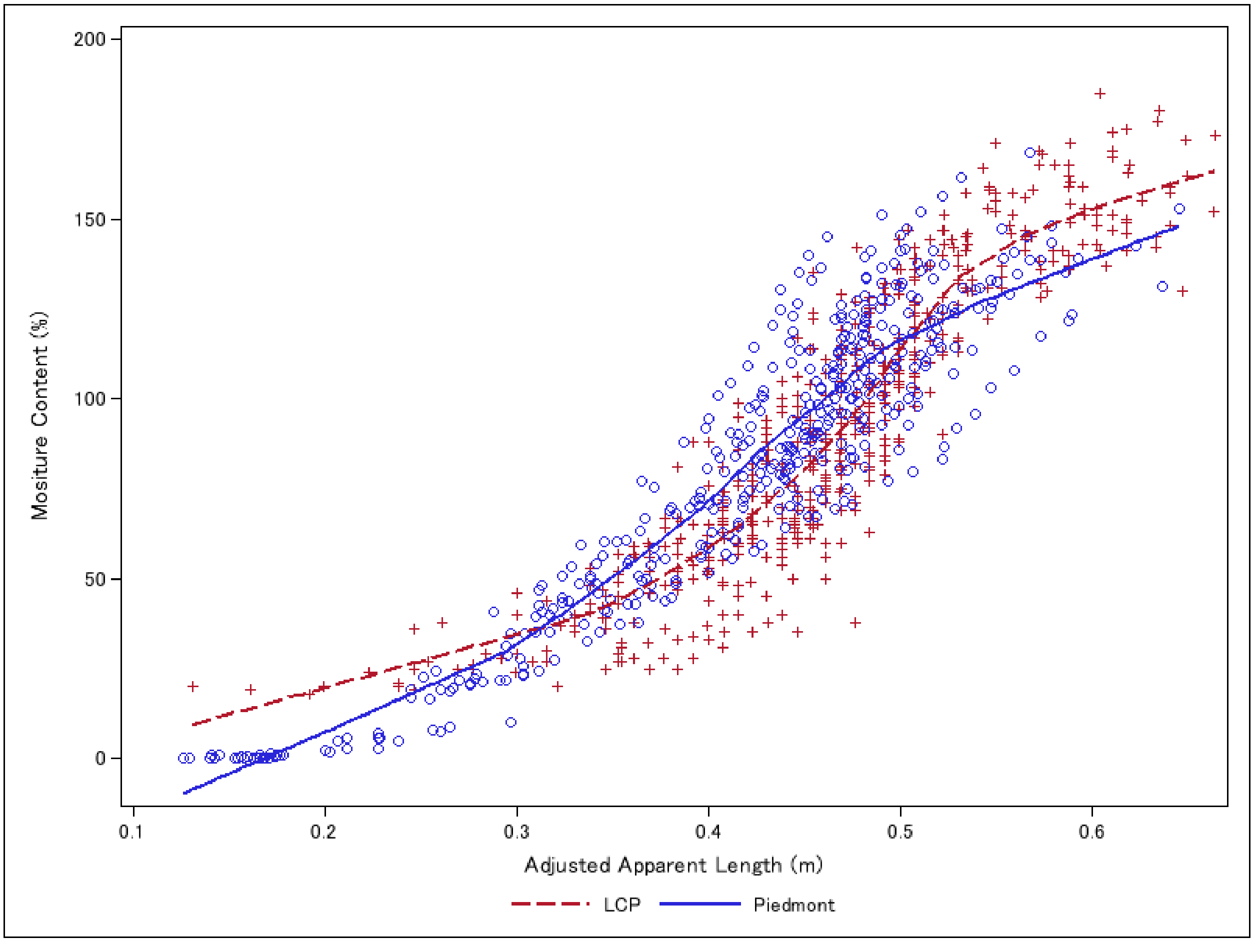

Figure 2.10. Data collected from the Lower Coastal Plain and the Piedmont adjusted to compensate for difference between TDR's.

Tables

Table 2.1. Nonlinear OLS summary of residual errors.

Equation	DF Model	DF Error	Sum Squared Error	Mean Squared Error	Root MSE	R-Square	adj. R-Square
mcp	7	1014	198302	195.6	13.98	0.8807	0.88

Table 2.2 Nonlinear OLS parameter estimates.

Parameter	Approx. Estimate	Std. Error	t Value	Pr > |t|
b0	21.47434	2.4923	8.62	<.0001
b11	159.2184	2.7007	58.96	<.0001
b12	9.518983	1.729	5.51	<.0001
b21	0.097086	0.0652	1.49	0.1337
b22	0.056287	0.0114	4.95	<.0001
b23	-0.00204	0.0005	-4.14	<.0001
b3	0.055754	0.0029	18.95	<.0001

Table 2.3. Nonlinear OLS parameter estimates.

Parameter	Estimate	Approx. std. Error	Approx. 95% confidence Limits	
a11	89.1872	20.7019	48.4956	129.9
a12	5.7939	1.38	3.0814	8.5064
b	7.3816	0.4825	6.4332	8.3299
c	12.9444	1.5518	9.8942	15.9946

CHAPTER 3

TRACKING TEMPORAL CHANGES IN STANDING TREE MOISTURE CONTENT USING TIME DOMAIN REFLECTOMETERY

Introduction

Moisture storage and movement in living trees is fundamental to tree health and poorly understood due to the destructive nature of most sampling methods. Low cost systems that continuously monitor the moisture content (MC) of standing trees could lead to early warning for a variety of tree diseases and insect infestations, as well as improve water resource allocation. Therefore research is required into methods that allow long term tracking of stem water within actively growing trees.

Determining the MC of wood involves one of two commonly used methods: electrical resistance or the oven-dry method. When lumber is tested it is usually done with an electrical resistance meter that uses the level of electrical resistance to estimate MC, this method is fast and accurate as long as the MC is between 6% and 30%. This method is inexpensive, repeatable, and relatively nondestructive but the average MC of sapwood in living trees is typically much higher than 30% depending on species (Wood Handbook 2010).

When the MC of standing trees is desired, the oven-dry method is often utilized. The oven dry method is accurate at any MC but requires a sample of wood be removed, weighed, oven-dried, and then reweighed. Depending on the type of sample taken this could take several hours (when wood shavings are used) or several days (when bolts or disks are used). The oven-dry method is considered destructive, though this can be minimized by utilizing small samples. Unfortunately when the oven dry method is employed for estimating the MC of standing trees some part of the tree must be removed and this can be problematic for long term monitoring of tree moisture for two important reasons. First, the same location cannot be sampled twice. Patterson and Doruska (2005) showed MC varies with height, so differences in consecutive MC readings cannot be distinguished between actual changes in tree MC or variability arising from sampling, secondly, with the oven-dry method an opening has to be created in the tree which exposes living tissue to the open air. While the tree can respond to the wound, multiple sampling from the same individual could increase the likelihood for disease or insect attack which would in turn affect how the tree stores and transports water.

Other, rarely utilized, methods of MC determination are available and include Gamma-ray attenuation (Edwards and Jarvis 1982), where radioactive elements and heavily shielded equipment make the process difficult to perform safely and requires equipment that would be irresponsible to leave in the field. Computer tomography has shown some promise (Raschi *et al.* 1995) utilizing ultrasound technology to determine density in order to infer MC; unfortunately the equipment is cumbersome and requires extensive expertise to setup for each reading making this technique impractical for long term studies. Nuclear magnetic resonance has also been used on wood with success (Merela *et al.* 2009) but the equipment is far too large to monitor living trees in the forest. Near infrared (NIR) spectroscopy is another alternative but repeated measures from the same location in pines would become difficult due to resin build-up and data is only collected from the outer most layer of wood, the area most susceptible to water loss by exposure to the elements.

Time domain reflectometry (TDR) may be able to overcome some of the limitations that hinder the feasibility of the other methods. TDR utilizes inexpensive probes that remain in the wood over long periods of time limiting tree damage and allowing repeated measurements from the same physical location each time. The equipment is moderately expensive but one TDR unit can sample as many trees as have been fitted with probes, and is small enough to transport to and from the field.

TDR has a long history of reliability in telecommunications and has been successfully used to measure soil moisture for many years (Ledieu *et al.* 1986). More recently the concept of using TDR for estimating soil moisture has been adapted for use in wood and woody plant applications. TDR works in a manner similar to two dimensional radar, an electromagnetic pulse is sent from the unit into a cable and part of that signal is reflected when the medium it is traveling through has a break or a change in dielectric constant (k) (Pettinelli *et al.* 2002). In the telecommunications field this concept is used to find line breaks or damage negating the need to unearth the entire cable and inspect it.

The technique relies on the k which is associated with a materials ability to transmit an electromagnetic pulse. In wood k_{water} (80) is much higher than that of k_{wood} (2) so the rate at which the signal is reflected will depend on the amount of water in the wood.

If a greater understanding of how MC fluctuates in living pines can be acquired it could have an influence on logging operations by harvesting during those times of year where trees have the lowest levels of moisture to minimize trucking expenses or increase mill efficiency by harvesting during periods that have optimal MC for each mill's product demands. Along with the benefits to loggers, if a simple and inexpensive method of MC determination could be utilized in the field for monitoring on a regular basis it could provide foresters and land managers with a new tool for predicting events that may cause changes in MC, i.e. disease or insect infestation. In the field of arboriculture this type of monitoring could be used on individual high value trees to track changes in water use from year to year in order to maintain proper irrigation and evaluate overall tree health. Orchard managers could also benefit from this type of long term tracking to maximize water use to investigate trends in moisture levels and harvest quality. This type of orchard monitoring has already been used in Israel with some success (Nadler *et al.* 2003).

Moisture in living trees, even within a single species, can be highly variable. Within *Pinus taeda* L. (loblolly pine) Patterson and Doruska (2005) describe MC variability with tree height, by season, and with location due to the change in specific gravity (SG). Antony *et al.* (2012) examined this variability and identified a regional trend in MC and SG with MC increasing moving inland from the coast and SG decreasing. Antony *et al.* (2012) also determined for *P. taeda*, MC at 25% of total tree height best represented overall tree MC.

In the Southeastern United States lumber production is dominated by two species of pine: *Pinus elliottii* Engelm. (slash pine) and *P. taeda*. Using the TDR calibration developed in Chapter 2 I plan to examine MC changes over the course of one year for *P. elliottii* and *P. taeda* and to:

- Determine the usefulness of the calibration developed in Chapter 2 on living pines in the Southeastern United States,
- Monitor MC changes in living pines to determine if moisture fluctuates between seasons; and
- Determine if TDR is accurate enough to detect regional differences between the Lower Coastal Plain and the Piedmont of the Southeastern United States.

Materials and Methods

In order to determine species differences between *P. elliottii* and *P. taeda* a stand of each was selected in the Lower Coastal Plain of northern Florida. In order to observe regional differences within the distribution of *P. taeda* one stand was chosen in the Piedmont of Georgia.

The two stands in the Lower Coastal Plain were on land owned by Rayonier in the city of Yulee, FL. In the Piedmont of Georgia a stand of *P. taeda* owned by the Warnell School of Forestry and Natural Resources at the University of Georgia was utilized and was located North of Athens, GA.

Trees selected were between 19-23 years of age with diameters (at 25% tree height) above 100mm (Table 3.1). Diameters above 100mm were necessary to accommodate probes with rod lengths of 100mm and small diameters were preferred to avoid heartwood, which could bias my readings. Two Rayonier employees from the Fernandina Beach research station were trained in the use of the TDR. A sampling height of 25% was selected based on the work of Antony *et al.* (2012) in an effort to obtain a MC reading representative of the whole tree.

In May 2011 trees were selected at each site for the standing tree study and probes were inserted at 25% tree height into 10 *P. elliottii* and 10 *P. taeda* trees at the Lower Coastal Plain site and 10 *P. taeda* trees at the Piedmont site. The standing tree data was collected from the same 30 trees for an entire year (from June 17, 2011 to May 14, 2012) on a weekly basis. Data collection was done using the same method as the calibration in Chapter 2 and described in the work by Schimleck *et al.* (2011). As the probes were installed at 25% of total tree height a cable was attached to facilitate data collection from the ground and this additional cable was measured as part of the reference length when the probes were installed.

Results and Discussion

Predictions were made for all TDR readings with the appropriate calibration from Chapter 2. Predicted MC's for the Lower Coastal Plain trees are displayed for both species in Figure 3.1 and for individual species in Figure 3.2, averages for both species are displayed in

Figure 3.3. The Piedmont MC predictions are shown for all trees in Figure 3.4 and averages are presented in Figure 3.5.

The standing tree results were unexpected. Trees from the two regions behaved differently even within the same species. The predicted MC of Lower Coastal Plain trees dropped rapidly and stayed low for approximately a month and then began returning toward original predicted MC levels (Figures 3.1 through 3.3). The Piedmont trees (Figure 3.4 and 3.5) also had a steep decline in predicted MC but tended to stay at this lower MC range for the entire year. Earlier studies also examined live trees (Constantz and Murphy 1990, Holbrook *et al.* 1992, Wullschlenger *et al.* 1996, Irvine and Grace 1997, Sparks *et al.* 2001, Nadler *et al.* 2003, Hernandez-Santana and Martinez-Fernandez 2008) with only limited mention of initial MC fluctuations. Three of the TDR studies of wood dealt with live *Pinus spp*. (Constantz and Murphy 1990, Irvine and Grace 1997 and Sparks *et al.* 2001) but none mentioned fluctuations early in their study. Within the hardwood studies two mentioned a phenomenon similar to what I experienced with early readings rapidly changing. Wullschlenger *et al.* (1996) noted an "overestimation of water content was possible with TDR as a result of wounding following wave guide (probe) installation" and Nadler *et al.* (2003) simply referred to Wullschlenger *et al.* (1996) and installed probes 50 days before taking measurements to avoid the wound response. While this is interesting, the response noted by Wullschlenger *et al.* (1996) was the opposite of what I observed in my study.

To better understand the wound response a supplemental calibration was performed utilizing five of the trees in the Piedmont study and five trees that were not involved in the study. The five trees from the Piedmont study were felled and 600mm bolts were cut from the section of bole containing the probe, and from 25% tree height from the un-probed trees. The calibration was done in the same way the original calibration was conducted in Chapter 2. The goal of this calibration was not to define a new calibration set as was done in Chapter 2, rather I wanted to determine whether a calibration specifically designed for standing trees was possible and whether the lower than expected predictions were caused by the wound response. All ten trees were *P.taeda* from the same stand used for the Piedmont study. To save time I chose to start the calibration immediately after felling rather than soak the bolts in water (as was done with the calibration in Chapter 2) because I was not interested in the whole MC range, only the difference between the bolts with and without a wound response.

My results with the supplemental calibration were inconclusive (Figure 3.6) as very little change was observed in apparent length with regard to MC. It is worth noting slope could not be discerned in the relationship between MC and apparent length, but with more sophisticated data collection it may be possible to develop a calibration. More puzzling is why soaking the bolts had such an effect on the relationship between MC and apparent length. Most of the published work on TDR and wood MC make some effort before or during the calibration to either maximize the initial MC to get the full moisture range (Constantz and Murphy 1989, Sparks *et al.* 2001, Hernandez-Santana and Martinez-Fernandez 2008, Schimleck *et al.* 2011) or to slow the drying process so the moisture is evenly distributed (Irvine and Grace 1997). To our knowledge we are the first group to develop two calibrations in a manner allowing them to be compared side by side (Figure 3.6).

It is possible the wound response established the need for the new calibration could be responsible for the change in shape of the relationship between moisture content and apparent length. Samples were soaked before calibration would understandably have a suppressed or absent wound response to probes. Therefore it seems reasonable the wound tissue would be atypical when compared to samples where probes were immediately inserted after felling and a wound response could be mobilized. Further any calibration done on felled trees would differ in level of wound response from probes inserted into actively growing trees, making a true living tree calibration difficult.

Assuming a wound response to the probe is causing the initial drop in, and subsequent under prediction of MC, a better understanding of wound responses in trees is necessary. The idea of a hypersensitive response in conifers was established in the 1960's (Reid *et al.* 1967), and was described in *P. taeda* by Cook and Hain (1985). The hypersensitive response is a process common to most plant species as a reaction to injury and pathogens. Initially the cells around the affected area die and levels of monoterpenes and phenolics increase, these dead cells, now filled with compounds toxic to most insects and fungi, act as protective barrier. The chemical concentrations tend to increase the level of starches and decrease free sugars in an effort to flood the area with toxins and limit available nutrients (Cook and Hain 1985), causing the affected area to darken in color.

The presence of high levels of monoterpenes and phenolics could have an effect on the dielectric constant reducing the change in apparent length with regard to MC. It is possible the tree's hypersensitive reaction zone actually has a dielectric constant much higher than dry wood. If the wounded area bridges the gap between the stainless steel probes so the apparent length remains stable regardless of MC we might expect a result similar to the supplemental calibration (Figure 3.6).

According to work done by Cook and Hain (1985) the size of the wound response can vary depending on pathogens in the environment. Control wounds (13mm hole) had discolored areas that averaged 27.5 mm in length after 4 weeks while trees inoculated with fungi grew to

90mm (inoculated with *Creatocystis minor* Hedgc.) and to 50.1mm for trees inoculated with *C. minor var. barrassi* (Taylor) in the same period of time (Cook and Hain 1985). This indicates even without a pathogen to expand the wound response this zone will bridge the gap (25mm) between the probes. The severity of the hypersensitive reaction could have a dramatic effect on the levels of chemicals flooding the area. It is worth noting the measurements taken by Cook and Hain (1985) were on the discolored area seen on the wood beneath the bark, the photographs I took after the data was collected (an example is shown in Figure 3.7) indicate these wounds are not uniform in shape and may be smaller or larger than the discolored surface suggests.

The possibility of a greater wound area when associated with a pathogen could explain the different reactions seen between trees growing on the Piedmont and Lower Coastal Plain sites (Figures 3.1 through 3.5). If there was a pathogen present severe enough to increase the hypersensitive response, and that response affects the TDR readings by bridging the gap between the probe rods, we might expect the apparent length to change rapidly and fluctuate around the new dielectric constant of the wounded area; this would agree with the results seen for the Piedmont trees (Figure 3.4). Alternatively if the pathogens present in the environment at installation were not a serious threat, then we would expect an initial reaction followed by the removal of much of the chemical buildup gradually returning the MC predictions to a level significantly below what we might expect for southern pine species, as observed for trees from the coastal plain (Figures 3.1 through 3.3).

Assuming the Piedmont site suffered from a more aggressive species or higher concentration of pathogens, no significant change in apparent length would be expected after the wound response occurs, and this is what I observed (Figures 3.4 and 3.5). If the Lower Coastal Plain was more typical of a normal response the expectation would be an initial drop in predicted

MC followed by an underestimated MC level for the remainder of the study, again this is what I observed. When I compare this data with expected MC levels described by Patterson and Doruska (2005) the Lower Coastal Plain follows the same seasonal shifts (albeit at an under predicted MC due to the wound response) but the Piedmont data does not because we may no longer be measuring moisture, instead we could be detecting the elevated chemical saturation of the wound area (Figures 3.8 and 3.9).

The work of Antony *et al.* (2012) described a trend toward increasing MC across the range of *P.taeda* moving away from the coast toward the Piedmont. It was my intention to determine whether TDR based wood MC predictions were sensitive enough to detect this difference. Unfortunately, due to the differing degree of wound response between the two sites determination not possible. I do believe with a calibration more oriented toward living trees this method could become sensitive enough to detect regional MC differences.

As discussed in Chapter 2, the issue of human variability is important. It has been clear from the early stages of this research there is a small but significant variation in how each individual identifies the inflection point on the TDR oscilloscope display. The identification of a reliable method of data collection involving a data logging device is imperative. The level of precision required is simply not achievable, especially when data is collected by several individuals. Both TDR devices work in increments of 0.008m. When used properly, this means measurements taken just one or two increments away from the correct position could mean a difference in predicted MC of up to 6.6% depending on the moisture content of the wood, this coupled with poor resolution on screens and the difficulty of working in the field makes obtaining good readings difficult without an automated method of data collection. Another benefit of a data logging device would be the ability to record and revisit data points that appear in error.

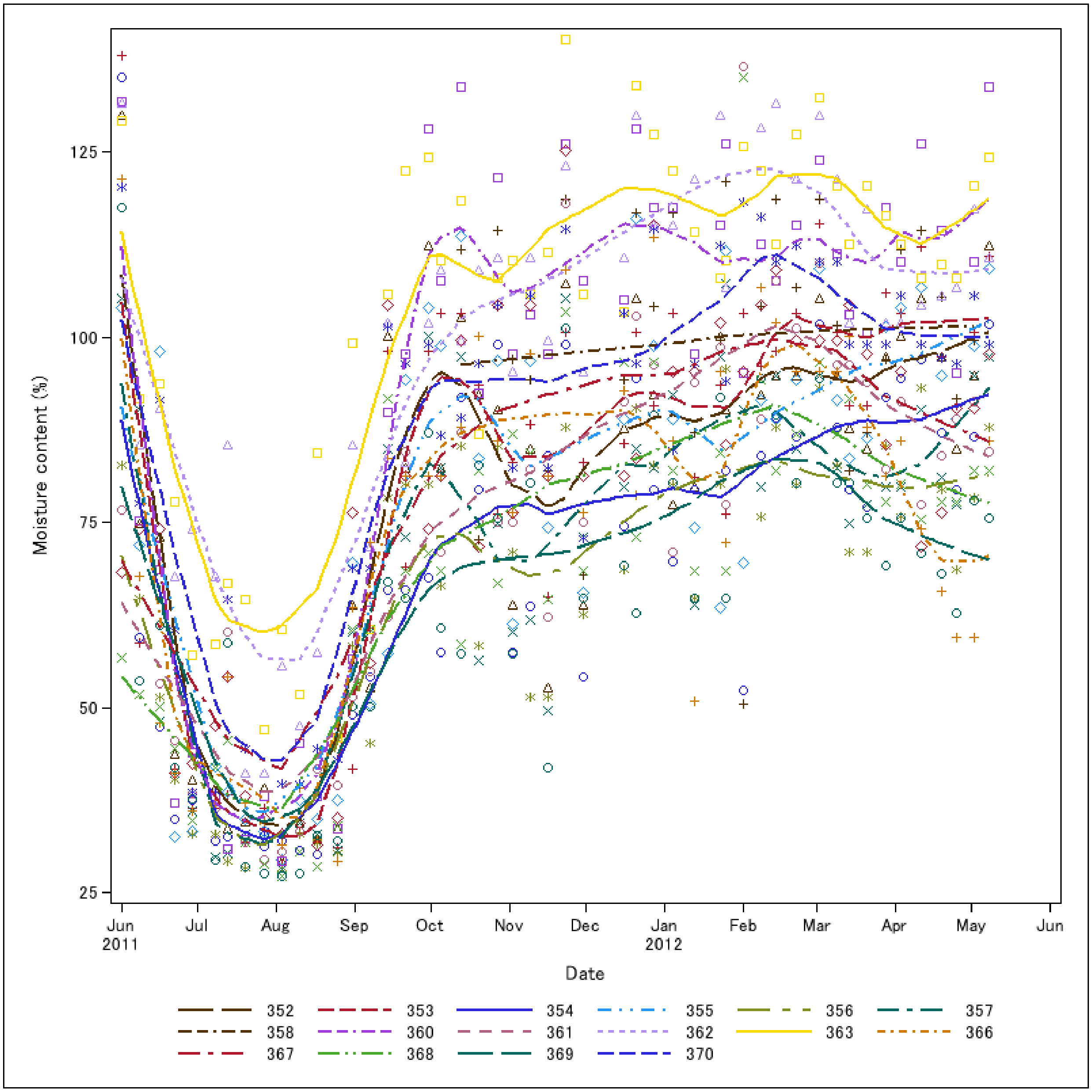

Figure 3.1 Predicted MC of all trees at the Lower Coastal Plain site.

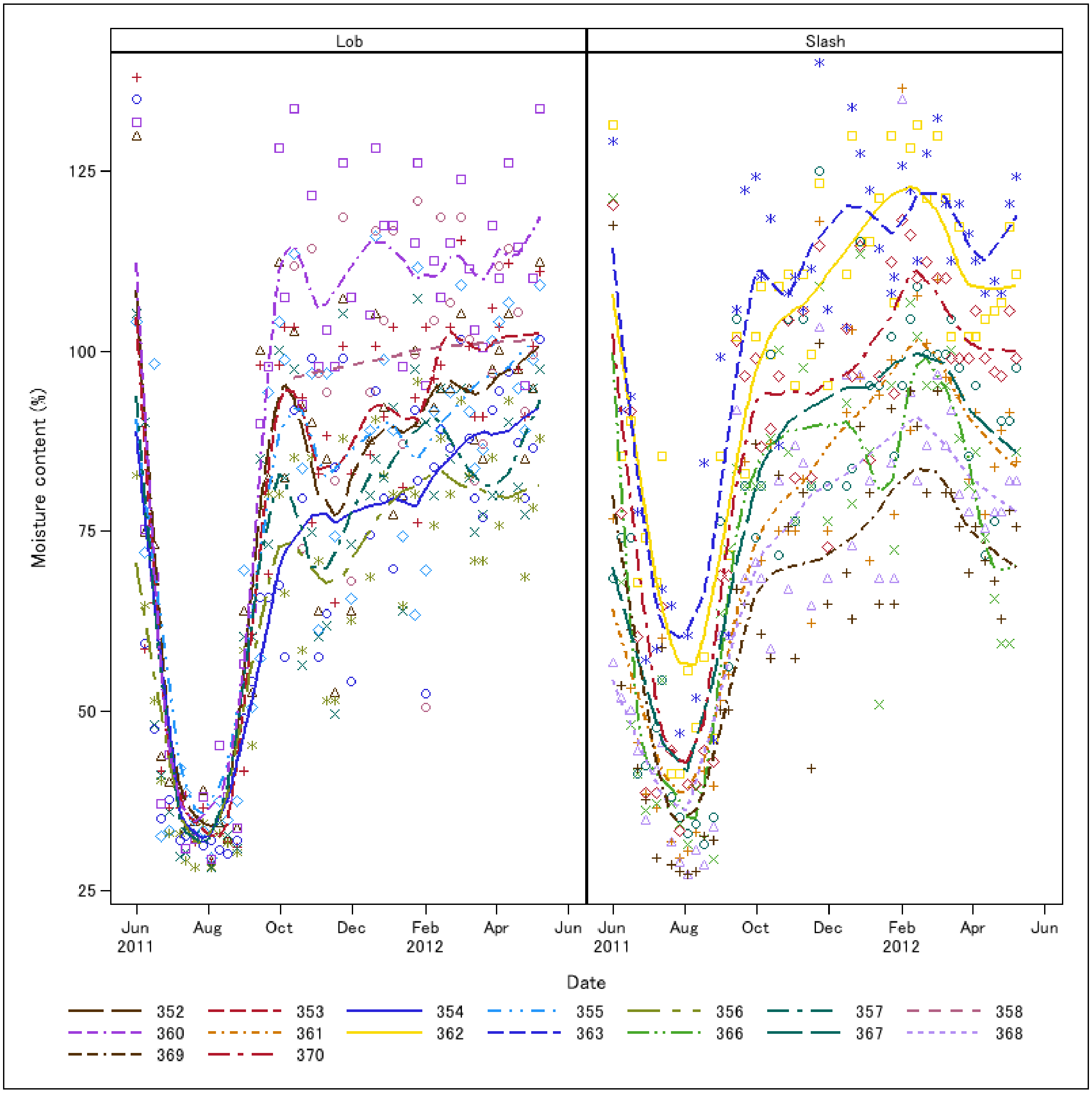

Figure 3.2. Predicted MC of *P. taeda* (loblolly pine) and *P. elliottii* (slash pine) trees at the Lower Coastal Plain site.

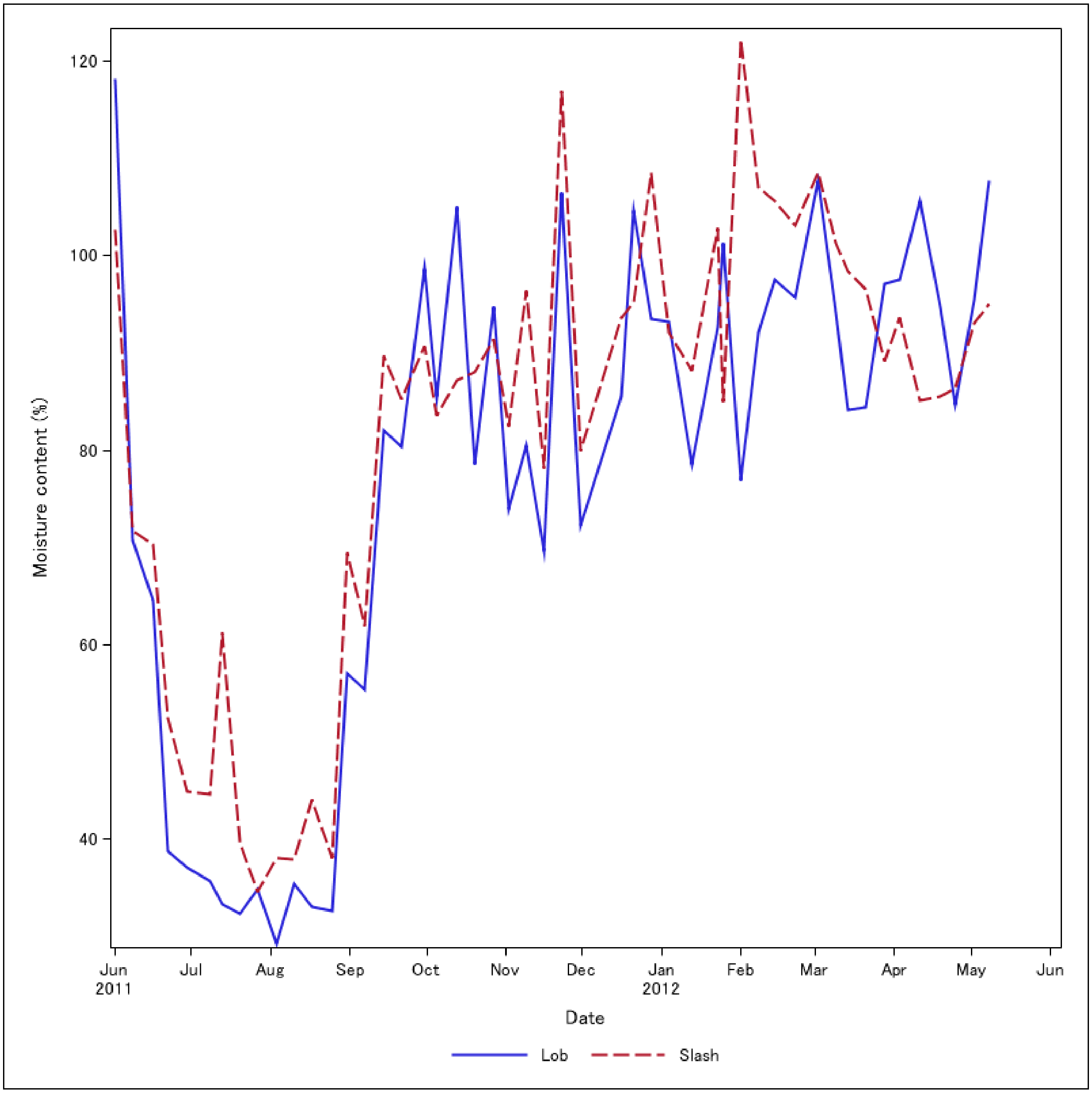

Figure 3.3. Average predicted MC for of *P. taeda* (loblolly pine) and *P. elliottii* (slash pine) at the Lower Coastal Plain site.

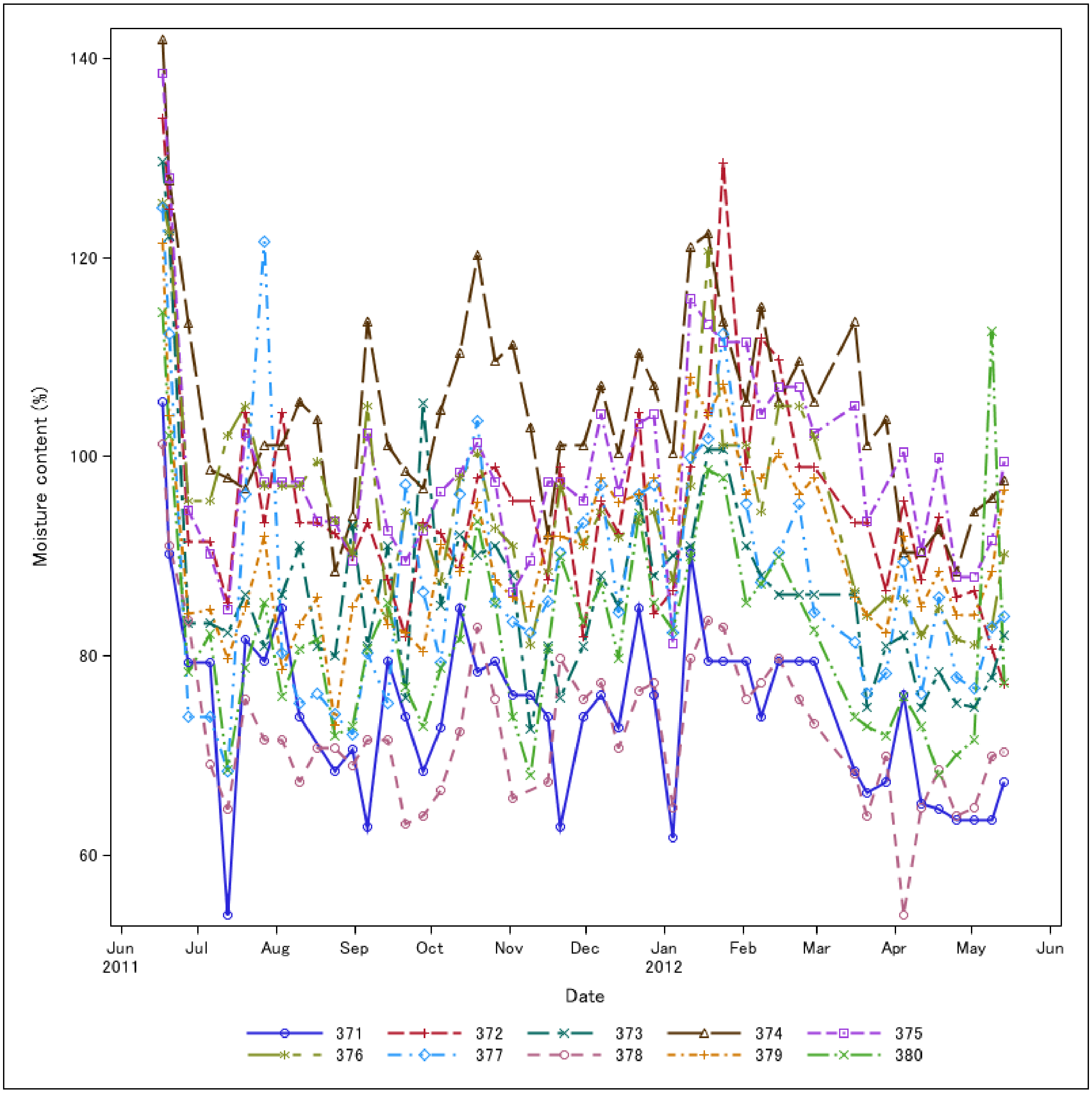

Figure 3.4. Predicted MC of all *P. taeda* trees at the Piedmont site.

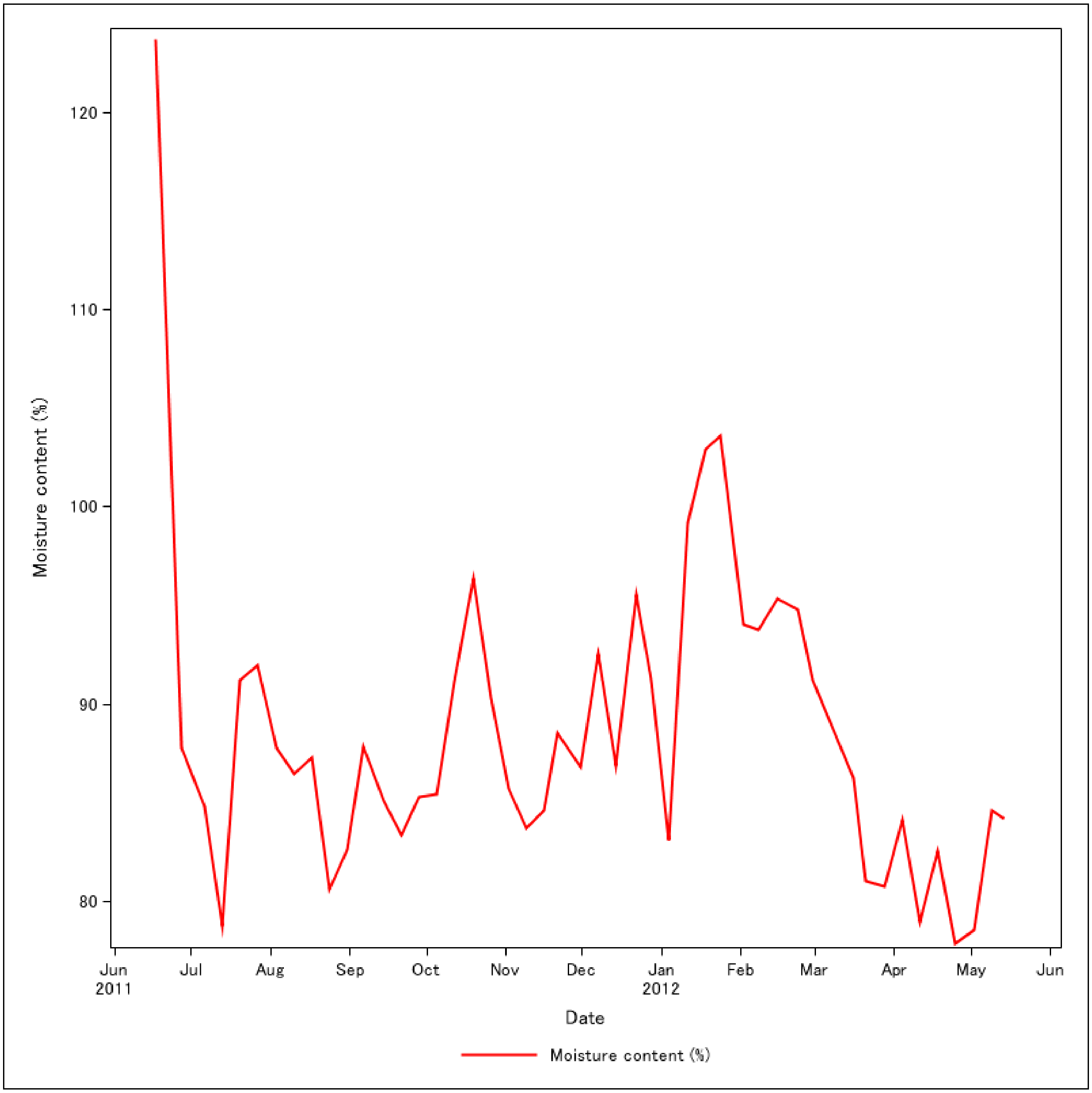

Figure 3.5. Average predicted MC for all *P. taeda* trees at the Piedmont site.

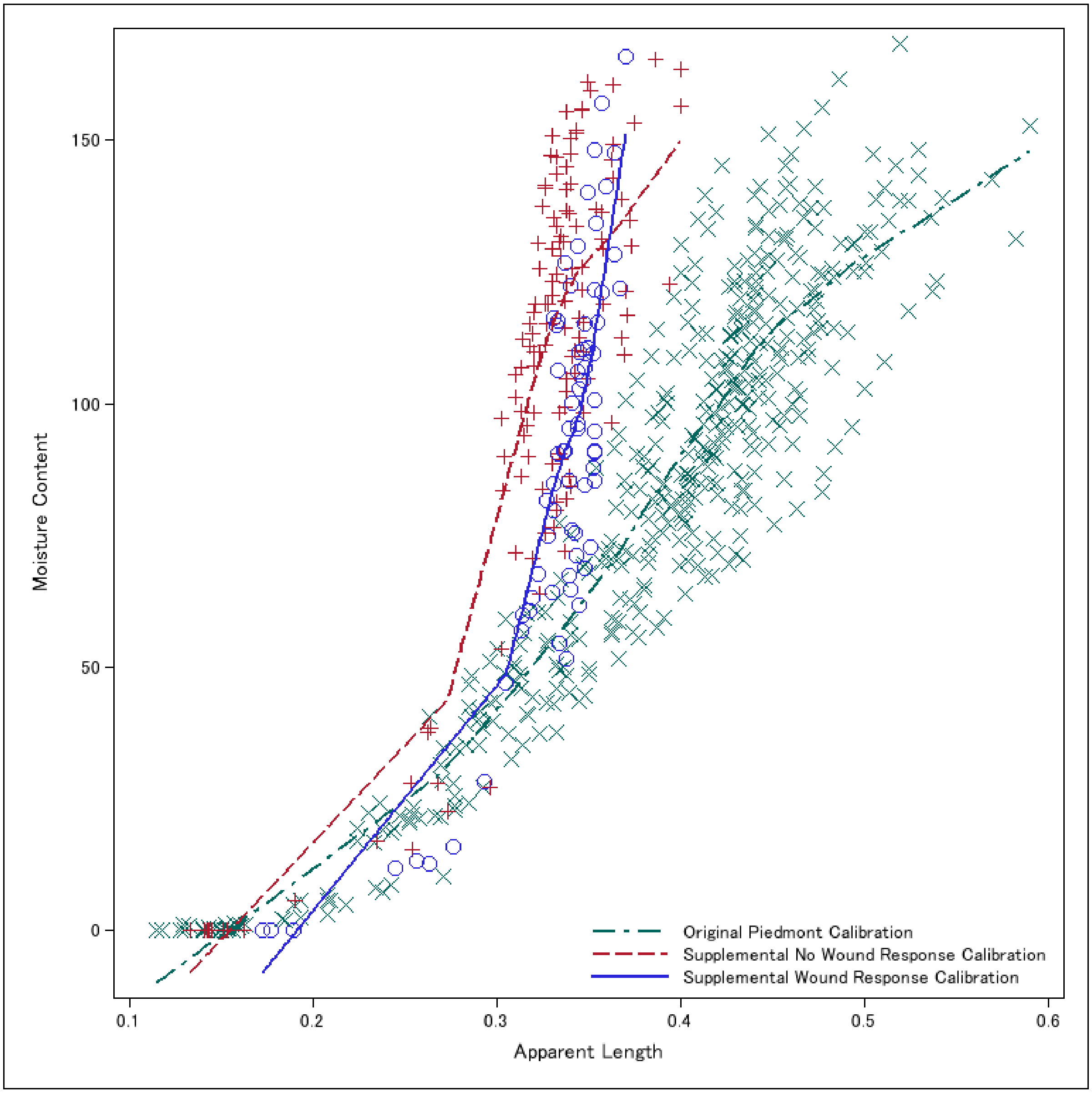

Figure 3.6. Original Piedmont calibration data along with supplemental calibration data.

Figure 3.7. The wound reaction zone of tree number 372 from the radial side. The black line is to emphasize the boundary. The wound response above the probe was left unaltered.

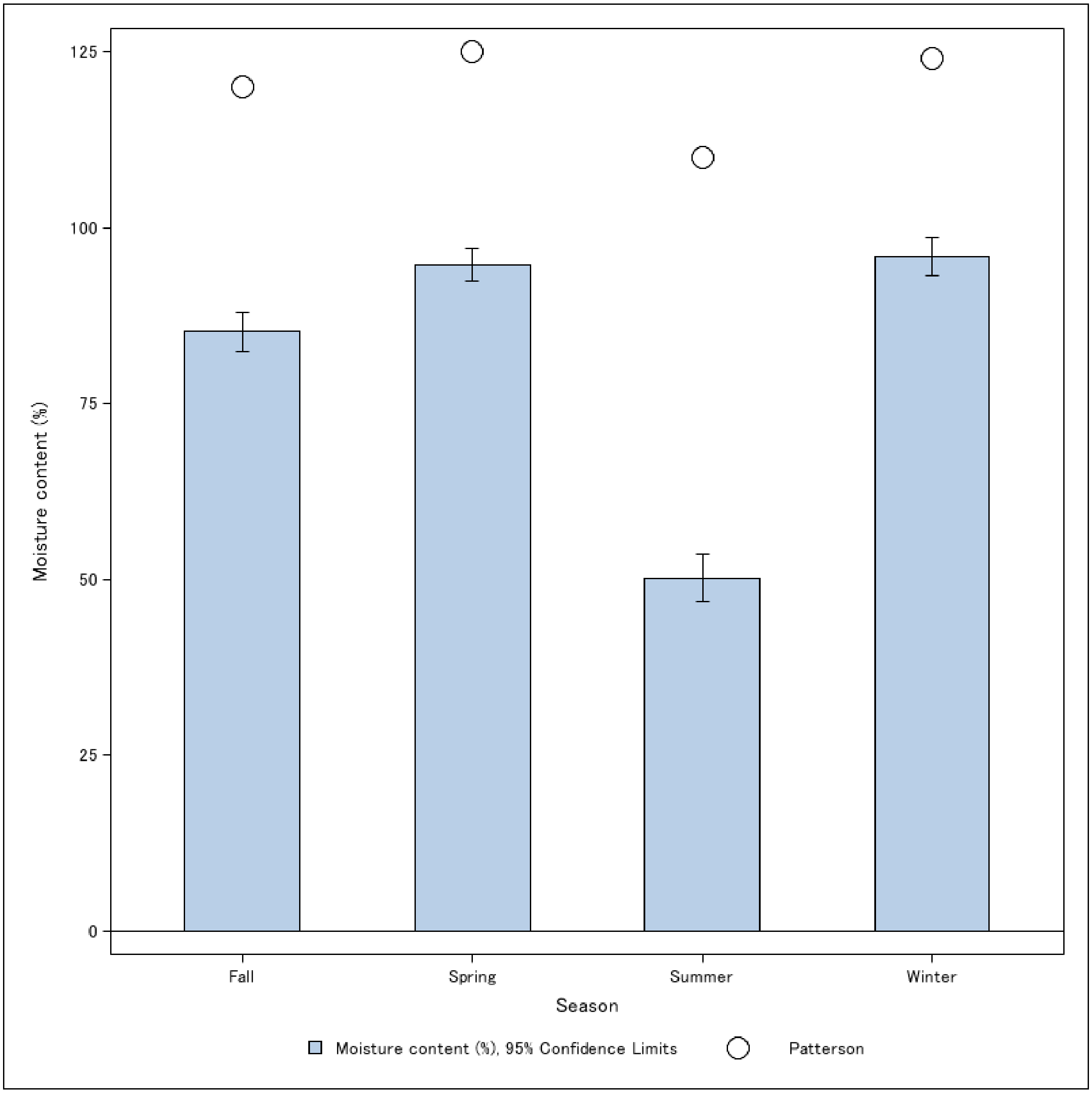

Figure 3.8. Average predicted MC of all Lower Coastal Plain trees and observed MC of mid-section of trees from Patterson and Doruska (2005) by season.

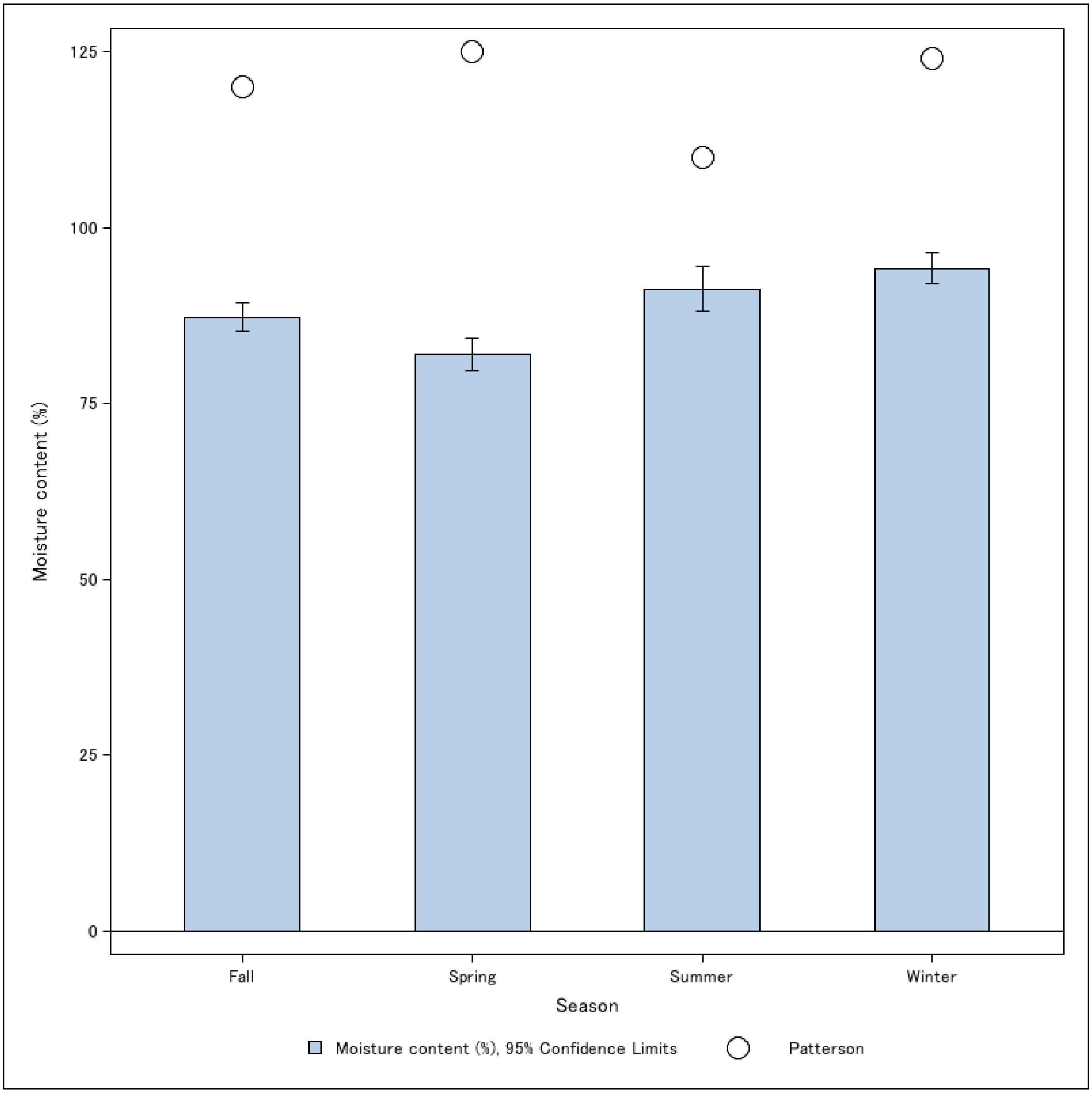

Figure 3.9. Average predicted MC of all Piedmont trees and observer MC of mid-section of trees from Patterson and Doruska (2005) by season.

Tables

Table 3.1. Summary of trees examined at the Lower Coastal Plain and Piedmont sites.

Species	Location	Mean*	Standard error
P. taeda	Piedmont	159	8.1
P. elliottii	LCP	127	2.5
P. taeda	LCP	139	2.8

*diameter (in mm) at 25% of total tree height

CHAPTER 4

CONCLUSIONS

Demand for an inexpensive and reliable way to predict moisture content (MC) in living trees is well recognized and TDR could potentially be used for this purpose. The estimation of standing tree MC using TDR was examined for two important commercial species *Pinus elliottii* Engelm. (slash pine) and *Pinus taeda* L. (loblolly pine) in this thesis.

Calibration data was collected in the Piedmont of Georgia for *P. taeda* from 22 trees with one bolt measured over time from each, along with bolts from 43 trees in the Lower Coastal Plain of northern Florida (21 *P. elliottii* Engelm. and 22 *P. taeda*). Moisture content predictions at a given apparent lengths for the two species at both locations are given in Appendices I through III to facilitate conversion of apparent lengths to MC in the field. The calibrations I developed strongly indicate one calibration curve will be sufficient for both species. It is probable the same applies for location but more research, using the same TDR to collect data from samples from different sites, will have to be done to verify if this is correct.

I developed my calibration with two TDR instruments because of the distance between the sites for the standing tree studies. The Piedmont data was collected with a 1502C metallic cable tester manufactured by Tektronix Inc. and the Lower Coastal Plain data was collected using a TV220 Cable Scout manufactured by tempo Textron. While there is a linear relationship between the outputs of the two devices I chose to develop specific curves for each device in order to maximize the accuracy of these predictions.

Variability among users in how they identify the inflection point on the oscilloscope display has proven to be a significant obstacle. Both of the instruments used in this research display a relative length in increments of 0.008m. While I believe this is sufficient to track changes in MC it becomes a problem when seen in relation to calibration data collected. Because of the steep nature of my calibration curve even a difference of 0.008m between two people collecting data becomes significant.

TDR based estimates of MC could be used to show MC trends for both species using either instrument, though it is important to recognize the Cable Scout TV220 (pulse type TDR) is less accurate. These calibrations appear to be more suited to monitoring MC in harvested wood, i.e. logs in wet decks, untreated utility poles, and large construction beams. Results from utilizing these calibrations on living trees suggest further research is necessary before accurate predictions could be made.

Calibrations developed in Chapter 2 were utilized to monitor MC in 30 pine trees in the Southeastern United States for a period of one year. Probes were inserted into 10 *P. elliottii* and 10 *P. taeda* in the Lower Coastal Plain and 10 *P. taeda* in the Piedmont.

The two sites behaved quite differently with Lower Coastal Plain predicted MC beginning in the normal range then dropping rapidly to nearly 30% then rising to between 60% and 120% for the remainder of the year. Piedmont predictions began between110% and 140% MC and also dropped rapidly but leveled off between 70% and 100% for the rest of the year. Average MC expected for sapwood in live southern yellow pines is 110% ("Wood Handbook"). It is my belief the low predictions from the study and initial drop in predicted MC were both caused by wound response of the trees studied.

To account for the effect of wound response on TDR readings I attempted a supplemental calibration. Results from this supplemental calibration showed almost no change in apparent length with regard to MC for trees with existing probes or with new probes. Since both new data sets showed the same characteristics I began to evaluate differences between the two new data sets and the original calibration data. The most obvious difference was original calibration bolts were saturated to insure entire range of MC could be observed while supplemental calibration was felled and taken to the lab for data collection without any additional saturation. It is possible saturated logs did not mount a chemical defense because all biological activity had ceased by the time probes were installed. Further research into hypersensitive response in pines suggested both differences between the two calibrations and the two study sites may have been caused by chemical responses of sampled trees to probe wounds and local pathogens.

It is possible a calibration that works on standing trees could be developed. Assuming pathogens are responsible for differences in MC predictions between sites then the focus of the next study should involve standardizing wound response. Size and shape of the hypersensitivity reaction area will have to be considered during calibration and field studies. If a strong fungicide was used during probe installation, and trees were allowed to respond to injury before being cut for soaking and subsequent development of a new calibration, then a new calibration for standing trees may be effective. The same process would have to be done when installing probes in the field.

The future of TDR for prediction of MC in wood will depend on refining the method and establishing a better understanding of factors that influence TDR readings. In time, TDR could be used by utility companies to track changes in telephone poles, arborists to monitor health of high value specimens, and foresters to track progress of disease and insect infestations. More research needs to be done, but this technique has potential to be a valuable tool for natural resource professionals across a wide variety of disciplines.

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Appendix I

Predicted moisture content for the Piedmont *Pinus taeda* L. (loblolly pine) based on data collected using the Tektronix TDR

	Diameter at Probe (cm)					
Apparent Length (m)	10	11	12	13	14	15
0.200	5.1%	5.3%	5.5%	5.7%	5.9%	6.1%
0.210	6.7%	7.0%	7.2%	7.5%	7.8%	8.0%
0.220	8.6%	8.9%	9.3%	9.6%	9.9%	10.3%
0.230	10.7%	11.2%	11.6%	12.0%	12.4%	12.9%
0.240	13.2%	13.7%	14.2%	14.7%	15.3%	15.8%
0.250	15.9%	16.5%	17.1%	17.8%	18.4%	19.0%
0.260	18.9%	19.6%	20.4%	21.1%	21.8%	22.6%
0.270	22.1%	23.0%	23.8%	24.7%	25.6%	26.4%
0.280	25.5%	26.5%	27.5%	28.5%	29.5%	30.5%
0.290	29.1%	30.3%	31.4%	32.6%	33.7%	34.9%
0.300	32.9%	34.2%	35.5%	36.8%	38.1%	39.4%
0.310	36.9%	38.3%	39.8%	41.2%	42.7%	44.1%
0.320	40.9%	42.5%	44.1%	45.7%	47.3%	48.9%
0.330	45.0%	46.7%	48.5%	50.3%	52.0%	53.8%
0.340	49.1%	51.0%	53.0%	54.9%	56.8%	58.8%
0.350	53.3%	55.4%	57.5%	59.5%	61.6%	63.7%
0.360	57.4%	59.7%	61.9%	64.2%	66.4%	68.7%
0.370	61.5%	63.9%	66.4%	68.8%	71.2%	73.6%
0.380	65.6%	68.2%	70.8%	73.3%	75.9%	78.5%
0.390	69.6%	72.3%	75.1%	77.8%	80.6%	83.3%
0.400	73.5%	76.4%	79.3%	82.2%	85.1%	88.0%
0.410	77.3%	80.4%	83.4%	86.5%	89.5%	92.5%
0.420	81.0%	84.2%	87.4%	90.6%	93.8%	97.0%
0.430	84.6%	88.0%	91.3%	94.6%	98.0%	101.3%
0.440	88.1%	91.6%	95.0%	98.5%	102.0%	105.4%
0.450	91.4%	95.0%	98.6%	102.2%	105.8%	109.4%
0.460	94.6%	98.4%	102.1%	105.8%	109.5%	113.3%
0.470	97.7%	101.5%	105.4%	109.2%	113.1%	116.9%
0.480	100.6%	104.6%	108.6%	112.5%	116.5%	120.4%
0.490	103.4%	107.5%	111.6%	115.6%	119.7%	123.8%
0.500	106.1%	110.3%	114.4%	118.6%	122.8%	127.0%
0.510	108.6%	112.9%	117.2%	121.4%	125.7%	130.0%
0.520	111.0%	115.4%	119.8%	124.1%	128.5%	132.9%
0.530	113.3%	117.7%	122.2%	126.7%	131.1%	135.6%
0.540	115.4%	120.0%	124.5%	129.1%	133.6%	138.2%

Apparent Length (m)	Diameter at Probe (cm) 10	11	12	13	14	15
0.550	117.5%	122.1%	126.7%	131.3%	136.0%	140.6%
0.560	119.4%	124.1%	128.8%	133.5%	138.2%	142.9%
0.570	121.2%	125.9%	130.7%	135.5%	140.3%	145.0%
0.580	122.9%	127.7%	132.5%	137.4%	142.2%	147.1%
0.590	124.5%	129.4%	134.3%	139.2%	144.1%	149.0%
0.600	126.0%	130.9%	135.9%	140.8%	145.8%	150.8%
0.610	127.4%	132.4%	137.4%	142.4%	147.4%	152.5%
0.620	128.7%	133.8%	138.8%	143.9%	149.0%	154.0%

Appendix II

Predicted moisture content for the Lower Coastal Plain *Pinus elliottii* Engelm. (slash pine) based on data collected using the Cable Scout TDR

Apparent Length (m)	Diameter at Probe (cm) 10	11	12	13	14	15
0.010	21.5%	21.5%	21.5%	21.5%	21.5%	21.5%
0.020	21.5%	21.5%	21.5%	21.5%	21.5%	21.5%
0.030	21.5%	21.5%	21.5%	21.5%	21.5%	21.5%
0.040	21.6%	21.5%	21.5%	21.5%	21.5%	21.5%
0.050	21.6%	21.5%	21.5%	21.5%	21.5%	21.5%
0.060	21.6%	21.6%	21.5%	21.5%	21.5%	21.5%
0.070	21.6%	21.6%	21.6%	21.6%	21.6%	21.6%
0.080	21.6%	21.6%	21.6%	21.6%	21.6%	21.6%
0.090	21.7%	21.6%	21.6%	21.6%	21.6%	21.6%
0.100	21.7%	21.7%	21.6%	21.6%	21.6%	21.6%
0.110	21.8%	21.7%	21.7%	21.6%	21.6%	21.6%
0.120	21.8%	21.7%	21.7%	21.7%	21.7%	21.7%
0.130	21.9%	21.8%	21.7%	21.7%	21.7%	21.7%
0.140	21.9%	21.8%	21.8%	21.8%	21.8%	21.8%
0.150	22.0%	21.9%	21.9%	21.8%	21.8%	21.8%
0.160	22.2%	22.0%	21.9%	21.9%	21.9%	21.9%
0.170	22.3%	22.1%	22.0%	22.0%	22.0%	22.0%
0.180	22.4%	22.2%	22.1%	22.1%	22.0%	22.1%
0.190	22.6%	22.4%	22.2%	22.2%	22.2%	22.2%
0.200	22.9%	22.6%	22.4%	22.3%	22.3%	22.3%
0.210	23.1%	22.8%	22.6%	22.5%	22.5%	22.5%
0.220	23.4%	23.0%	22.8%	22.7%	22.6%	22.7%
0.230	23.8%	23.3%	23.0%	22.9%	22.9%	22.9%
0.240	24.3%	23.7%	23.4%	23.2%	23.1%	23.2%
0.250	24.8%	24.1%	23.7%	23.5%	23.5%	23.6%
0.260	25.5%	24.6%	24.1%	23.9%	23.9%	24.0%
0.270	26.2%	25.2%	24.7%	24.4%	24.3%	24.5%
0.280	27.1%	25.9%	25.3%	24.9%	24.9%	25.0%
0.290	28.2%	26.8%	26.0%	25.6%	25.5%	25.7%
0.300	29.4%	27.8%	26.8%	26.4%	26.3%	26.5%
0.310	30.8%	28.9%	27.8%	27.3%	27.2%	27.5%
0.320	32.5%	30.3%	29.0%	28.4%	28.2%	28.6%
0.330	34.5%	31.9%	30.4%	29.6%	29.5%	29.9%
0.340	36.8%	33.8%	32.0%	31.1%	30.9%	31.4%
0.350	39.4%	36.0%	33.9%	32.9%	32.7%	33.2%

Apparent Length (m)	Diameter at Probe (cm) 10	11	12	13	14	15
0.360	42.4%	38.4%	36.1%	34.9%	34.6%	35.3%
0.370	45.8%	41.3%	38.6%	37.2%	36.9%	37.7%
0.380	49.6%	44.5%	41.5%	39.9%	39.6%	40.4%
0.390	53.8%	48.2%	44.8%	43.0%	42.6%	43.5%
0.400	58.4%	52.3%	48.4%	46.4%	46.0%	47.1%
0.410	63.5%	56.8%	52.5%	50.3%	49.8%	51.0%
0.420	68.9%	61.7%	57.1%	54.6%	54.1%	55.4%
0.430	74.6%	67.0%	62.0%	59.3%	58.8%	60.2%
0.440	80.6%	72.6%	67.3%	64.5%	63.8%	65.4%
0.450	86.7%	78.5%	73.0%	69.9%	69.3%	70.9%
0.460	92.8%	84.6%	78.9%	75.7%	75.0%	76.7%
0.470	99.0%	90.7%	84.9%	81.7%	81.0%	82.7%
0.480	105.0%	96.9%	91.1%	87.8%	87.1%	88.9%
0.490	110.7%	102.9%	97.3%	94.0%	93.3%	95.0%
0.500	116.2%	108.8%	103.3%	100.1%	99.4%	101.1%
0.510	121.3%	114.4%	109.1%	106.1%	105.4%	107.1%
0.520	126.1%	119.6%	114.7%	111.8%	111.1%	112.7%
0.530	130.4%	124.5%	119.9%	117.2%	116.6%	118.1%
0.540	134.2%	128.9%	124.8%	122.3%	121.7%	123.1%
0.550	137.7%	133.0%	129.2%	126.9%	126.4%	127.6%
0.560	140.8%	136.6%	133.2%	131.1%	130.6%	131.8%
0.570	143.4%	139.8%	136.8%	134.9%	134.5%	135.5%
0.580	145.8%	142.6%	139.9%	138.3%	137.9%	138.8%
0.590	147.8%	145.0%	142.7%	141.3%	141.0%	141.8%
0.600	149.5%	147.1%	145.2%	143.9%	143.6%	144.3%
0.610	151.0%	149.0%	147.3%	146.2%	145.9%	146.5%
0.620	152.3%	150.6%	149.1%	148.2%	147.9%	148.5%

Appendix III

Predicted moisture content for the Lower Coastal Plain *Pinus taeda* L. (loblolly pine) based on data collected using the Cable Scout TDR

Apparent Length (m)	Diameter at Probe (cm) 10	11	12	13	14	15
0.010	21.5%	21.5%	21.5%	21.5%	21.5%	21.5%
0.020	21.5%	21.5%	21.5%	21.5%	21.5%	21.5%
0.030	21.6%	21.5%	21.5%	21.5%	21.5%	21.5%
0.040	21.6%	21.5%	21.5%	21.5%	21.5%	21.5%
0.050	21.6%	21.6%	21.5%	21.5%	21.5%	21.5%
0.060	21.6%	21.6%	21.6%	21.6%	21.6%	21.6%
0.070	21.6%	21.6%	21.6%	21.6%	21.6%	21.6%
0.080	21.7%	21.6%	21.6%	21.6%	21.6%	21.6%
0.090	21.7%	21.6%	21.6%	21.6%	21.6%	21.6%
0.100	21.7%	21.7%	21.6%	21.6%	21.6%	21.6%
0.110	21.8%	21.7%	21.7%	21.7%	21.7%	21.7%
0.120	21.8%	21.8%	21.7%	21.7%	21.7%	21.7%
0.130	21.9%	21.8%	21.8%	21.7%	21.7%	21.7%
0.140	22.0%	21.9%	21.8%	21.8%	21.8%	21.8%
0.150	22.1%	22.0%	21.9%	21.8%	21.8%	21.9%
0.160	22.2%	22.0%	22.0%	21.9%	21.9%	21.9%
0.170	22.3%	22.2%	22.1%	22.0%	22.0%	22.0%
0.180	22.5%	22.3%	22.2%	22.1%	22.1%	22.1%
0.190	22.7%	22.5%	22.3%	22.2%	22.2%	22.3%
0.200	23.0%	22.6%	22.5%	22.4%	22.4%	22.4%
0.210	23.2%	22.9%	22.7%	22.6%	22.5%	22.6%
0.220	23.6%	23.1%	22.9%	22.8%	22.7%	22.8%
0.230	24.0%	23.5%	23.2%	23.0%	23.0%	23.1%
0.240	24.5%	23.8%	23.5%	23.3%	23.3%	23.4%
0.250	25.1%	24.3%	23.9%	23.7%	23.6%	23.7%
0.260	25.7%	24.8%	24.3%	24.1%	24.0%	24.2%
0.270	26.5%	25.5%	24.9%	24.6%	24.5%	24.7%
0.280	27.5%	26.2%	25.5%	25.2%	25.1%	25.3%
0.290	28.6%	27.1%	26.3%	25.9%	25.8%	26.0%
0.300	29.9%	28.2%	27.2%	26.7%	26.6%	26.9%
0.310	31.5%	29.5%	28.3%	27.7%	27.6%	27.9%
0.320	33.3%	30.9%	29.5%	28.9%	28.7%	29.1%
0.330	35.4%	32.6%	31.0%	30.2%	30.0%	30.5%
0.340	37.8%	34.6%	32.8%	31.8%	31.6%	32.1%
0.350	40.6%	37.0%	34.8%	33.7%	33.4%	34.0%

Apparent Length (m)	Diameter at Probe (cm) 10	11	12	13	14	15
0.360	43.8%	39.6%	37.1%	35.8%	35.6%	36.2%
0.370	47.4%	42.7%	39.8%	38.3%	38.0%	38.8%
0.380	51.5%	46.1%	42.9%	41.2%	40.8%	41.7%
0.390	56.0%	50.0%	46.4%	44.5%	44.1%	45.1%
0.400	61.0%	54.4%	50.3%	48.2%	47.7%	48.8%
0.410	66.4%	59.2%	54.7%	52.3%	51.8%	53.1%
0.420	72.2%	64.5%	59.5%	56.9%	56.3%	57.7%
0.430	78.3%	70.1%	64.8%	62.0%	61.3%	62.9%
0.440	84.6%	76.1%	70.5%	67.4%	66.8%	68.4%
0.450	91.2%	82.4%	76.5%	73.3%	72.6%	74.3%
0.460	97.8%	88.9%	82.8%	79.5%	78.7%	80.5%
0.470	104.3%	95.5%	89.3%	85.9%	85.1%	87.0%
0.480	110.7%	102.1%	95.9%	92.4%	91.6%	93.5%
0.490	116.9%	108.6%	102.5%	99.0%	98.2%	100.1%
0.500	122.8%	114.8%	109.0%	105.6%	104.8%	106.6%
0.510	128.2%	120.8%	115.2%	111.9%	111.2%	113.0%
0.520	133.3%	126.4%	121.2%	118.1%	117.3%	119.0%
0.530	137.9%	131.6%	126.7%	123.8%	123.2%	124.8%
0.540	142.0%	136.4%	131.9%	129.2%	128.6%	130.1%
0.550	145.7%	140.7%	136.6%	134.2%	133.6%	135.0%
0.560	149.0%	144.5%	140.9%	138.7%	138.2%	139.4%
0.570	151.9%	147.9%	144.7%	142.8%	142.3%	143.4%
0.580	154.4%	150.9%	148.1%	146.4%	146.0%	147.0%
0.590	156.5%	153.6%	151.1%	149.6%	149.2%	150.1%
0.600	158.4%	155.8%	153.7%	152.4%	152.1%	152.8%
0.610	160.0%	157.8%	156.0%	154.8%	154.5%	155.2%
0.620	161.4%	159.5%	157.9%	156.9%	156.7%	157.2%