Within-tree Fuel Quality of Loblolly Pine (*Pinus taeda*)

by

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Abstract

There is a lack of knowledge in the whole tree's fuel quality and how that quality might change within the tree or between size classes of trees. A sample set of 20 loblolly pines (5 trees within 4 diameter at breast height (DBH) size classes) were sampled at 5 cuts across the trunk and 4 sections of the tree's crown and limbs with respective height and diameter measurements. Fuel quality in this study specifically measured and compared the proximate analysis, higher heating value, and the ultimate analysis of loblolly pine crowns and ash content, density, higher heating value, and ultimate analysis of loblolly pine bark-free stemwood.

Ash content (db.) comparisons and correlations were found to progressively increase on average from the base of the tree (0.36%) to the top of the crown (1.68%). Higher heating value increased from the lowest stemwood section (20.878 MJ/kg) to the highest crown section (21.381MJ/kg) and is significantly larger than all of the stemwood disc sections. It was discovered the current notion of ash's negative effect on energy content is not supported with the finding of minimal increase of authigenic ash content as it changes across the tree's total height in both the crown and the stemwood sections. Individual regression results on each tree found a general increase in ash correlated to diameter of the respective crown and stemwood disc sections, not the height. DBH class regression results yielded only the tree's DBT as the only indicator for predicting ash content and HHV.

Ultimate analysis yielded the chemical composition of the loblolly pine samples. In crown sections, Dulong calculations consistently underestimate the HHV of crown samples with a root mean square error (RMSE) of 2.80 MJ/kg and Boie equation estimates the crown sample HHV much better with a RMSE of 1.09 MJ/kg. Double bark thickness in both stemwood and crown regression analysis was shown to be the only significant variable to understand the ash and HHV variability within individual trees. Proportional sections as determined by the tree's total height and crown length proved to be useful in determining fuel quality changes. The lower half of tree crowns can be utilized as a bioenergy feedstock if harvested with only authigenic ash content is low enough (<1%) for the combustion process. The residue could be gathered and processed into chips or pellets to use in high-valued fuel processes or fossil fuel co-combustion. The results from this study is useful for bioenergy fuel quality purposes and can serve as a baseline for understanding the fuel quality variability between tree components on a per tree or DBH class.

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Chapter 1: Introduction

Lignocellulosic biomass is the only feedstock for renewable energy capable of producing combustible liquid fuels. The predicted contributions of wood and other biomass energy allocations are expected to nearly double by 2020 and generate 24.7 billion kWh. As a response to meet this increase in demand for woody biomass, short rotation woody crops (SWRC) are now purposefully grown (Abt et al., 2014; Hinchee et al., 2009; Mercker, 2007), and they only require 1-3 years to mature. However due to harvesting frequency of SRWC, soil nutrients are quickly depleted from the forest floor. The quality of the feedstock makes it attractive to turn into liquid fuels or pellets (Nelson et al., 2013). The feedstock quality for pellets includes a low moisture content, (<10% d.b.), low ash percentage (<0.7% d.b.), and large net calorific value (between16.5 MJ/kg to 19.0 MJ/kg) (European Pellet Council, 2013). They are low economic value because SWRC do not have a large enough diameter to meet lumber or pulp demands and still are required to be chipped or ground into pellets before combustion.

In the United States, approximately 30% of every tree's total biomass is left as residue in the field after logging operations (U.S. Department of Energy, 2011). Annually, this adds up to approximately 68 million tons of dry woody biomass residue (Smith et al., 2009). The residues, consisting of tree tops, limbs, and foliage, pile at the logging landing site. With the tree's stripped of their crowns, and the crowns left behind in brush piles at the landing site, decomposing nutrients are never redistributed to the forest soil (Gautam et al., 2012; Giuntoli et al., 2015).

SWRC can only meet partial pellet and wood fuel demand, to meet this demand in the Southeastern United States, harvesting pine residues will be essential.

Loblolly pine trees dominate over 50% of the Southeastern United States forests, populating over 30 million acres (Smith, et al., 2009) and are vital feedstock for the lumber and paper mills. Loblolly pine has been deemed a model bioenergy candidate; it is available in large quantities, a harvesting system is well established, and it can be converted to high quality liquid fuels (Abt et al., 2014; U.S. Department of Energy, 2011).

Trees in general are not uniform in their quality as they change in height and can vary given a number of growth, location, climate, and management factors (Daniels et al., 2002; Landsberg et al, 2001; Megraw, 1985). There is an underlying intrinsic set of properties regarding strength and durability for using loblolly pine as lumber at varying heights in the stemwood (Antony et al., 2011; Schimleck et al., 2005). The measuring techniques used to determine if loblolly pines are suitable for use as lumber might also be used to determine its suitability for using logging residues effectively as fuel.

When forests are purposefully grown to only use the trunk of the tree as in short rotation plantations for bioenergy processes, it contributes to the logging residue problem (Hinchee et al., 2009; Mercker, 2007). Trees selected and harvested based on lumber quality properties leave behind a potential feedstock for bioenergy. However it is not well understood how the fuel quality properties change throughout the height of loblolly pines, making it difficult to economically harvest the tree tops. Measuring and understanding the fuel quality properties within an entire tree allows an increased yield during tree harvesting which leads to economic gains in the bioenergy sector of forestry.

This study tested samples of loblolly pine trees at different diameters and heights, between the stemwood and the crown, and gathered fuel quality characteristics : density, moisture content, ash percentage, and energy content. After comparing results between the classes of trees and sections, we determined which of the proposed models and logical input variables are most useful to predict fuel characteristics.

1.1 Objectives

To achieve these goals, the following objectives were carried out:

1. Investigate the effect of within tree variability, i.e. across tree heights and diameters, between crown and stemwood on fuel quality parameters, specifically proximate analysis and higher heating value.
2. Determine the effect among individual trees, i.e. across DBH classes and crown variability, on fuel quality parameters, specifically ash content and, higher heating value.
3. Investigate the effect of chemical composition on higher heating value for loblolly pine crown and stemwood.

Chapter 2: Literature Review

2.1 Logging Residue: an untapped resource

Forests are essential to the United States and provide many resources for civil development and ecosystems for wildlife. The Southeastern region accounts for 55% of the forest land in the United States and annually produces roughly 64% of the national total wood harvest (Smith et al., 1997). This is due to the abundance and variety of species in both hardwood and softwoods in the Southeastern region of the United States. Wood is a valuable engineering material because of the variety of species, strength to weight ratio, chemical composition, workability, and easy access to a renewable resource (Forest Products Laboratory, 2010). Forests in the Southeastern United States contribute to the lumber and paper mills.

There are two main categories of trees, which dictate the tree's value: hardwoods and softwoods. Softwoods are a major feedstock for timber, pulp and paper, and bioenergy production. This is due to their fast growing rates, yielding 4 dry tons per acre annually (Mercker, 2007), and inexpensive costs of production by the non-industrial forest landowners. Softwood species include the southern yellow pine species: loblolly pine, longleaf pine, slash pine, shortleaf pine, and other species. Their needles are often baled and used as an alternative for mulch in landscaping. Industrialized harvesting of southern yellow pines supplies the world with 18% of the world's timber production, which makes the United States the world's largest single wood producer. A model candidate for bioenergy and timber production from southern yellow pine is the loblolly pine species (Forest Products Laboratory, 2010; Nelson et al., 2013; U.S. Department of Energy, 2011). In short rotation woody crops, its used as bioenergy feedstock but it's residues from the pulpwood and round wood forests can also contribute as feedstocks.

The loblolly pine residue's size is too small for lumber and too variable to sort for paper quality, but it can contribute as a feedstock for bioenergy production (Gautam et al., 2012; Nelson et al., 2013; U.S. Department of Energy, 2011). With the predicted contributions of wood and other biomass energy allocations projected to nearly double in 2020 to generate 24.7 billion kWh, harvesting residues will be essential to meet this demand (Conti, 2015). Justification for using the logging residues in heating or other energy production have faced the following: relatively high costs of production, combusting the residues contribute more to emissions, i.e., NO_x and SO_2, than natural gas, and the residue is inherently higher in ash content and contaminated with soil, yielding less energy output. Regulating biomass emission controls could help bring these factors down. However, life cycle analysis shows using natural gas for heating is still more harmful than using forest derived fuels in overall GHG emissions (Giuntoli et al., 2015).

The next part of this review will focus on loblolly pine (*Pinus taeda*), its characteristics, chemical composition, and valued uses.

2.2 Loblolly pine (*Pinus taeda*)

Loblolly pine, one of the Southern pine species, is the most abundant tree in the Southeastern United States, covering 55 million acres (Smith et. al., 2009). While it is classified as a softwood, it is one of the harder pines in strength testing and is greater in strength than some hardwoods (Meier, 2016). It is an important feedstock in the lumber, pulp, and paper industry. Loblolly pine thrives with optimal management and fertilizer application (Colberx et al., 1990), but it also grows well on reclaimed mine land and is competitive to naturally grown stands (Priest et al., 2015). Loblolly pine cultivation takes roughly 12-15 years for pulpwood and 23-30 years for saw timber purposes (Hinchee et al., 2009). In addition, loblolly pine can yield 4 tons/acre/year when grown in a 20-year rotation. The complete loblolly pine tree consists of the root, stump, merchantable stemwood, crown, and unmerchantable stem top (Figure 2.2) (Young, 1964). The merchantable stemwood is from the base of the cut to the predetermined length or minimum top diameter. The unmerchantable top includes the upper stemwood and branches. The whole tree section is also known as the above-ground biomass (AGB). Chemical composition and properties of the AGB is different among its three components: stemwood, bark, and the crown (Vassilev et al., 2010).

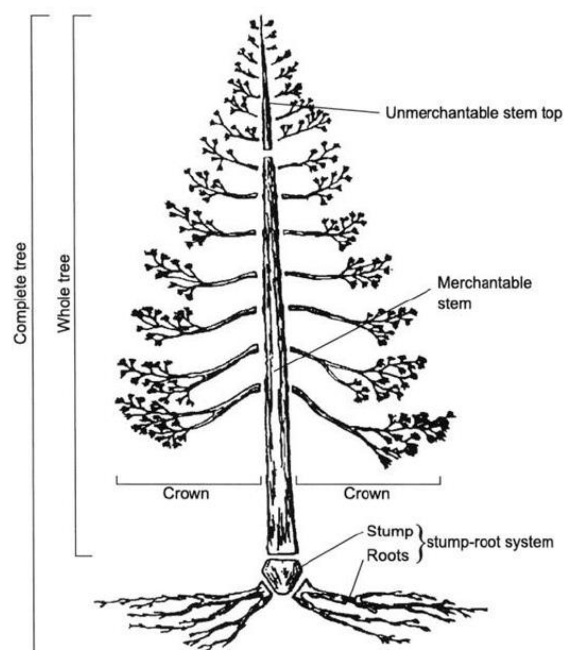

Figure 2.2 The biomass components of loblolly pine tree (redrawn from Young, 1964).

Based on species and size for their respective industry current loblolly pine forestry operations harvest trees: large trees at greater than 13” diameter at breast height (DBH) for timber, midsize trees at 10-13 in. DBH for chip-and saw (CNS) timber, smaller trees for pulp and paper with 6-9 in. DBH, and short rotation woody crops (SRWC) (1-3 years of age) for bio-energy production (Parajuli et al., 2016). Reports of tree acreage separate the forest stands by size and species. Forest farms have lead to size separation in labelling for optimal production, denoting some forests as timber land, pulpwood, and short rotation woody crops (SRWC) (U.S. of Energy, 2011). All sectors of forestry however, harvest the stemwood of the trees, leaving behind residues from each respective process (Figure 2.3). Utilizing certain sections of trees for valued-added products is not a new concept in the forest industry. Increasing strength properties in pulp and paper operations or reducing ash content in wood- fueled furnaces have propelled the idea to selectively use parts of trees.

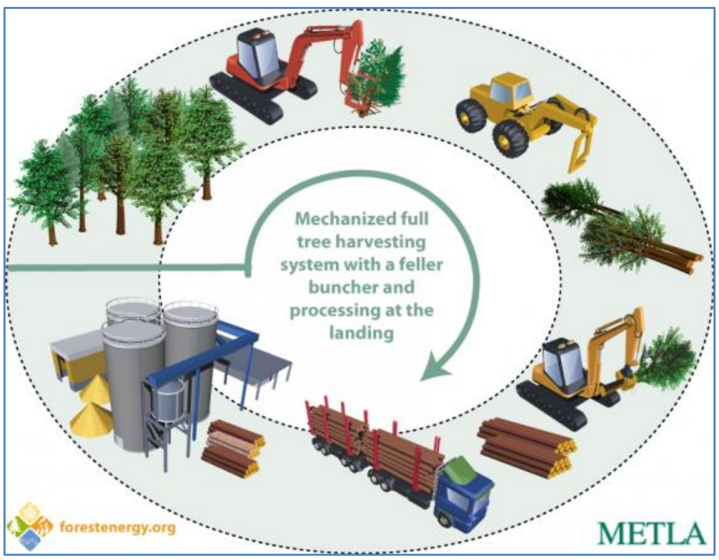

Figure 2.3 Harvesting system of a full tree to a landing for lumber processing. (Source: forestenergy.org)

Sustainability in forestry requires applicable sections of the same tree used in different industries. For instance, logging waste residues provide little economic gain as a decomposing fertilizer, but proper harvesting and gathering techniques can use this carbon source as fuel for energy. Lumber mills require the stemwood in the end product but often use the bark as fuel for heating the process or for the facility. Additionally, the stemwood in the unmerchantable top is applicable towards pulp and paper production. Ideally, a whole tree harvesting process provides feedstock for all three sectors of forestry.

Logging residues, though not commercially viable for timber or pulp, are still counted in the renewable biomass supply (U.S. Department of Energy, 2011). Removing logging residues will increase biomass yield but also removes available nutrients and solid carbon from the forest floor (Hacker, 2004). Ultimately, the concept of using logging residues for energy demands relies on the timber and pulp wood harvest (Figures 4a and 4b). The shift to focus on new species of SRWB has strived to meet this demand which logging residues could not. With the additional land use and growing inputs, the now prominent issue is the extra purpose-grown forest for energy production. Economics of harvesting logging residues or SRWB will drive this process to one forest type or another (Abt et al., 2014).

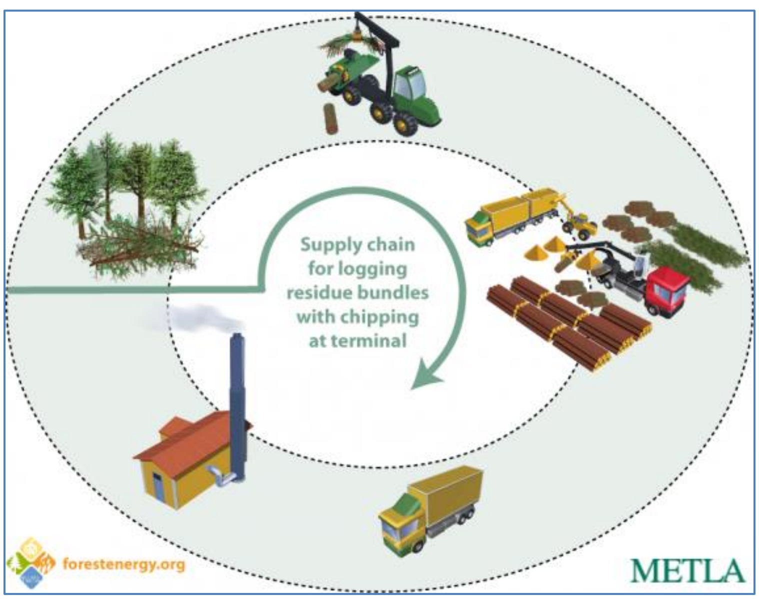

Figure 2.4a. Supply chain of logging residues post-harvest to use in combustion. (Source: forestenergy.org)

Figure 2.4b. Integrated harvest for logging residues and round wood. (Source: forestenergy.org)

2.3 Modeling Wood Quality

Generally, tree and stand quality falls into four main categories: merchantable volume in terms of stemwood and bark, unmerchantable volume, density, and moisture content. Other aspects of wood quality are specific to the lumber and paper industries such as modulus of elasticity (MOE), modulus of rupture (MOR), and microfibril angle (MFA).

2.3.1 Merchantable stemwood volume

In terms of forest and stand yield, merchantable volume is hard to measure directly and is more for a quantity than a quality factor. Quality in lumber wood includes the lack of knots, bends and spiral grain. Log size, however, is a quality for a particular product. Because larger trees are more suitable for lumber and paper mills, SRWB stands are used in the bioenergy sector. For example, 1 ton of wood as SRWB size stems and 1 ton of timber size stems might have the same mass but not the same quality of volume. Sampling techniques with DBH measurements has made this much simpler, however, with calibrated allometric models. In order to build these models, field data must be collected. The tree's DBH, along with incremental measurements of double bark thickness (DBT) and height (H) is capable of giving the tree volume including the bark (Hakkila, 1989). For economic success in utilizing whole trees for biomass and forest operations, planning and logistics require accurate volume predictions. Field measurements, i.e. DBH and total tree height (TTH), are used in calculating the total tree's merchantable stem wood volume (Cao & Burkhart, 1980). The merchantable stem is the most valued product of the loblolly pine tree because of its physical qualities to turn from timber into sawn lumber, veneer, or telephone poles. Volume ratio models and form factors are the main ways foresters and researchers predict a tree's merchantable volume before harvesting (Cao et al., 1980; Spurr, 1952).

Three common formulas exist to compute the tree volume (table 2.1). The common practice is to use Smalian's formula using the short sections of logs. Huber and Newton's formula often achieve a better computation and are more accurate, especially in southern pines where the butt log base swells and gives an inaccurate measure of uniform diameter throughout the section (Cao & Burkhart, 1980; Spurr, 1952). The ability to calculate volume estimations in field and the demand for precise forest growth prediction relies on diameter and length measurements.

Table 2.1 Common Tree Volume computations

Common Tree Volume Computation	Equations
Smalian Fomula	$V = \frac{(D_{bottom}+D_{top})}{2} * L$
Huber Formula	$V = D_{middle} * L$
Newton Formula	$V = \frac{(D_{bottom}+4D_{middle} + D_{top})}{6} * L$

The stemwood is the trunk of the tree and the most economically valuable section of the tree. It is divided into the unmerchantable stemwood, and the merchantable stemwood which vary in top diameter sizes depending on the lumber or pulp mill specifications. The stem is comprised of the pith, the earlywood and latewood annual growth rings, the xylem and phloem, tracheids, and the inner bark and outer bark. Although the stemwood appears physically uniform, there are vast differences of intrinsic properties between these sections (Burdon et al., 2004; McMillin, 1968). Figure 2.5a shows the abrupt transition from earlywood to latewood. Earlywood is produced rather quickly during the large photosynthetic periods of spring and summer. Latewood is denser, not as thick, and the cell walls are much smaller (Forest Products Laboratory, 2005). Figure 2.5b also shows the small holes of tracheids which conduct water and nutrients to the needles for photosynthesis and respiration. Latewood tracheids provide structural support and can be twice as long as the earlywood tracheids.

Figure 2.5 a (left) and b (right): A longitudinal cut of loblolly pine (with vertical axis) and latitudinal cut (horizontal axis) of loblolly pine. (Source: www.wood-database.com/loblolly-pine/)

Measuring a forest stands height and diameter assist in estimating the amount of wood available before harvest. Height measurement is a time-consuming process, requiring in-field calculations, and usually involve some measure of error (Spurr, 1952). DBH measurements, however, are relatively simple to measure, using tree calipers. Knowing a few key factors such as DBH, height, and age can predict the height of a tree stand and also project annual incremental height gain (Liu et al., 1995; McElligott & Bragg, 2013). Empirical equations for estimating tree volume has given rise to a large set of prediction equations specific to particular species in a certain region. Table 2.2 displays a few of these equations. Because stemwood is generally considered a mix of a cylinder, neiloid, paraboloid, and cone shape, the equations use square diameters and height measurements as the variables, similar to the Smalian, Huber, and Newton equations (table 2.1) (Spurr, 1952; Weiskittel et al., 2011). All of these add up to the forest's net primary production, NPP. NPP has been modeled to predict the outcome of rising carbon dioxide concentrations and their effect on loblolly pines (Sampson et al., 1998). Carbon dioxide and sunlight are the limiting reactants for photosynthesis reactions, and with an increase of CO_2 in the atmosphere, loblolly pine growing potential will be affected (Sampson et al., 1998).

Table 2.2 Tree Volume Estimation Equations (Spurr, 1952; West, 2009)

Tree Volume Empirical Equation Names	Estimation Equations
Comprehensive	$V = a + bD + cDH + dD^2 + eH + fD^2H$
Meyer	$V = a + bD + cDH + dD^2 + eD^2H$
Australian	$V = a + bD^2 + cH + dD^2H$
Combined variable	$V = a + bD^2H$
Constant form factor	$V = aD^2H$
Logarithmic combined variable	$\log(V) = \log(a) + b * log(D^2H)$

In table 2.2, a, b, c, d, e, & f are all empirically derived coefficients for different tree species and forest stands. D is DBH and H is total tree height. In the logarithmic combined variable model, log is assumed to be $\log_{10}$ but natural log (ln) has been used as well (B. W. Smith & Brand, 1983; Williams & Gregoire, 1993). The use of these equations has brought about site and specie specific tree volume models, and continuing this over time has developed yield and growth models (Clutter, 1963; Weiskittel et al., 2011)

A general assumption about the wood in trees is that uniformity exists throughout the trunk while the only thing that changes is the decreasing diameter size. However, properties of trees change with growing ages and the stemwood itself is full of variability. Specific gravity, MOE, MOR, MFA, are some of the properties which will vary within the trees and can affect the end product quality to the lumber and paper mills (Burdon et al., 2004; Megraw, 1985). Pith to bark models describe the radial variation that can explain the differences in properties (Daniels et al., 2002). For instance, the pith is sometime found as inferior for veneer applications, while latewood (the darker rings) are harder wood. Juvenile wood is usually fast growing wood in the core emerging the first few years around the pith. Mature wood consists of older rings and closer latewood rings which provide more stability in the tree (Burdon et al., 2004). The changes of latewood percentage affect the density at those heights, which in turn makes a stronger lumber board.

Sawdust and bark are commonly used as fuel for process heat in lumber and paper mills. However, once the local feedstock is consumed within the lumber or paper mill's reach, biomass will need to be sourced from other areas (Abt et al., 2014). Feedstock quality is always an issue in selecting process operating parameters (Taylor et al., 2012). If the lumber and paper quality of stemwood drives the lumber mill forward, the bioenergy industry will also need to know the quality of trees prior to combustion (Nelson et al., 2013).

2.3.3 Bark

Bark is the outermost part of the stemwood and protects the trees from pests, diseases, animals, and fire. Bark decreases in thickness as the height increases, meaning a proportional amount of bark is added with each growing season. Bark is mostly lignin and degrades very slowly for the tree's protection (Hakkila, 1989). Trunk diameter is generally measured prior to debarking operations; therefore the measurement includes the stem wood's double bark thickness, (DBT) at DBH. Due to tree's natural decrease in diameter as it grows in height, there are taper equations which empirically estimate the bark percentage and diameter inside bark (DIB) (Miles & Smith, 2009; West, 2009). These taper equations predict the tree's total volume or board feet before harvesting. Performing these calculations from a random sample in a tree stand predicts the forest stand's yield. The DIB prediction is also important because bark protects the stemwood from soil contamination during the felling and skidding process and the bark is removed to use in process heat at wood mills. The bark will pick up soil and other contaminants during the harvest process which can increase the ash content. The best use for bark is either mulch or a feedstock for direct combustions because it offers no advantage in the lumber or paper industry for the end product. However, bark used in direct combustion causes ash fouling resulting in higher costs for maintenance and prolonged downtime; clean pine chips are used for cleaner combustion, gasification, and pyrolysis processes (Yildiz et al., 2015).

2.3.4 Unmerchantable Volume and Tree Crown

The unmerchantable volume is any part of the stemwood not used, most typically the crown. The crown begins at the lowest live limb and extends to the tree's total height. The crown length and height are used to determine the crown ratio of a tree. A typical crown ratio for loblolly pine is between 20 to 40%. Foresters use crown growth to indicate factors such as competition and growth vitality (Husch, et al., 2002). Branch and foliage weight are used to measure carbon allocation and explain other existing models like MAESTRO (Baldwin et al., 1997).

The branches of loblolly pines produce the needles, which offer more surface area than leaves for photosynthesis. The lower half of the branch is known as compression wood because it bears the weight of the tree limb; this cantilever reaction produces denser wood compared to the upper area of the branch. Needles from loblolly pine trees are the photosynthetic factories for converting sunlight to glucose. Needles collected after falling are used for compost in landscape bedding and aromatic extractives for scents and fragrances. Harvesting the crown serves no economic gain for the lumber and paper mills because of its variable quality between unmerchantable stem, limbs, and foliage. However, there are still threats to pine trees crowns including crown fires and pests. Pine beetles have threatened pine species in their crown and have caused forests to cease productively regenerating (Page et al., 2015). When this occurs, the crown slowly begins to remove moisture from the limbs and needles, leaving optimal condition for forest fires to spread tree top to tree top. However quantifying the crown can help determine its fuel potential as the limbs and needles drop to the forest floor (Contreras et al., 2012; Sackett & Haase, 1991). Crown residues are a plausible source of renewable fuel.

2.3.5 Density & Specific Gravity

One of the common qualities used to characterize wood is its density. Density of biomass is an intrinsic property and it is defined as the mass per unit volume of the biomass. For forestry, the term specific gravity is used instead of density. Specific gravity of wood is the density of an object divided by the density of water. In the metric system, the density of water is $1 g/cm^3$ ($62.4 lb/ft^3$ in English), therefore both specific gravity and density are numerically the same (Megraw, 1985). However, specific gravity is dimensionless and always reported on a dry basis, or with the samples' moisture content.   Density and specific gravity are intrinsic properties which are essential to know for processing in wood product applications.

Density is important for all forestry sectors as it correlates with strength in lumber. Most of the modeling is on lumber strength, i.e. modulus of elasticity (MOE) and modulus of rupture (MOR). The density of loblolly pine affects both MOE and MOR which tend to decrease as sample height increases (Antony et al., 2011; Megraw, 1985). Focusing on increasing the density of wood against its other properties is driven by the wood market in the southern United States (Nelson et al., 2013). The changing density in tree height is a good basis for investigating other intrinsic tree properties. Similar quality models by tree height would benefit biomass fuel industries because it would help the conversion process operators and design engineers know the inputs and variation of these properties.

Depending on the biomass's shape and structure, different density measurements may be used, i.e. basic density, bulk density, and particle density. Basic density is calculated as the material mass divided by the volume. However, irregularities in shape and void spaces often found in biomass can make it difficult to measure the volume. Unless density it designated otherwise, basic density is an object's density. Biomass's mass is measured and collected into a bulk container, i.e. shipping truck; the mass of the material divided by the volume of the container is known as the bulk density. Bulk density is the primary parameter for handling, transportation, and storage purposes where size and weight limits are regulated. The density of the solid material, known as the particle density, is measured by taking out the void areas by means of a gas pycnometer and tends to produce the most accurate density (Fasina, 2007).

In loblolly pines, a general trend of density/specific gravity decreases as height increases and also tends to increase from the pith to the bark (Daniels et al., 2002; Megraw, 1985). However, this is not a perfectly linear relationship and can change depending on the tree's age and genetics because of the development of early crown wood while it is a juvenile tree. Daniels et. al. (2002) mapped specific gravity with a logistic model in 3D using two parameters, height and ring number, which show the variation from stump to tip and from pith to bark. Earlywood specific gravity can be as low as 0.25 and the latewood specific gravity can reach as high as 0.80. Ring to ring specific gravity increased from 0.35 to 0.45 (unextracted o.d. weight per green volume) as ring numbers increased in the disc sample. Additionally, the specific gravity of a tree from stump to tip decreases from approximately 0.45 to 0.35with increasing height (Megraw, 1985).

The specific gravity of oven dried loblolly pine varies from 0.43 to 0.57 (Antony et al., 2015; Forest Products Laboratory, 2010; J. C. Jenkins, Chojnacky, Heath, & Birdsey, 2003). However, Cregg et al. (1988) found the late wood percentage and specific gravity of loblolly pines were different but not significantly affected by thinning operations. Specific gravity can vary within a tree's percent of latewood and early wood, between a tree's DBH and TTH, and forest site latitude (Megraw, 1985).

However, the theory that genetically faster growing trees have less specific gravity is routinely confounded if not taking into account the sampling height or the ring width (Megraw, 1985). Daniels et al., (2002) showed that specific gravity varies in both the horizontal and vertical axis of the tree. Disc measurements have been used to sample the properties of an entire tree by taking disc samples through the stemwood (Antony et al., 2015). This study investigated the effects of age, DBH, and TTH, on both wood and bark specific gravity, green weights, and moisture content. Because of the experimental design, samples were taken from the same height while accounting for the TTH and also converted to a relative percentage of tree height. Due to the narrow range of DBHs across the study and the other large variations from location to location, these predictor variables were not strong enough on their own to estimate the observed variables (Antony et al., 2015). Antony et al. (2010) plotted specific gravity with relative height value on loblolly pines to create a model as forest location changes and follows the trend of decreasing specific gravity of the entire disc as the relative height increases. Specific gravity modeling is useful for most applications but proximate analysis and heating value modeling is still unavailable for prediction in energy uses to know a consistent fuel quality in certain parts of the tree

Density, especially basic density, is influenced by the moisture content of biomass because biomass shrinks and losses mass as water is removed from its cells. Therefore it is important to specify the moisture content when reporting biomass with its density or specific gravity (Miles & Smith, 2009).

2.3.6 Moisture content

Fuel quality is characterized by determining a feedstock's proximate analysis. Proximate analysis is performed on all forms of fuels including coal and biomass (ASTM E870, 2011). Proximate analysis provides the moisture, volatile matter, fixed carbon, and ash contents of biomass. Moisture content is the amount of water in the sample either outside or inside the cell wall. Green samples, freshly cut samples, have approximately 50% moisture content. Moisture content is determined by recording an initial mass, drying in an oven or using a halogen lamp, and then recording the final weight. Moisture content is reported in either wet basis or dry basis. Dry basis is used to normalize and compare data. All biomass samples should be prepared according to ASTM, 2011 which specifies how to dry, chip, and preserve samples prior to analysis.

While harvesting any biomass sample, the free water in the sample dries, reducing the overall weight, and then the water inside the cells is transpired, resulting in a loss of volume. This volume loss is known as shrinkage, specifically from less turbid cells and collapsing tracheids. In loblolly pine, shrinkage is about 4.8% radially, 7.4% tangentially, and 12.3% volumetrically (Forest Products Laboratory, 2010). For this reason, it is necessary to specify the samples' moisture content, mass, and volume measurements as either green or oven dry. In addition, high moisture content can lower the calorific value of a feedstock, yielding less energy captured during combustion (Ince, 1979).

2.4 Modeling Fuel Quality

Coal, petroleum, biomass and all forms of carbon-based energy sources undergo fuel quality testing. There are many metrics which can define the fuel quality of an energy source; the two most common are the proximate and ultimate analysis. Proximate analysis consists of the moisture content, volatile matter, ash content and fixed carbon. While it is not a part of the proximate analysis, calorific content is often also reported. Ultimate analysis reports the percent of carbon, hydrogen, oxygen, nitrogen, and other trace elements such as sulfur. Previous studies have specifically focused on ash and energy content and their interactions for fuel quality purposes (Gautam et al., 2012; Taylor et al., 2012).

2.4.1 Ash content

Ash is the inorganic mass left behind after decomposition or combustion of wood. These are small trace amounts of elements used for light and dark reactions or any other soil contaminants picked up during the harvesting process. Ash is used in fertilizers, hydroponic solutions, and composts to return these elements to biota in the growing medium. The chemical makeup of ash consists of alkali and alkaline metals, (Masiá et al., 2007; Pettersen, 1984; Stahl et al., 2004; Vassilev et al., 2010). Further analysis in examining the chemical contents are beyond the scope of this analysis but can be found in the previous references. In co-firing power plants, the amount of ash residue can affect turbine efficiency and increase required maintenance on the furnace system. High ash content in biomass is undesirable because it causes catalyst deactivation in pyrolysis (Yildiz et al., 2015), fouling in combustion chambers, and absorbs process heat. Gasification and pyrolysis systems have faced issues with high ash content contaminating the catalyst. When the trees are skidded across the forest floor, the dirt is trapped in the bark and the stemwood is protected and remains clean until debarking operations occur at the mill.

Ash content is divided into two categories: authigenic and detrital. Authigenic ash content are the inorganic compounds taken up by the roots and transported to the tissues. Any ash which does not present itself naturally in forest biomass samples is often picked up due to soil contamination during mechanical harvest and is known as detrital ash. Both ash categories are derived from the soil matter, however, the determining factor is the manner in which it is present in the biomass. To reduce detrital ash content, screening applications which sift out dirt particles trapped in the residues such as rotary trammel are applied. A reduction in authigenic ash content would require mixing known quantities of lower ash content feedstock (Keefe et al., 2014). Pradhan (2015) found that grinding wood chips in a hammer mill was as sufficient as a sieve shaker in reducing ash content. Table 2.3 shows the ash percentage of the different components of loblolly pines as reported in literature.

Table 2.3 Ash content of loblolly pine tree components from literature

Loblolly pine section	Ash % (d.b.)	Reference
Wood chips	0.61	Cutshall et al., 2011
Pine stem	0.41	McMillin, 1968
Pine chips	5.95	Masiá et al., 2007
Foliage	2.59	Taylor et al., 2012
Limbs	1.38	Taylor et al., 2012
Stemwood without bark	0.40	Taylor et al., 2012
Bark	1.37	Taylor et al., 2012
Stem wood	0.32	Owen et al., 2015
Bark	1.31	Owen et al., 2015
Limbs/Foilage	1.36	Owen et al., 2015
Whole tree	1.80	Acquah et al., 2016
Wood and bark	1.50	Acquah et al., 2016
Residue	1.90	Acquah et al., 2016
Stem wood	0.40	Acquah et al., 2016

For Loblolly pine, a number of studies have shown the differences in proximate analysis values in order to recognize the fundamental variation between its stemwood, bark, and the crown (Owen et al., 2015; Vassilev et al., 2010; Wiedemann et al., 1988). In looking at softwood logging residues specifically, larger diameter branches had lower ash content than small diameter branches, 3.4% and 6.1%, respectively (Gautam et al., 2012). The wide range of variability between the different tree components and their proximate analysis values doesn't achieve a standard fuel quality prior to harvesting the tree. Clean stem wood ash content is much lower when compared with coal where ash content is roughly 4.7-5.7% (d.b.) (Wiedemann et al., 1988). Ash fouling and slagging can impede boiler efficiency in combustion conversion process (Masiá et al., 2007). The location within the tree's sample of bark and stemwood was usually the

DBH and only in Owen et al., 2015 was specific precautionary action used to ensure no soil contamination when collecting samples. Because ash content is the constituent of proximate analysis directly having a negative impact on combustion, it will be directly investigated in this study.

2.4.2 Heating Value

Energy content is the amount of energy measured from combusting a sample in an oxygen-rich environment. The energy content of biomass typically increase with decreasing ash content (Owen et al., 2015). Moisture content of a sample can significantly decrease the amount of energy it yields due to energy required to evaporate the water, and then volatilize the organic compounds (Ince, 1979). When the water is vaporized and then released from the combustion process as a vapor, the captured energy is known as the lower heating value (LHV) and is the amount of heat actually recovered. Higher heating value (HHV) is the theoretical yield of heat energy if the evaporated gasses were condensed and recovered. Because the LHV can change due to the feedstock's moisture content, HHV is usually calculated to compare energy values regardless of moisture. In terms of energy yield, HHV and LHV are both divided by the sample mass, i.e. J/kg or BTU/lb. Carbon rich sources of fuel such as coal or petroleum offer a large amount of energy content but increase atmospheric CO_2 levels and are considered carbon negative. Biofuel feedstocks are considered carbon neutral because the intake of atmospheric CO_2 during photosynthesis will be released again during combustion. Water reduces woody biomass's energy content and taking up half the tree's weight, in-field drying by means of transpiration is a method to reduce the payload of harvesting trucks without incurring drying costs which achieve the same energy output. Ash and energy content of southern pines were not affected by transpirational drying methods after 4 and 8 weeks, even when accounting for the changes in moisture content (Cutshall et al., 2011). Table 2.4 displays the differences between loblolly pine sections and their higher heating values.

Table 2.4 Higher heating value loblolly pine tree components from literature

Loblolly pine part	BTU/o.d. lb	MJ/kg	Reference
Wood chips	8230	*19.14*	Cutshall et al., 2011
Bark	9400	*21.86*	Ince, 1979
Pine chips	*8508*	19.79	Masiá et al., 2007
Foliage	8195	*19.06*	Taylor et al., 2012
Limbs	7773	*18.08*	Taylor et al., 2012
Stem without bark	8111	*18.87*	Taylor et al., 2012
Bark	8029	*18.68*	Taylor et al., 2012
Stem	*8212*	19.10	Owen et al., 2015
Bark	*8512*	19.80	Owen et al., 2015
Limbs/Foliage	*8727*	20.30	Owen et al., 2015
Whole tree	*8684*	20.20	Acquah et al., 2016
Wood and bark	*8512*	19.80	Acquah et al., 2016
Residue	*8856*	20.60	Acquah et al., 2016
Stem wood	*8770*	20.40	Acquah et al., 2016

*Italicized values were converted using 0.002326 MJ/kg = 1 Btu/lb. and are not in original reference.

The tree components with the most amount of bark and compression wood in the branches tends to have a higher amount of energy content. This is due to its chemical makeup which includes more lignin (26.7 MJ/kg) as opposed to simple chains of cellulose (17.3 MJ/kg) (Jenkins et al., 1998). Use of transpirational drying methods of logging residues has been shown to reduce the residue's moisture content without significantly compromising the calorific value. Softwoods have proved to be superior to hardwoods with lesser amount of ash content and larger calorific value (Gautam et al., 2012).

The general effect of ash content on HHV is negative as reported by (Taylor et al., 2012). In Taylor's study however, samples possessed relatively large quantities of ash percentage <5%. The correlations were derived by adding precisely measured detrital ash content to the sample's authigenic ash content. The gradual reduction in HHV was present in samples above 5% ash content (Figure 4.9). Figure 4.9 shows the negative effect ash content has on HHV of clean pine wood. Significant amounts of ash content will significantly reduce HHV, (Owen et al., 2015; Taylor et al., 2012). The reported regression line has a negative slope of 92.479 BTU/lb (0.215 MJ/kg) per ash content percentage. At ash contents <5%, a cluster of data points shows an inconclusive trend between 8000-9000 BTU/lb. (18.6-20.9 MJ/kg).

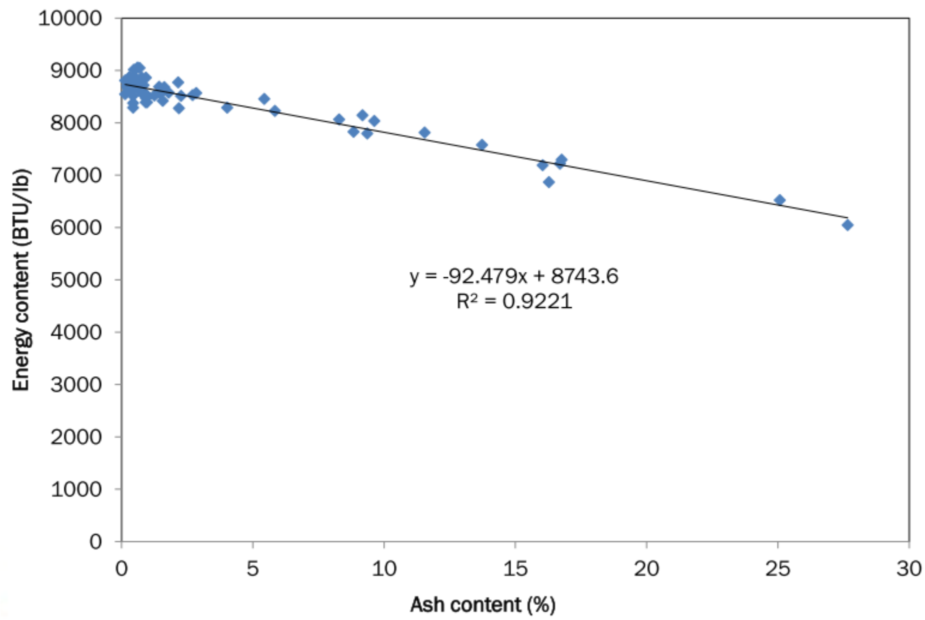

Figure 2.6 Energy versus Ash content (reproduced from (Taylor et al., 2012))

2.4.3 Ultimate Analysis: CHNOS

Ultimate analysis determines the chemical composition of a fuel or feedstock in terms of percentage of carbon, hydrogen, nitrogen, and sulfur. Coal and biomass are often subjected to this test to find the ratio of carbon to other combustion elements. These percentages vary for different loblolly pine samples depending on the harvesting process and the different sections of the tree. The ultimate analysis of loblolly pine range has reported a vast range of values due to variations in harvesting methods, and unspecified sections taken during sampling.

The elemental analysis of biomass varies greatly depending on the feedstock. Chemical composition from ultimate analysis and proximate analysis of pine bark, chips, pruning, and sawdust, recreated from Vassilev et al. (2010) are shown Table 2.5.

Table 2.5 Overview of the Chemical Composition of Pine

Reference	Pine Material	Proximate Analysis % (d.b.)			Ultimate Analysis % (d.b)					
		VM	FC	Ash	C	O	H	N	S	Sum*
(Bryers, 1996)	Bark	73.7	24.4	1.90	53.8	39.9	5.9	0.3	0.07	99.97
(Masiá et al., 2007)	Chips	72.4	21.6	6.00	52.8	40.5	6.1	0.5	0.09	99.99
(Moilanen, 2006)	Sawdust	83.1	16.8	0.10	51	42.9	6	0.1	0.01	100.01

*Summations are not exact due to rounding.

A biomass sample can have an increase in energy content if the sample has a low ash content. Dulong equation and Boie equation is a prediction method to estimate the heating value of a feedstock if the elemental composition is known.

The equation was originally used in determining the heating value of coal varieties using the dry basis percentages of carbon (C), hydrogen (H), sulfur (S), and oxygen (O). The results from ultimate analysis have been used to predict valuable information about a sample's quality including higher heating value.

$$\text{Dulong Equation}, HHV_{(d.b.)}\left(\frac{\text{MJ}}{\text{kg}}\right) = 33.823 * C + 144.25(H - O/8) + 9.419 * S)$$

$$\text{Boie Equation}, HHV_{(d.b.)}\left(\frac{\text{MJ}}{\text{kg}}\right) = 35.16 * C + 116.225 * H - 11.09 * O + 10.465 * S)$$

Predictability of biological materials has always presented a challenge given the inherent genetic, environmental, and processing variability in manufactured products. Even in loblolly pines there exists specific gravity and ash variation in stump to tip and bark to pith distribution (Antony et al., 2015; Daniels et al., 2002; McMillin, 1968)

2.5 Conclusion

In conclusion, Loblolly pines (*Pinus taeda*) are the most abundant and well adapted woody biomass to meet energy demands. The crown residues could be removed from the field as a precaution to forest fires and convert to biofuels if the industry knew critical proximate analysis data. Likewise, the density and other characteristics are shown to change as height changes. Optimizing harvesting processes to utilize the whole tree can allow for higher yields and more energy efficient forests. A prediction model for loblolly pines intrinsic fuel qualities using field measurements such as DBT at DBH and other allometric parameters is in demand to predict fuel quality prior to harvesting a forest site.

Chapter 3: Materials & Methods

3.1 Experimental design

Loblolly pine fuel qualities were established by testing higher heating value and ash content, at various heights of loblolly pines. A nested block design which controlled for the diameter at breast height (DBH) variability while also measuring the following unique physical features: crown length, stemwood diameters, density, green mass. This type of design is not uncommon among agricultural and biological experiments. Sample size determination was developed using criteria from a previous study in a similar area of loblolly pine trees. In a similar previous study, Owen, et. al. (2015), used 28 loblolly pine trees with a mean DBH of 154.94 mm (SD 35.82 mm), 6.1 in. (SD 1.41in). Using the data used from Owen, et. al. (2015), the coefficient of variation (CV) was calculated to 23.12. Equation 3.1 was used to calculate the sample size with the previous study's CV as an estimate for the variation for the population for the loblolly pine trees in a similar forest stand (Eq. 3-20) (Husch et al., 2002).

$$n = \frac{t^2 * CV^2}{(E\%)^2} \tag{3.1}$$

where:

t = t value from the hypothetical degrees of freedom (n-1)

CV = coefficient of variation, 100*σ/μ

E% = degree of allowable error

A degree of allowable error between 10-11% was considered tolerable given the nature of variability in tree sizes. Most often, foresters and other biological experiments use an estimate of 20% error from the mean for sample size calculations (Husch et al., 2002; Whitlock & Schluter, 2009). The window of error allowed n to reach a reasonable whole integer. The sample size, n, was calculated after iterating the approximate t values with respective degrees of freedom for the previous n. The final iteration is shown in equation 3.2.

$$n = \frac{t^2 * CV^2}{(E\%)^2} = \frac{(2.0930)^2 * (23.119)^2}{(10.8\%)^2} = 20 \tag{3.2}$$

From the results of equation 3.2, a sample size of 20 trees was sufficient for sampling. The, standard error rate yields diminishing returns as sample size increases for a standard normal distribution (μ=0,σ=1), therefore incremental decrease in standard error would not justify increasing the sample size above 20. DBH classes were added to balance the study with 5 trees for each class. Previous studies of loblolly pine choose analysis with DBH of at least 4 inches in DBH because it is considered the smallest merchantable stemwood size.

3.2 Sample Collection and Preparation

The samples used in this study were obtained from loblolly pine trees harvested from the Mary Olive Thomas Tract demonstrationa forest in Auburn, Alabama. The stand is of mixed age (38-17 years old) from a low intensity loblolly plantation with no fertilizer inputs. Twenty trees were preselected and placed into DBH classes, 4 blocks of DBH classes were formed at 11.43, 13.97, 16.51, and 19.05 cm, ±1.27 cm, (4.5, 5.5, 6.5, & 7.5 inches) (± 0.5 inches) with 5 trees for each DBH class. These DBH classes are the same as performed in Aleixo da Silva et al., (1994). The trees were tagged, labelled, and manually felled with a chain saw. Each tree was sampled at predetermined heights, separating the crowns into 4 equal lengths (C1-C4) and the stemwood into 5 disc samples (D1-D5) (Figure 3.6). When referring to the individual DBH classes, the metric (cm) notation will be used, however when DBH and sections are used, the English (in.) will be used.

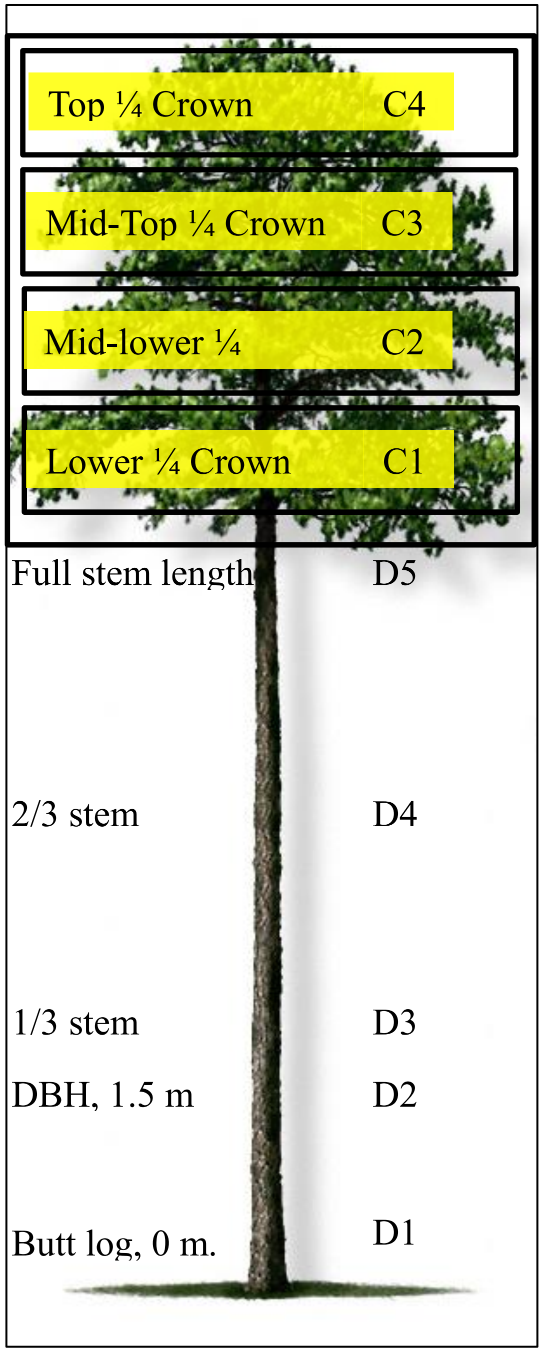

Figure 3.1. Illustration of loblolly pine sampled sections with respective heights (original picture obtained from O'Brien, 2007).

3.2.1 Crown Samples

The process steps for obtaining crown samples and preparing them for fuel quality assessment are shown in Figure 3.2. In total, eighty crown samples were collected, 4 samples from each of the 20 trees. The height, and crown lengths were measured to document variations in crown size. The crown of each of the 20 pine trees were quartered by height sections to generate the Crown 1, 2, 3, and 4 groupings which are denoted as C1-C4 (Figure 3.1). The quartered crown sections were then chipped with a brush chipper (model M12R, Morbark Beever brush chipper, Winn, MI) and collected into bags to measure weight and for transportation.

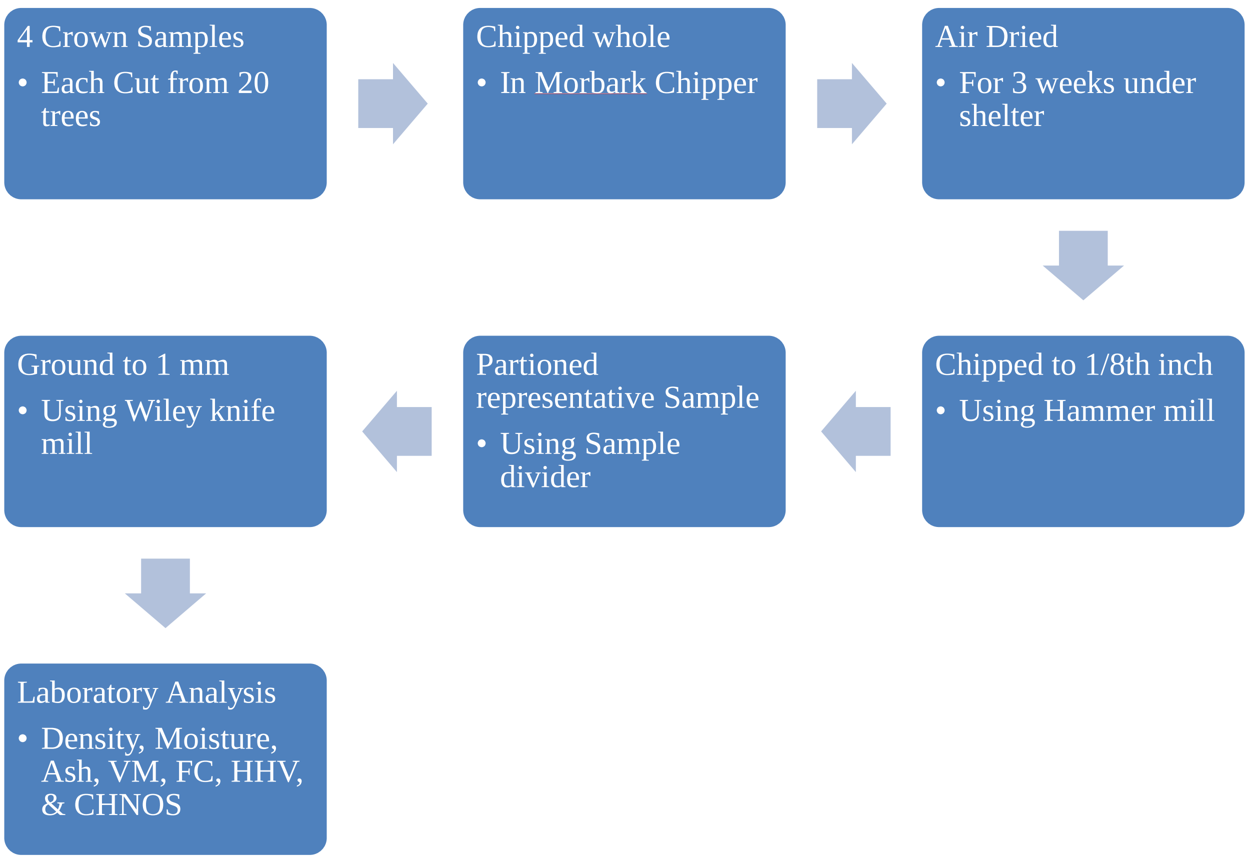

Figure 3.2 Flow Chart of Crown Sample Procurement, Collection, and Analysis

Figure 3.3: *Top Left*: Transporting crown samples with care to reduce soil contamination. *Top Right*: Chipping loblolly pine tree crowns. *Bottom Left*: Morbark Beever M12 brush chipper used to reduce crowns to wood chips. *Bottom Right*: Crown samples air drying before further size reduction and analysis.

This study specifically required minimal detrital ash contamination for accurate fuel quality measurements. The only time during the harvesting process when crown samples contacted the soil was during the initial felling of the tree. Crown samples were lifted and hauled without dragging to the chipper for quartering and chipping. Photos of the process of preparing the crown samples for further analysis are shown in Figure 3.3. The crown chips were weighed green and moisture content was determined to establish the total dry weight of each crown section. The chips were then air dried in an open shelter (Figure 3.3, *Bottom Right*). The particle size of the samples were reduced before further analysis. The eighty air-dried crown samples were prepared for analysis by grinding through the 1/8 inch (3.125 mm) screen of a hammer mill (model 10HBLPK, C.S. Bell Co., Tiffin, OH), followed by using a sample divider (model

PT200, Retsch GmbH, Hann, Germany), and lastly, grinding through the 1.0 mm screen of a Wiley mill (model 4, Thomas Scientific, Swedesboro, N.J.). All fuel quality metrics measured for the crown samples were conducted on the ground samples that passed through the 1.0 mm screen of the Wiley mill.

3.2.2 Stemwood Samples

Figure 3.4 shows the steps used to prepare the stemwood samples for fuel quality assessment. Five disc samples were collected, approximately 5 – 7.5 cm (2-3 inches) thick, and were taken from different heights up the tree. Disc 1 (D1) was obtained from the base of the tree (0.0 ft.), and the second disc (D2) was from the breast height (1.5 m, 4.5 feet, from the ground). D1 and D2 have the strongest correlation for predicting the whole tree size (Cao et al., 1980). The remaining three discs samples were obtained at 1/3 (D3), 2/3 (D4), and at the full height (D5) of the limb-free stemwood as shown in Figure 3.1.

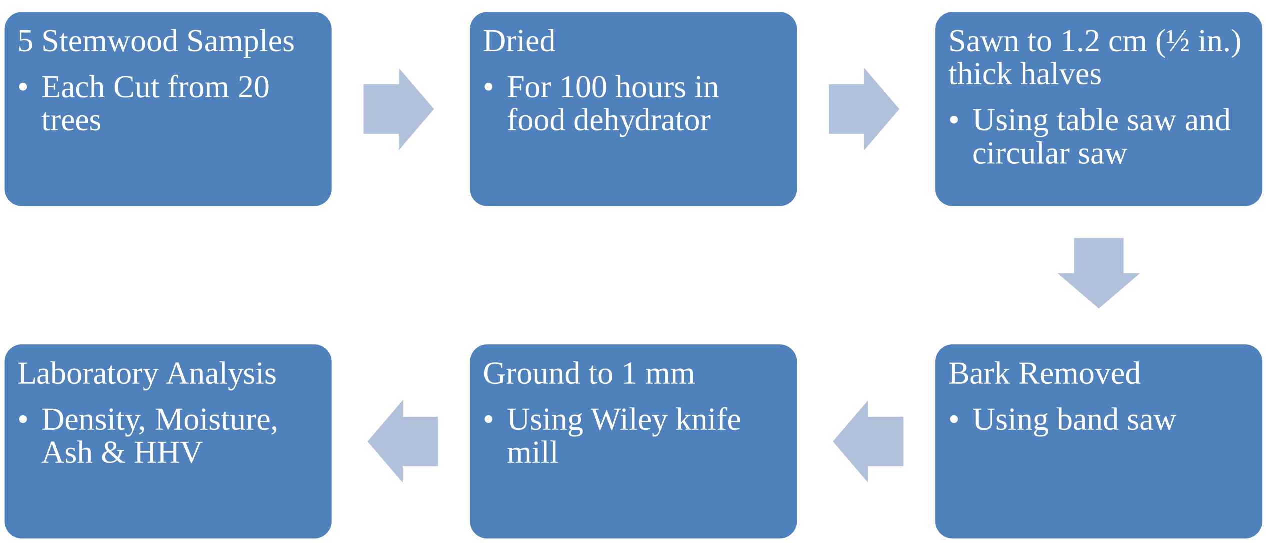

Figure 3.4 Flow chart of stemwood sample procurement, processing, and analysis.

All trees were large enough such that the D3 cut (1/3 of the height from the limb free stemwood) were beyond 1.5 m (4.5 feet) and therefore taller than the breast height mark. This method of sampling is suggested in McMillin, (1968) and is similar to the stratified random sampling in Parresol, (1999).

The green mass and outside-bark diameter (OBD) were measured with a mass scale and tree calipers immediately after harvest to establish a green weight. Samples were then dried at 50°C in a dehydrator (model 2 Zone, Excalibur Dehydrators, Sacramento, CA.) for 100 hours. This ensured interior moisture within the disc samples was removed before further processing. The mass and diameter of the disc samples were measured again after 100 hours of drying. The 100 disc samples were prepared for fuel quality analysis by cutting into equal 1.27 cm (0.5 inch) widths using a table saw (Dewalt, Flexvolt, Model DCS7485B) and the bark was removed by using a circulating band saw (Craftsman, Wood/Metal Band saw, Model 351.224500). Age was accounted for by counting the rings on the disc, where the D1 age was used for the tree’s total age. The 1.27 cm (0.5 inch) discs were cut symmetrically and one of the halves was ground through 1.0 mm screen of a Wiley mill (model 4, Thomas Scientific, Swedesboro, N.J.). The sample divider was not used for obtaining a representative sample due to the small mass size of the ground disc samples.

Figure 3.5 Wood discs stacked by tree samples.

3.3 Laboratory Analysis for Fuel Quality

Measurements of the fuel quality parameters were carried out on the crown (C1-C4) and stem wood (D1-D5) samples fully processed to pass 1mm screen. Several metrics included moisture content, density, ash percentage, and HHV tests all followed their respective ASTM International (2011) procedures. These metrics give a detailed description as to how each section of the tree behaves differently during combustion conversion and help in determining which sections are most suitable for bioenergy.

3.3.1 Age by Ring Counts

Age was determined by counting the earlywood rings in the disc samples. Age was not counted in the crown samples prior to chipping operations. User discretion was employed to determine false rings which are common in southern pine species (Megraw, 1985). A thin latewood ring abruptly followed by further earlywood in the sample indicates a false ring.

3.3.2 Moisture Content

Moisture content (MC) of the samples was measured with moisture analyzer (OHAUS) that was programmed according to Method B of ASTM E1756, (2002), which calculates moisture based on equation 3.3. The initial mass (m_i) is approximately 2 g, which is heated at 105°C until the change in sample mass was less than 0.05% within 1 minute interval, achieving the final mass (m_f). Each sample was tested in a round of triplicates to produce an average for that sample. The MC converts the fuel quality metrics to a dry weight basis, specifically for specific gravity, heating value, and proximate analyses on a dry basis (Equation 3.4).

$$\text{Moisture content (\% w.b.)} = \left[\frac{\mathrm{m_i} - \mathrm{m_f}}{\mathrm{m_i}} \text{ x } 100\right] \quad (3.3)$$

$$\text{Moisture content (\% d.b.)} = \left[\frac{\mathrm{m_i} - \mathrm{m_f}}{\mathrm{m_f}} \text{ x } 100\right] \quad (3.4)$$

3.3.3 Density and Specific Gravity

The ratio of the oven-dried mass to the green volume for each sample was used to estimate the basic density (Equation 3.5). Basic density (ρ_B)was measured initially on the disc samples prior to drying and after drying. The specific gravity (SG) for the stemwood samples with no bark was determined using the oven-dry mass divided by the oven-dry volume multiplied by a conversion factor for the density of water (ASTM D2395, 2016) (Equation 3.6). However, due to the inconsistent nature of disc thicknesses, the discs were cut to a standard 1.27 cm (0.5 inch) thickness and the bark was removed. For irregular volumes not easily estimated or measured, water immersion is usually the best method to determine volume. To avoid water sweeping into the disc samples and changing the mass and the volume of the discs due to swelling, disc area was determined using picture software ImageJ and the procedure found in Igathinathane et al., (2010). This method used pixel sizing from a calibrated uniform scale to measure the area of the samples. The area (cm^2) multiplied by the 1.27 cm (0.5 inch) thickness produced the volume (V_{max}) (cm^3).

$$\text{Density } (\rho_B) = \mathrm{m_0/V_{max}} \tag{3.5}$$

$$\text{Specific Gravity } (\mathrm{SG}_B) = \mathrm{K * m_0/V_{max}} \tag{3.6}$$

3.3.4 Volatile Matter

Volatile matter for loblolly pine is reported between 72.4- 82.2% (d.b.) with sample variations attributed to the differences in the stemwood, bark, and needle composition and harvesting processes (Owen et al., 2015; Vassilev et al., 2010). ASTM E872 lays out the procedure to determine volatile matter of a biomass combustible sample using a muffle furnace. The initial weight of the sample is recorded and placed in a crucible with a lid. The samples are then placed at 975°C for 7 minutes and are promptly removed to cool in a desiccator. Once cool, the samples are weighed again for their final weight. Volatile matter is determined by weight difference and the moisture content of the sample is used to convert to dry basis (Eqn 3.7).

Volatile matter is the matter which ignites rapidly and creates the vapors CO_2, CH_4, CO, and other vapors. A large amount of volatile matter is desirable for pyrolysis and gasification processes. Volatile matter consists of the compounds burned during the combustion process.

$$\text{Volatile Matter } (\%\ \mathrm{d.b.}) = \left[\frac{\mathrm{Weight_{crucible\ and\ VM}} - \mathrm{Weight_{\ crucible}}}{\mathrm{Weight_{initial\ sample}}}\ \mathrm{x}\ 100\right]\left[\frac{100}{100-MC}\right] \tag{3.7}$$

3.3.5 Ash Content

Ash content of the samples was determined according to ASTM E1534, 2013. Ash is determined on a mass reduction basis, ultimately destroying the sample (Equation 3.4). About 1.0 g of each individual ground samples were measured into a ceramic crucible. The crucible was individually weighed before adding sample and after combustion to measure the mass difference to the nearest 0.1 mg. The following sequence was used to reduce flaming inside the crucibles: 1) ramp from 22°C at 20°C /minute to 105°C and hold at 12 mins, 2) ramp to 250°C at 10°C /minute and hold for 30 minutes, 3) ramp to 575°C at 20°C/minute and hold for 180 minutes, 4) allow oven to cool down to 105°C. Each sample was tested in a round of triplicates to produce an average for that sample. Moisture content is accounted for by converting to a dry basis because it can affect the weight reported at the scale during the initial weighing of the sample into the crucible.

$$\text{Ash content (\% d.b.)} = \left[\frac{\text{Weight}_{\text{crucible and ash}} - \text{Weight}_{\text{crucible}}}{\text{Weight}_{\text{initial sample}}} \text{ x } 100\right]\left[\frac{100}{100-\text{MC}}\right] \qquad (3.8)$$

3.3.6 Fixed Carbon

Fixed Carbon is the amount of carbon stored in the biomass burned off. It is not ash but the combustible residue after the volatile gasses are burned off. This value is determined by a mass balance and not actually measured by mass difference. The following equation is used to determine fixed carbon:

$$\text{Fixed Carbon (F.C.) \%} = 100\% - \text{M.C. (w.b.)\%} - \text{Ash(d.b.)\%} - \text{V.M.(d.b.)\%} \qquad (3.9)$$

3.3.7 Higher Heating Value

Higher heating value (HHV) was measured with a bomb calorimeter (model C200, IKA Works, Inc., Wilmington, N.C.) (ASTM D5865, 2003). About 0.6-0.7 g of sample was measured and pressed into a pellet; the pellet’s final mass was recorded and placed into the bomb crucible. The bomb was pressurized to approximately 30 psi (206.8 kPa) of oxygen. The bomb calorimeter measured the temperature rise of the water jacket during the biomass combustion and computes the energy released per mass of sample (MJ/kg). Each sample was tested in a round of triplicates to produce an average for that sample. Because of the moisture content of the sample, the bomb calorimeter measures the higher heating value on wet basis (Sokhansanj, 2011). The following equation was used to calculate the higher heating value given the samples moisture content as a decimal mass fraction.

$$HHV_{(d.b.)}\left(\frac{\text{MJ}}{\text{kg}}\right) = \frac{HHV_{(w.b.)}}{1-MC(w.b.)} \tag{3.10}$$

3.3.8 Ultimate Analysis

Ultimate analysis was conducted on the CHNS Elemental Analyzer. For this analysis, both the crown and stemwood samples were analyzed in a CHNS Ultimate analyzer (VarioMicro Select Elementar, Germany). Both sample sets were ground to passing through 1mm screen sieve and subject to 24 hours of drying in an oven at 105°C in order to achieve complete drying. Each sample was tested in duplicates and used the 5mg method in the program. Oxygen in the ultimate analysis sample is calculated on a mass difference from the summation of the other chemical composition percentages. The software program and tests are in accordance with ASTM D5373, (2017). The Dulong and Boie equations, Equations 3.11 and 3.12 respectively, were used to determine the effectiveness of ultimate analysis to predict HHV. C, H, O, N and S are all decimal percentages by weight as measured.

$$\text{Dulong Equation}, HHV_{(d.b.)}\left(\frac{\text{MJ}}{\text{kg}}\right) = 33.823 * C + 144.25(H - O/8) + 9.419 * S) \tag{3.11}$$

$$\text{Boie Equation}, HHV_{(d.b.)}\left(\frac{\text{MJ}}{\text{kg}}\right) = 35.16 * C + 116.225 * H - 11.09 * O + 10.465 * S) \tag{3.12}$$

3.3.9 Statistical Analysis

Statistical Analysis Software (SAS) (SAS Institute, Inc. Cary, NC, USA) was used to determine statistically significant differences between different grouping categories for each of the fuel quality metrics. Two sample t-test, analysis of variance (ANOVA), Tukey HSD, and linear regression analysis were conducted with SAS programming. The specific coding sequence used to conduct the ANOVA analysis is PROC ANOVA. PROC MIXED was employed to perform Tukey-HSD tests (α=0.05) between group comparisons, DBH nested groups, within all trees and nested DBH classes (Appendix C). Linear regression coding used the PROC REG procedure with simple variable selection and stepwise variable selection. Completed analysis results and other data trends were graphed and tabulated with MS Excel (Microsoft Corp. Redmond, WA, USA).

Chapter 4: Results and Discussion

4.1 Allometric Analysis: Sample Validation

Allometric relationships for forest stands are used for predetermining volumes and densities in the tree prior to tree harvesting. The tree samples in the crown and the trunk were weighed and measured for their density and their height to diameter relationship. Crown ratio, crown section lengths, and total crown length in the tree were also measured during harvest. The crown sample's mass was determined after chipping and moisture content was taken into account to report on dry basis. Crown mass has been estimated prior to harvesting using regression techniques (Baldwin et al., 1997; Liu, et al., 1995). In the stemwood disc samples, log diameter and the diameter at breast height squared times the tree total height (D^2H) are two regularly computed variables for the estimation of volume in logging tables (Saucier et al., 1981).

The forest from which the samples were procured are classified as a codominant uneven aged growth stand. Codominant uneven aged forests are not in straight rows and the trees had varying sunlight and nutrient competition. This yields a wide range of tree sizes as opposed to regenerated well managed forest stands where the trees grow at similar rates. Figure 4.1 shows the mean sample height for each section nested within the DBH classes. As expected the height of trees increased with increasing DBH classes (Norby et al., 2001; B. W. Smith & Brand, 1983). All D1 sample heights are at the stemwood base (0 m), while all D2 samples are at the tree's DBH (1.5 m). However, between the 13.97 and 16.51 cm DBH class (6.5 and 7.5 in.) cut heights; the increase in tree height was due to the increase in the crown length, not the stemwood length. This is exemplified in Figure 4.2, displaying the large range of heights within and among all classes. The 19.05 cm (7.5 in.) DBH class will possess proportionally more stemwood in the crown samples. Other differences between sections in the DBH classes could be present due to the height with changes between proportions of stemwood, bark, and limbs, resulting in changes in fuel quality.

An initial analysis of variance was conducted between the DBH blocks and the tree total height (Table A.1, Appendix A). This is shown in Figure 4.1 with the large variation of total tree height (TTH) in the 4.5 DBH class and progressively getting smaller with larger DBH classes and taller average heights. The initial analysis tested total tree height, which is entire length of the tree measured after felling from the base of the cut. The 19.05 cm (7.5 in.) DBH class (mean =18.32 m, 60.12 ft., SD=0.88 m, 2.89 ft.) was the largest and significantly different from the 13.97 and 11.43 cm (5.5 and 4.5 in) DBH class (mean = 14.47 m, 48.46 ft., SD=1.78 m, 5.86 ft.) (mean = 13.27 m, 43.54 ft., SD=2.07 m, 6.82 ft.), respectively. The 16.51 cm (6.5 in.)DBH class shared both Tukey letter designations (a & b).

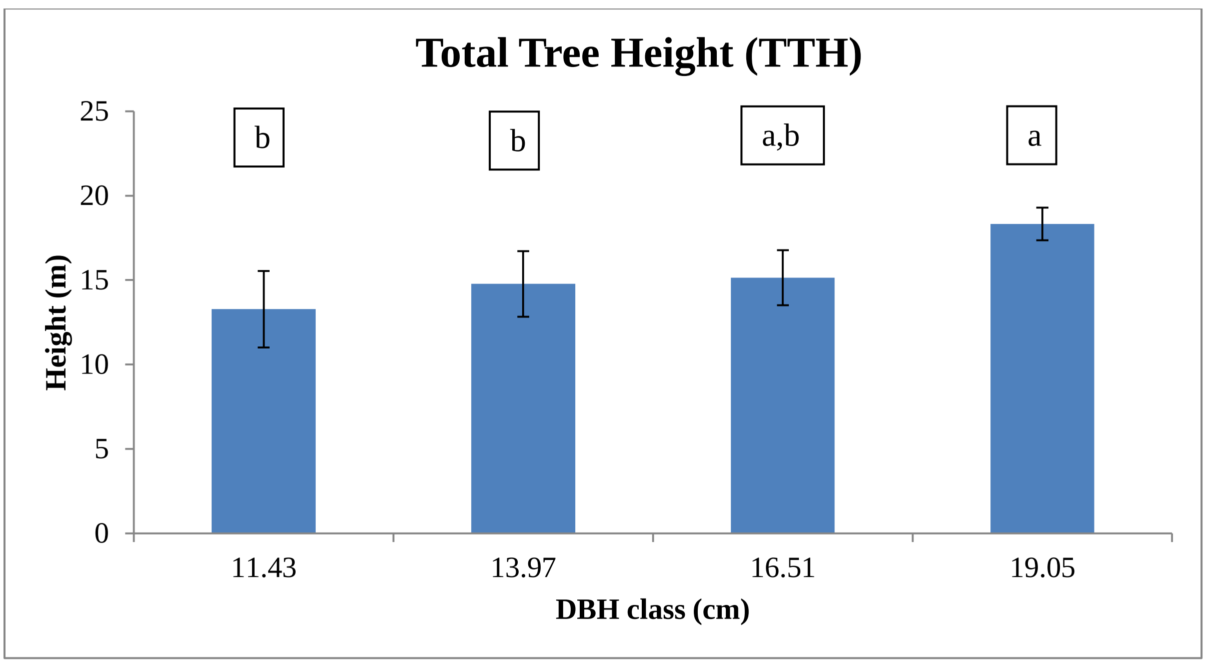

Figure 4.1 Average Total Tree Height for each DBH class (n=5)
Error bars are standard deviations. Means with different letters are significantly different at α=0.05 significance level using Tukey's multiple comparison.

A secondary two-way analysis of variance was conducted to investigate the change in sample heights by section and any interaction between the DBH classes (Table A.2.1, Appendix A). The corresponding section means with standard deviations by DBH class are in Table A.2.2 (Appendix A). The second analysis showed that all heights of the disc sections within the DBH groups section (D1-D5) was significantly different in height ($p<0.0001$). The DBH term was also significantly different ($p = 0.0109$). When the interaction term was added to the ANOVA, it was observed not be a significant factor in the changes in height. This is important for further analysis in response variables which use height as an explanatory variable.

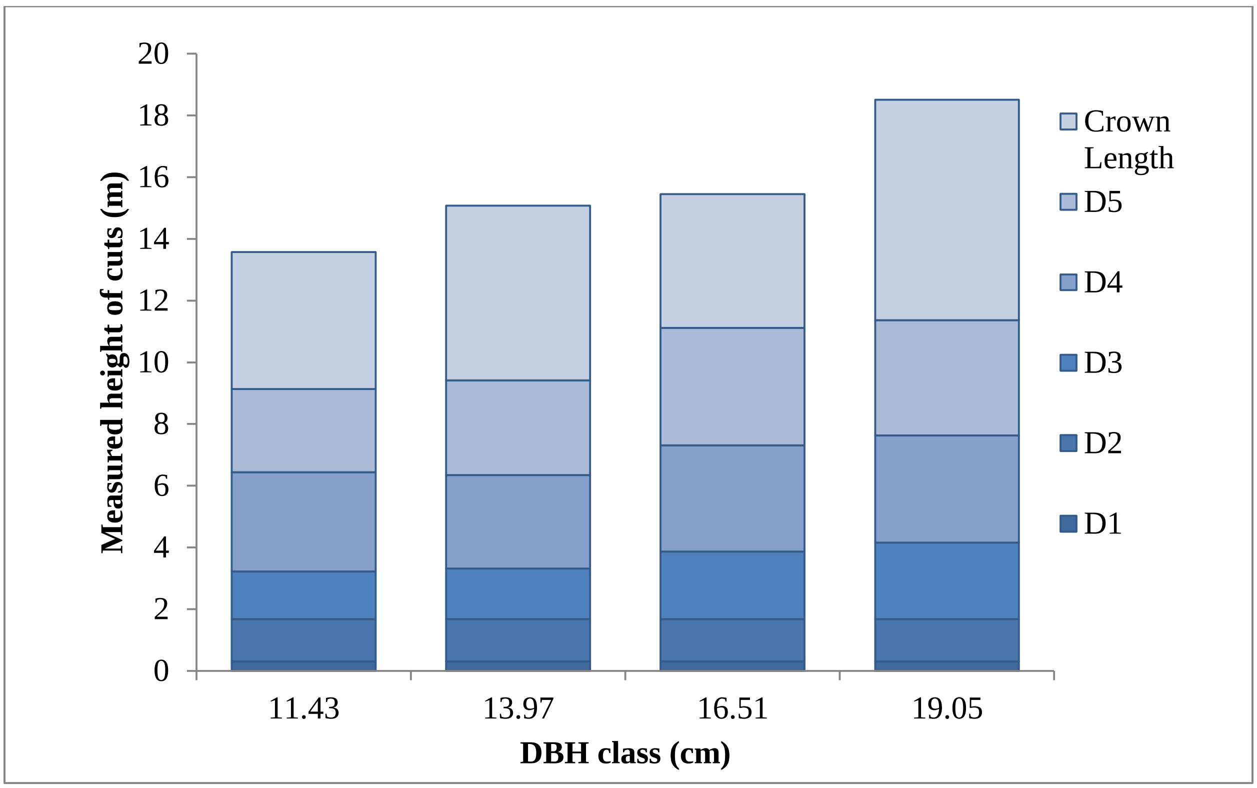

Figure 4.2 Summarization of DBH class averages by stemwood disc sample heights and crown length (n=5).

To ensure overlapping heights across DBH classes would not confound the analysis, a grouping variable ID was introduced and is the DBH class followed by the section number, e.g. (4_D4) means DBH class 4.5 and stemwood disc section 4. When grouped by the ID, the results showed a linear trend of heights increasing from the smallest DBH classes lowest height sections. D1 and D2 were the same for all DBH classes; with the start of D3, the heights increased in order of ascending DBH classes (Figure 4.3). The only time this general relationship is not followed is in the D4 section where the 4.5 DBH class, height = 6.14m (height = 20.13ft.) is 1.69% taller than the 5.5 DBH class in D4 height = 6.04 m (height = 19.80 ft.). Standard error (SE) bars increased with increasing sample section height.

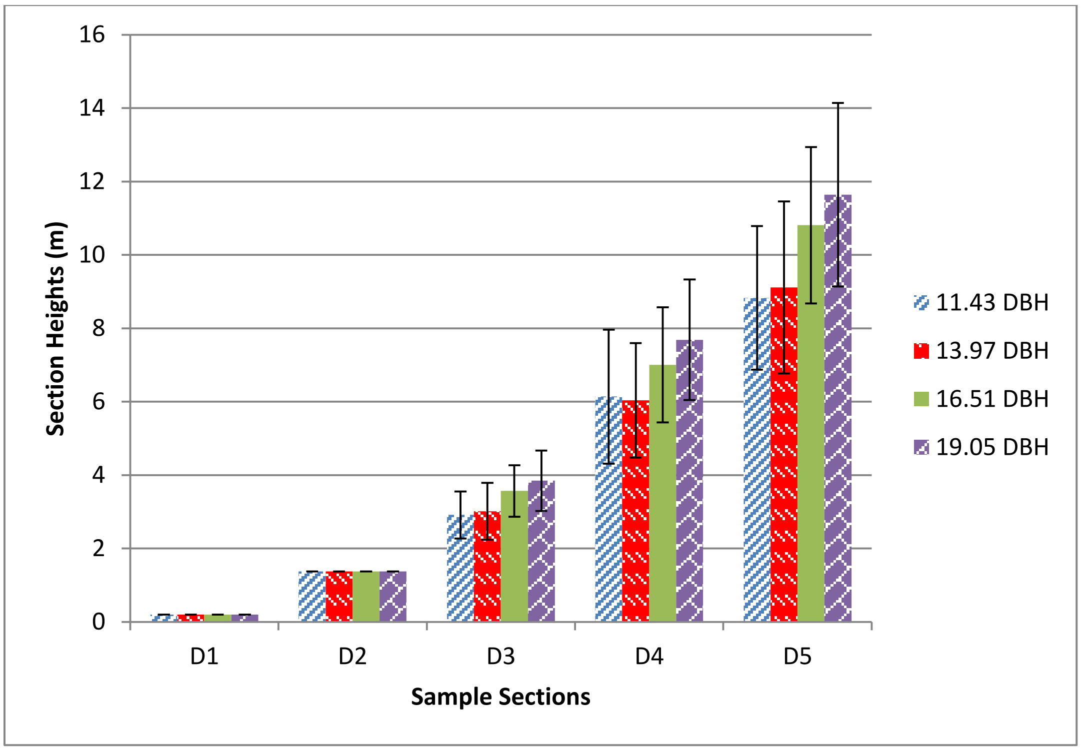

Figure 4.3 Height trends by DBH class for each section within the DBH class. Error bars are the sample standard error.

The crown and stemwood sections are physically different and were analyzed as separate sections for all experiments in this analysis. Group comparisons between and within the crown and stemwood were made for analyzing fuel quality results.

4.1.1 Crown Section Allometry

The physical measurements of diameters, green masses, lengths, and heights were made prior to the crown samples being gathered, chipped, dried and tested for lab analysis. Crown diameters are an important measurement during tree harvest since logging companies strip the trunk to a 10.16 -5.08 cm (4 - 2 in.) top diameter. The following analysis was conducted using the SAS code found in Appendix C and the corresponding ANOVA tables are in Appendix A.

Sample height variance was analyzed using a two-way ANOVA Tukey HSD test. The section levels C1-C4, DBH classes, the interaction of the DBH and the sections were investigated. Both terms on their own were significantly different ($p<0.0001$), however the interaction of those terms (DBH*section) were not ($p = 0.9947$) (Appendix A, Table A.3.1). Between the DBH classes, the 19.05 cm (7.5 in.) diameter class (mean =15.82 m (51.89 ft.), SD = 2.37 m (7.75 ft.)) was significantly larger in crown section heights than the others which decreased with decreasing DBH classes. Between the sections, which were quartered in heights by crown length (CL), the tallest section (C4), was significantly larger at 15.38m (50.45 ft.), than C2 and C1. The section height analysis with Tukey letter designations is shown in Table 4.1. Due to the natural variability of trees and their growing conditions, this sample set follows the allometric proportions (McElligott & Bragg, 2013). Some pine trees can grow to be short and thicker or tall and slender, however, the trees in this study do not appear as allometric anomalies.

Table 4.1 Crown height means with standard deviation from two-way ANOVA.

Section	Height (m)	Tukey group	DBH (cm)	Height (m)	Tukey group
C1	11.42±2.28	c	19.05	15.82±2.37	a
C2	12.74±2.27	b,c	16.51	13.52±2.02	b
C3	14.06±2.34	a,b	13.97	12.65±2.47	b,c
C4	15.38±2.49	a	11.43	11.60±2.30	c

Tukey comparisons are separate by columns, values with the same letters within the same column are not significantly different (α=0.05).

The previous analysis describes how the crowns, though variable in height, allometrically followed proportionally correct trends with respect to the DBH class. Height and diameter relationships are a key variable in many tree models (Antony et al., 2010; Cao & Pepper, 1986).

Crown double bark thickness (DBT) section diameters were analyzed using two-way ANOVA to determine the differences across the DBH classes and if there were any interactions from the sections within the DBH classes (Appendix A, Table A.3.2). The Tukey results were significantly different for both DBH and sections groups ($p=0.0019$), ($p<0.0001$), respectively, with an increasing trend in diameter with increasing DBH class and increasing crown section groups. However, when including the interaction term (section*DBH) it was found to be not significant ($p=0.4252$). The 19.05 DBH class is: (a) different than the 11.43 DBH class, (b) which is different than the marginal trend described when categorizing strictly by DBH class. The 13.97 and 16.51 DBH class possess both Tukey results letters (a & b). Every crown section group was statistically different from the other three. It should be noted the C4 crown sections were all measured as 0.0 cm as the tree ends at the top. For crown estimates, the DBH measurement is a variable used to predict the crown mass and relative change in crown growth (Liu et al., 1995). The crown section diameter cannot be measured directly before harvesting, but once harvesting has occurred, the top diameters would yield the crown residue diameter for these sections.

Crown mass was measured for each section from each tree. Crown mass is a characteristic of vitality for the tree with larger limbs and unmerchantable stem. Crown mass was assessed using a two-way ANOVA to compare the DBH class means, the section level means and assess any interactions of the nested levels within separate DBH classes. ANOVA Tukey results yield only the 19.05 DBH class (mean=19.915 lbs., SD=11.27) was significantly greater than the means of the other three DBH classes ($p<0.0001$) (Appendix A, Table A.3.3). This could be due to the extended crown length seen in Figure 4.2 which was the main contributor to the 19.05 DBH class TTH when compared to the other DBH classes. Branch distribution throughout the crown, height of the first live limb, and the total crown length influenced the mass attained in the section sample. When C1-C4 masses were analyzed, C1 sections had a mean mass of 8.14 kg (17.945 lbs.), SD = 5.126 kg (11.30 lbs.) and was significantly greater than C4 sections with a mean= 3.43 kg, (7.56 lbs.) SD= 1.80 kg) (3.95) ($p=0.0017$). C2 and C3 resulted in both Tukey groups (a & b). A few outliers of extremely large and extremely small section masses were the cause for large standard deviations. The following crown samples were further than 1SD from the crown mass mean: Tree 12_C3, Tree 26_C1, Tree 23, C1, and Tree 7_C2 were 0.68, 0.59, 1.09, 0.77 kg, (1.5, 1.3, 2.4, and1.7 lbs.), respectively. These four smallest outliers came from the three smallest DBH classes. The largest DBH class held the largest crown section masses with Tree 3_C1, Tree 8_C1, Tree 13_C2, and Tree 22_C1 were 18.00, 13.56, 19.91, and 18.09 kg (39.7, 29.9, 43.9, and 39.9 lbs.), respectively. C1 crown sections started at the first live limb and the majority of the weight from this section was most likely due to the unmerchantable stemwood in the crown. The interaction term, DBH*section, was not significant in the model ($p=0.8467$).

The same two-way ANOVA Tukey tests was performed on tree specific crown values: total crown mass (TCM), crown length (CL), crown ratio (CR), and crown diameter (crown DBT). Section levels were not a factor in this analysis since all measurements are uniform for all samples within the same tree crown, therefore, only differences in DBH classes were analyzed. However, all the variables were not significantly different at the DBH class level except for TCM.

Total crown mass is the sum for all the crown section masses from the same tree. The 19.05 DBH class (mean = 36.13 kg, 79.66 lbs., SD=12.53 kg, 27.62 lbs.) is significantly different than 11.43 DBH class (mean = 13.02 kg, 28.7 lbs., SD = 4.04 kg, 9.71 lbs.). DBH classes 13.97 and 16.51 were not significantly different in either direction; both classes possessed both a & b Tukey letter designations. Comparing the tree's total crown mass ANOVA table to the sample's crown mass ANOVA table, shows continuity across the levels of analysis with the largest crown sample groups in the 19.05 cm (7.5 in.) crown classes (Appendix A, Table A3.4.). Based on these results, sample crown mass, total crown mass, and sample section diameters, show trends which changes with height sections and will be used as covariates in regression modeling in following sections.

4.1.2 Stemwood Disc Allometry

Three other allometric factors were measured directly for the stemwood discs: density, age and double bark thickness (DBT). The values of these allometric factors for stemwood generally decrease as stemwood sample height increases. Figures 4.6- 4.8 demonstrate this with the separate DBH class plots. Due to the trends observed, ANOVA and regression analysis were also conducted using DBH as a blocking factor and also testing for interaction within the blocks.

The smallest top diameter for logging purposes is 2 inches, which is smaller than all the D5 samples used in the study. Due to the different sizing in scales, it is also difficult to understand how each tree changes in comparison to the other DBH classes, other than the fact that no tree surpassed stemwood disc cuts higher than 12.19 m (40 ft.) in 4.5 and 5.5 DBH classes.

Figure 4.4 shows the change in tree diameter due to the tree height with respect to DBH classes. To the logging industry, this is important because many wood mill processes can only work with predetermined top diameter, usually 2 or 4 inches. Similarly to age and density, diameter also decreased proportionally with height. Each class is classified by DBH which shows a clear segregation between them. However, all four DBH classes show at least one tree surpassing a 10.16 cm (4 in.) crown diameter measured at the D5 disc. Conventional logging operations will specify a 2 inch top or a 4 inch top, yielding more crown residues left behind for the latter diameter. D1 measurements are on the y-axis for all the trees (0.0 m), and display butt swell which is common in pine trees (Cao et al., 1980; Forest Products Laboratory, 2010; West, 2009). The swelling of the tree increases the trunk stability and the DBT to protect the tree from fire and animals.

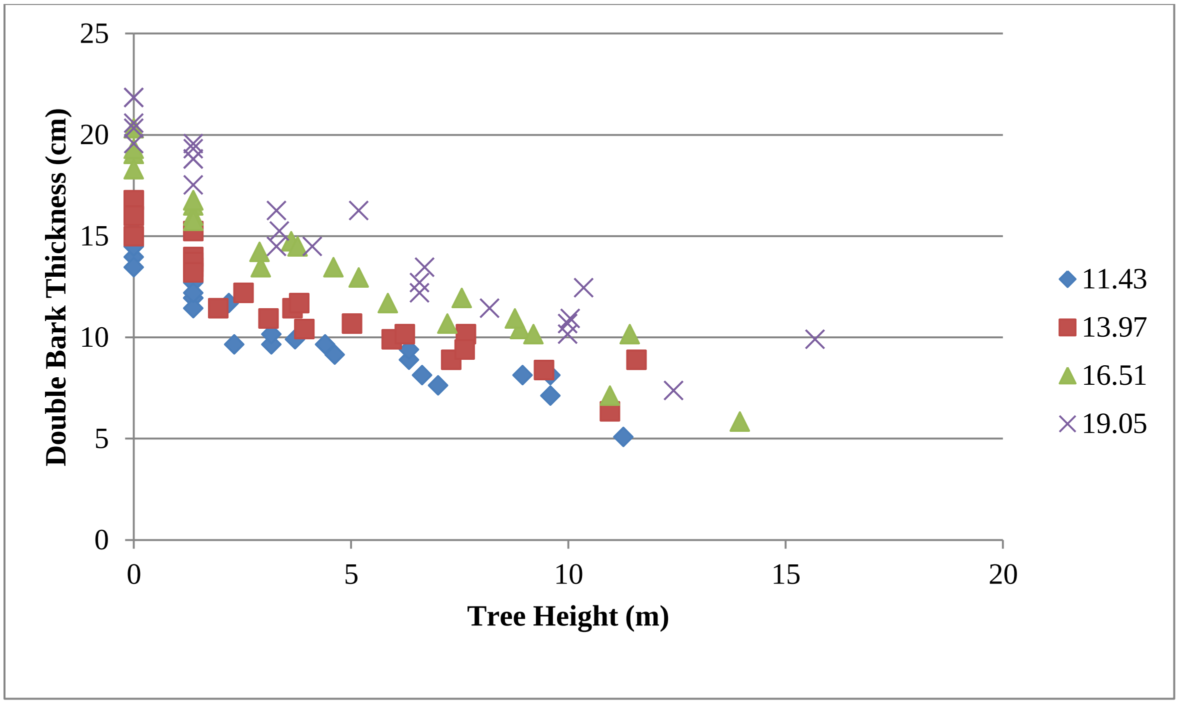

Figure 4.4 Scatterplot of the disc height and the double bark thickness (DBT) for stem wood disc samples separated by DBH classes.

Double bark thickness (DBT) is the average diameter of the stemwood discs, measured with a tree diameter tape measure across the disc with the bark intact. ANOVA Tukey analysis was conducted to see the changes in DBH class, disc sections, and any interaction between them. All three terms in the ANOVA model were significant ($p<0.0001$) (Appendix A, Table A.3.5). The $r^2 = 0.948$ and yields a good relationship to the categories distinction and the DBT. Every section (D1-D5) was significantly different from the others, and the DBH classes were also all significantly different from one another. Besides height, DBT is the other variable most useful when propagating tree growth models for crown estimates or yearly production (Duncanson et al., 2015; Landsberg et al., 2001).

It is well known that density within the stemwood of loblolly pine decrease with an increase in height (Acquah et al., 2016; Megraw, 1985; Oyedeji, 2015). However, how this change occurs within a DBH class or compared to other classes has yet to be examined. Figure

4.5(a-d) shows the changes in density with tree height by separate DBH classes. Density generally decreased in tree height, from 0.77 to 0.42 g/cm^3. Both the highest and lowest density values were in the 4.5 DBH class, and shows the largest variation. Variation between the DBH classes show the smaller classes consistently have lower densities for each point, especially the first two samples, D1 and D2, at 0 and 1.37 m, respectively. Density decreases in tree height (Megraw, 1985), and is an important metric in determining the energy density or energy volume of a fuel feedstock.

ANOVA was conducted on the DBH class groups, the sections D1-D5, and the interaction of sections nested within DBH classes to compare density (Table A.3.6). DBH group 4.5 (mean= 0.582 g/cm^3,SD = 0.079) was significantly greater than DBH group 6.5 (mean= 0.527 g/cm^3, SD = 0.055), DBH classes 5.5 and 7.5 were in the middle of the two and were not found significantly different from the others with a mean = 0.575 g/cm^3 , (SD=0.068) and mean = 0.572g/cm^3, (SD = 0.069), respectively. Additionally, ANOVA results in the sections D1-D5 were significantly different and ranging from 0.628 g/cm^3 in D1 samples and decreased to 0.495 g/cm^3 in D5 samples. With both grouping levels showing differences between the sample density, the interaction term, section*DBH, was also tested. The interaction term in the model yielded no significance, (p = 0.999), meaning the interaction of disc sections nested within DBH classes have no effect on the measured density of the disc. The interaction term does not improve the predicting power and reduced the original 5 section Tukey groups to 3.

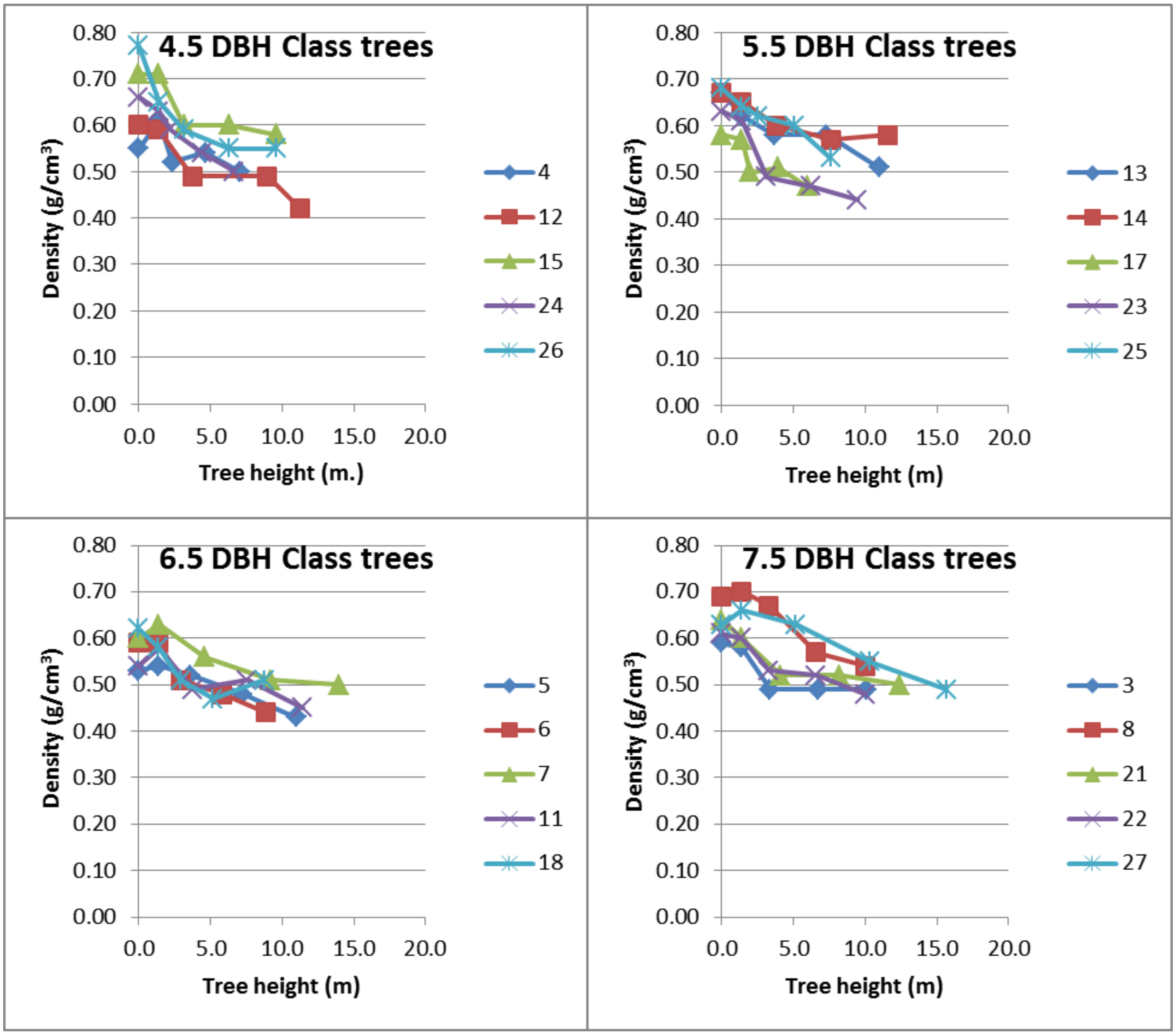

Figure 4.5 (a-d). Density in stem disc samples at tree height. (Legend numbers are tree identification numbers)

Figure 4.6 (a-d) shows the changes in rings with tree height. The forest from which the samples were procured is a mixed aged codominant stand with the trees at various stages of growth and ages. The oldest was in the 5.5 DBH class (Tree 14) at 38 years old. The youngest was 17 years old in the 4.5 DBH class (Tree 4). The ages across all DBH classes span between 20 and 30 years old, revealing that both younger and older trees may grow taller instead of increasing the trunk diameter. Age was considered a factor for carbon allocation because of the time the tree has used to grow.

ANOVA was conducted on the DBH class groups, the stemwood sections (D1-D5) and interaction within the DBH class's sections to test for significance in the disc ring counts (Table A.3.7). Rings between the DBH classes were found to be not significantly different from one another. All DBH groups, 4.5 – 7.5, possessed a large variation of rings with no particular trend where means were 19.4 (SD=7.0), 22.4 (SD=6.39), 20.1 (SD=6.00), and 23.3 (SD=6.4), respectively. However, each section, D1-D5, was different at a p-value<0.05. Tukey results show the decline from D1 ring averages at 28.9 (SD=4.8) to D5 with a mean of 13.6 (SD=2.4). As the ring counts increased from D1 sections to D5 sections, the variation of the sections decreased with smaller range of rings near the top of the stemwood. Based on these results in the disc samples for the rings and density, these two parameters will serve as covariates in the regression model for stemwood ash and HHV.

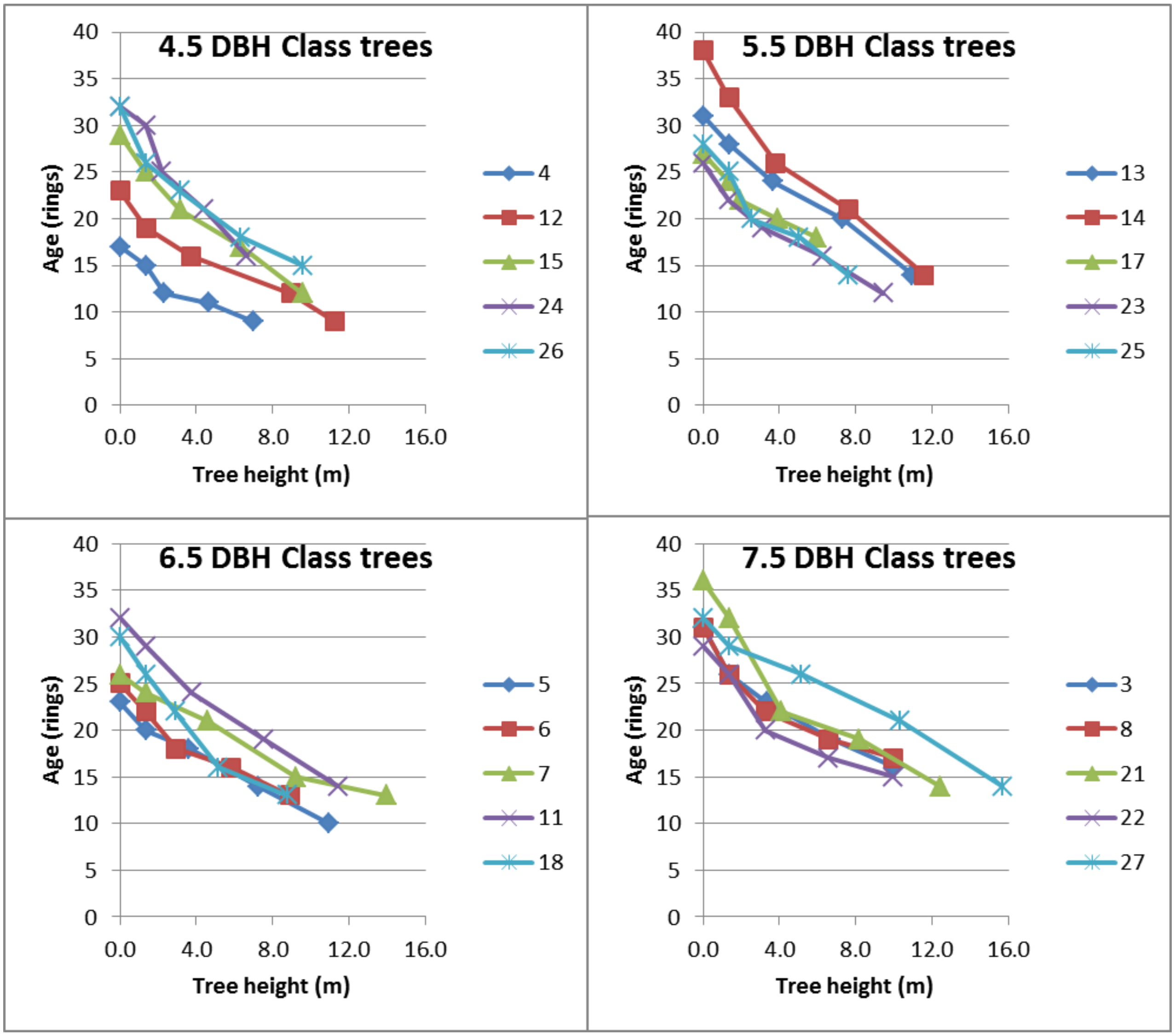

Figure 4.6 (a-d). Age of stem disc samples at tree heights.

4.2 Fuel Quality Analysis

Higher heating values in MJ/kg and ash percentage were conducted in triplicates for all the samples for continuity and the averages are reported in Appendix D. The ratio of the crown length to the total tree height is the crown ratio. For each disc and crown sample (D1-D5 and C1-C4), the sample's height, diameter, and green mass were taken and from this density, logarithmic diameter, and logarithmic height were computed. This is a nested design with three levels of experimental units: DBH classes (n=4), individual trees (n=20), and individual sampled sections categorized as either: stemwood samples (n=100) and crown samples (n=80).

Three grouped comparisons were made: the crown sections compared to the disc sections, each DBH class compared against each other, and each tree individually compared against the other trees. After reviewing the initial results, the nested comparisons were also made, allowing the inter-categorical means and variations to express the underlying differences among the disc and crown, DBH classes, and separate tree sections. ANOVA tables for the following four sections are found in Appendix B.

4.2.1 Stemwood and Crown Sample Comparisons

Higher heating value (MJ/kg) and ash content (% d.b.) were measured in triplicates for all the samples and the averages and standard deviations are reported in Appendix E. The first comparison was between the measured values of ash content and heating value between stemwood and the crown samples using a two-sample t-test (α=0.05). The mean ash content of crown samples was 1.17% (SD = 0.54%), while and stemwood disc samples had a mean ash content of 0.33% (SD=0.07%). The mean HHV for the crown and stemwood samples was 21.234 MJ/kg (SD = 0.346) and the 20.797 MJ/kg (SD = 0.401), respectively. While the populations in both t-tests are uneven (80 crown samples compared to 100 stemwood samples), the results were significantly different for both ash and HHV ($p<0.05$). The crown samples possessed higher energy content even with a higher average ash percentage compared to the stemwood discs. The measured ash content is authigenic ash and is found within the plant cells, not detrital ash from soil contamination. The increased authigenic ash content from clean stem wood samples to the crown residues is in line with reported literature where cellulose ash content consists of 0.3% (McMillin, 1968; Vassilev et al., 2010).

In 100 of the stemwood samples averaging 0.3%, the ash content measured is minimal and does not present an effect on the HHV. Only 2 samples out of the 80 crown samples in this study reached higher than 3% ash content and both were in the C4 crown section. While cellulose and lignin were not directly measured in the samples, the increase of higher heating value and ash content can be attributed to the larger proportion of lignin found in crown samples. Crown samples possess more lignin than stemwood samples (B. M. Jenkins et al., 1998) and are customarily left behind as logging residue.

4.2.2 Tree section Sample Comparison

The next level of comparisons was to determine which sections of the tree were significantly different from the others. Crown sections C1-C4 and stemwood discs D1-D5 were evaluated with a Tukey ANOVA (n=20). Figure 4.7 and figure 4.8 graphically represent the results for ash percentage and HHV, respectively. Ash content and HHV means and standard deviations with the corresponding Tukey group are shown in Tables 4.1.

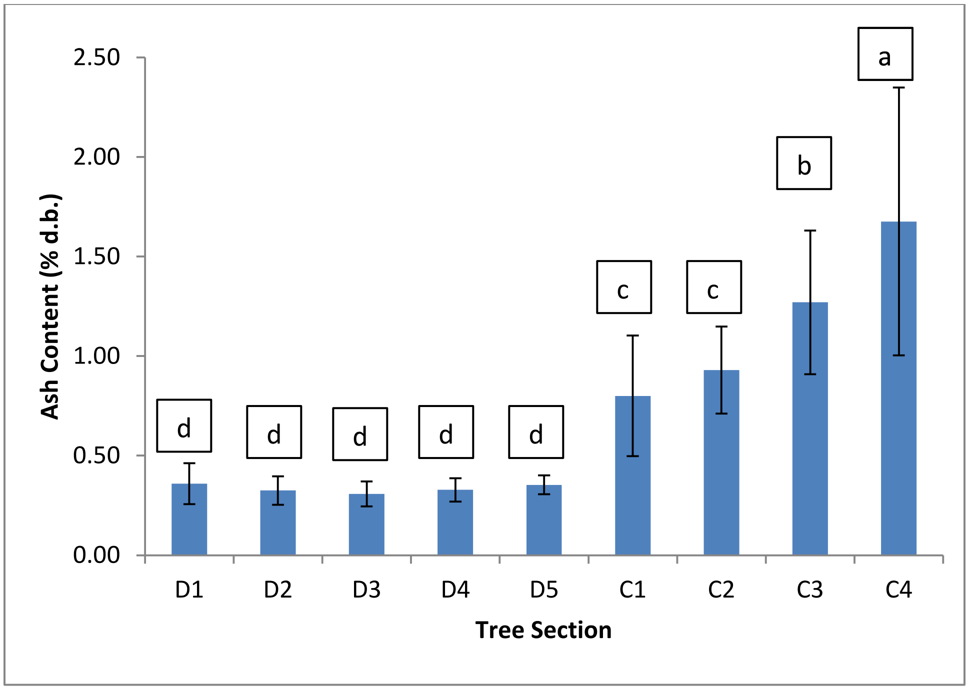

Figure 4.7 Mean tree section ash content (% d.b.) ANOVA Tukey results. Columns with similar letters are not significantly different.

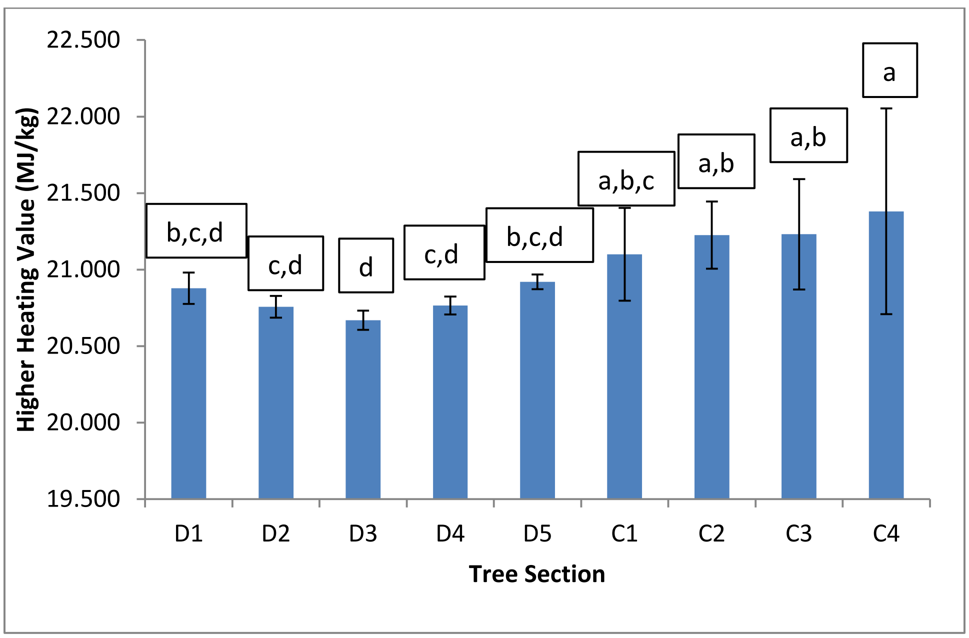

Figure 4.8 Mean tree section higher heating value ANOVA Tukey results. Columns with similar letters are not significantly different.

Table 4.2 Tree section ash percentage and HHV with Tukey grouping

Tree Section	Ash Percentage	Ash Tukey Group	HHV (MJ/kg)	HHV Tukey Group
D1	0.36±0.10	d	20.878±0.497	b,c,d
D2	0.33±0.07	d	20.757±0.239	c,d
D3	0.31±0.06	d	20.669±0.246	d
D4	0.33±0.06	d	20.765±0.299	c,d
D5	0.35±0.05	d	20.919±0.582	b,c,d
C1	0.80±0.30	c	21.100±0.469	a,b,c
C2	0.93±0.22	c	21.225±0.305	a,b
C3	1.27±0.36	b	21.231±0.309	a,b
C4	1.68±0.67	a	21.381±0.220	a

As previously determined in the two-sample t-test, the crown samples with the higher ash content also display higher HHV. Similar results reappear when comparing the tree sections to each other regardless of the DBH classes. This range reflects the data range shown in Table 4.1. Authigenic ash content in stemwood biomass is less than 0.36% and doesn't carry negative effects on loblolly pine HHV.

Higher heating value was found to have minimal increase between the disc samples heights. The lack of marginal trend from D1-D5 does not follow suit with other wood characteristics such as microfibril angle (MFA), (Megraw, 1985), or toughness and bending stress (Oyedeji, 2015). Both studies used 5 similar height locations within the stemwood within each tree. The changes in ash content or HHV in relative height sections did not follow a trend, nor was it similar to the trend found in relative height sections in the crown. DBH classes did not significantly affect the ash and HHV values (Appendix B, Table B.1.5 and Table B.1.6).

4.2.3 Individual Tree Regression Analysis

This study was to investigate the change in fuel quality throughout the changes within the tree. The previous analysis partitioned the independent samples into stemwood and crowns, separated into proportional sections, and blocking factors by DBH. However, this did not account for the variation in height among the proportional sample sections and the changes in heights across DBH blocks for both the stemwood and crown samples. Two analyses were conducted via regression to observe changes in fuel quality. The first analysis is to assess variable selection with both the crown and stemwood on a per tree basis, the second to investigate fuel quality differences by DBH groups with regards to height.

The stepwise regression for ash percentage (d.b.) took each the stemwood and crown samples tree's physical variables and used variable selection at $\alpha = 0.05$ to enter and stay in the model. The results found a general increase in ash due to diameter of the respective crown and stemwood disc sections, not the height. Table C.1.1 (Appendix C) displays that nearly all the regression analyses of the individual trees found only the DBT as useful in the model to predict the entire tree's fuel quality as while four trees found height and diameter as two most significant variable (Tree 11, Tree 18, Tree 25, and Tree 27). The addition of height in the model increased the model's power by converging Mallow's Cp to 3 for all four trees and an r^2 of 0.89, 0.94, 0.96, and 0.91, respectfully. Not every tree was able to converge on similar predictor variables but the diameter seemed to be the most prominent.

A further analysis of the averages of ash from each section within the DBH class was regressed and the only significant variable from all four was the diameter (Table C.1.2). The DBH class regression analysis returned the diameter as the most significant predictor and only the 4.5 and 6.5 class included height in the model which greatly improved the model's r^2 and Mallows Cp. Diameter seems to add an increase in the predictability of ash content over height.

HHV was not similar to ash content regression analysis in that not all trees yielded predictor variables nor were they similar for all trees (Table C.2.1). One tree (Tree 26) was found to not have any significant predicting variables. However, once they were grouped by DBH classes for regression, the DBH classes all selected diameter as the same significant variable.

4.3 Fuel Quality Analysis: Crown Sections

4.3.1 Crown Proximate Analysis: Ash

The ash content value was calculated based on the mass difference from combusting in a dry crucible following ASTM E1534. The average crown ash content (d.b.) for the entire population of 80 crown samples was 1.17% (SD = 0.54). This changes within the C1-C4 sections as well as the DBH classes. Table 4.3 and 4.4 show the summary statistics of ash content (% d.b.) between DBH classes, and C1- C4 sections, respectively. Stemwood typically has less ash content than the limb and bark portion of the tree. Proportionally C1 would possess more stemwood, therefore yielding a smaller ash content. Tukey HSD test was conducted to test the crown section categories, DBH classes and any interaction between them. The crown sections were significantly different from one another ($p<0.0001$) and show an increasing trend with proportional height. The DBH classes were also significantly different ($p= 0.0356$), but there was not a trend due to the change in DBH classes. There was not a significant effect from the interaction of DBH*section (Table B.1.1).

Table 4.3 Crown Ash Content Summary statistics by DBH Classes

Ash content (% d.b.)					
DBH Class (cm)	Mean	SD	Minimum	Maximum	N
11.43	1.17	0.39	0.47	1.94	20
13.97	1.19	0.64	0.28	3.09	20
16.51	1.35	0.65	0.59	3.37	20
19.05	0.96	0.37	0.43	1.76	20

Table 4.4 Crown Ash Content Summary statistics by Crown sections

Ash content (% d.b.)					
Crown Section	Mean	SD	Minimum	Maximum	N
C1	0.80	0.30	0.28	1.48	20
C2	0.93	0.22	0.65	1.49	20
C3	1.27	0.36	0.81	2.22	20
C4	1.68	0.67	0.77	3.37	20

The ash content in the crowns ranged from 0.28% to 3.37% ash content. The lowest percentage was found in the 13.97 cm (5.5 in) DBH class in section C1 and the largest was found in the 19.05 cm (7.5 in) DBH class in section C4. This is likely due an increase in limbs, foliage, and bark in the upper part of the crown relative to the amount of clean stemwood found in the crown. In order to compare all crown sections within each DBH class among the others, Tukey's HSD test was performed and the results are displayed in Table 4.5.

Table 4.5 Tukey HSD test for crown ash (% d.b.)

Ash content by crown sections (% d.b.)				
Crown Section (n=20)	C1	C2	C3	C4
Ash Content	0.80_{c}	$0.93_{b,c}$	1.27_{b}	1.68_{a}
Ash content DBH classes (% d.b.)				
DBH class (n=20)	11.43	13.97	16.51	19.05
Ash Content	$1.17_{a,b}$	$1.19_{a,b}$	1.35_{a}	0.96_{b}

*values with the same letters within the same row are not significantly different (p>0.05).

The gradual increase of ash content in the crown sections is most likely attributed to the lesser percentage of clean stemwood present in the crown and larger proportion of bark and needles. DBH classes are proportionally variable in the crown which is why there is minimal difference between each DBH class's sections. Other crown physical measurements were not different at the DBH level such as crown length, crown ratio, and crown diameter.

4.3.2 Crown Proximate Analysis: Volatile Matter

The volatile matter of the crown samples was conducted following ASTM E872 and measured in triplicates for each sample section. The DBH classes did not yield any significant differences from the other means, nor did the crown sections (p=0.06). The interaction between the two factors was also not significant (Table B.1.2). Table 4.7 and 4.8 displays the summary statistics of volatile matter in the crown by DBH class and crown sections, respectively.

Table 4.6 Crown Volatile Matter Summary statistics by DBH Classes

Volatile Matter (% d.b.)					
DBH Class (cm.)	Mean	SD	Minimum	Maximum	N
11.43	72.31	1.30	69.64	74.19	20
13.97	72.49	1.72	68.76	75.05	20
16.51	71.57	1.43	68.29	73.37	20
19.05	72.25	1.69	69.12	75.61	20

Table 4.7 Crown Volatile Matter Summary statistics by Crown sections

Volatile Matter (% d.b.)					
Crown Section	Mean	SD	Minimum	Maximum	N
C1	72.76	1.60	69.64	75.61	20
C2	72.05	1.73	68.29	74.31	20
C3	71.47	1.52	68.76	73.93	20
C4	72.34	1.16	70.42	74.76	20

4.3.3 Crown Proximate Analysis: Fixed Carbon

Fixed carbon was calculated using equation 3.9 as the mass difference of the moisture content (w.b.), ash content (d.b.) and volatile matter (d.b.). Fixed carbon varied as DBH classes increased, yet increased as the crown sections increased. A two-way ANOVA was conducted on FC (d.b.) to compare the DBH class, crown sections, and the interaction between the two factors. The interaction between the two factors did not yield significant however; both of the factors were significantly different from one another (Table B.1.3).

Table 4.8 Crown Fixed Carbon Summary statistics by DBH Classes

Fixed Carbon (% d.b.)					
DBH Class	Mean	SD	Minimum	Maximum	N
11.43	16.43	1.11	14.68	18.14	20
13.97	15.79	1.29	13.47	18.53	20
16.51	15.88	1.26	13.98	18.55	20
19.05	15.17	1.385	12.73	17.04	20

The fixed carbon showed a similar increasing trend as ash content did as the crown sections increased in height. Unlike ash percentage however, the smallest DBH class (11.43 cm) was the largest with 16.43% compared to the largest DBH class (19.05 cm) at 15.17%. This is most likely a trend due the fact that fixed carbon is based on the mass balance dry basis of the other three proximate analysis: moisture, volatile matter, and ash. The difference is small at 1.36% increase.

Table 4.9 Crown Fixed Carbon Summary statistics by Crown sections

Fixed Carbon (% d.b.)					
Crown Section	Mean	SD	Minimum	Maximum	N
C1	15.19	1.28	12.74	17.71	20
C2	15.53	1.06	12.86	17.36	20
C3	15.99	1.62	12.72	18.55	20
C4	16.57	0.84	15.33	18.14	20

Table 4.10 Tukey HSD test for Crown section FC (% d.b.)

Fixed Carbon by Crown sections (% d.b.)				
Crown Section (n=20)	C1	C2	C3	C4
Fixed Carbon	15.19_{b}	15.53_{b}	$15.99_{a,b}$	16.57_{a}
Fixed Carbon by DBH Class(% d.b.)				
DBH class (n=20)	11.43	13.97	16.51	19.05
Fixed Carbon	16.43_{a}	$15.79_{a,b}$	$15.88_{a,b}$	15.17_{b}

*values with the same letters within the same row are not significantly different (p=0.05).

4.3.4 Crown Higher Heating value

A two-way ANOVA was used to assess the crown sections, DBH classes and the interaction between these terms. The average HHV was 21.234 MJ/kg (SD=0.344). Tables 4.11 and 4.12 show the summary statistics for the difference in HHV between DBH classes and between crown sections C1-C4, respectively. However between the two factors and the interaction between them did not yield any significant difference. There was a marginal trend of

HHV from the proportional height increase in crown sections which increased from 21.10 MJ/kg to 21.38 MJ/kg.

Table 4.11 Summary Statistics for the DBH Class HHV.

Higher Heating value MJ/kg					
DBH Class	Mean	Standard Dev	Minimum	Maximum	N
11.43	21.289	0.303	20.885	21.890	20
13.97	21.191	0.395	20.573	21.980	20
16.51	21.271	0.328	20.699	22.010	20
19.05	21.153	0.362	20.193	21.783	20

Table 4.12 Summary Statistics for the Crown section HHV.

Higher Heating value (MJ/kg)					
Crown Section	Mean	Standard Dev	Minimum	Maximum	N
C1	21.100	0.469	20.193	22.010	20
C2	21.225	0.305	20.637	21.712	20
C3	21.198	0.309	20.678	21.877	20
C4	21.381	0.220	20.954	21.783	20

The mix of limbs, foliage, and unmerchantable stem wood in the crown sections gave a large variation of material to compose the crown samples. For this reason, the amount of variation between each crown section might have been too great to notice a significant difference by DBH class. The largest HHV of 21.783 MJ/kg came from the 16.51 cm (6.5 in.) DBH class and section C4. The smallest HHV came from the 19.05 cm (7.5 in) DBH class and the C1 section (20.985 MJ/kg). Examining Table 4.11, it is difficult to distinguish a difference between DBH classes. However, there is a noticeable increase in the mean HHV crown sections. For this reason, Tukey HSD test was used to test all means of the crown sections grouped by DBH class against the other means.

Table 4.13 Tukey HSD test of crown section HHV (MJ/kg)

Higher Heating Value MJ/kg				
DBH Class (cm)	C1	C2	C3	C4
11.43	21.150	21.284	21.254	21.468
13.97	21.098	20.984	21.413	21.399
16.51	21.167	21.345	21.268	21.304
19.05	20.985	21.287	20.988	21.352

Due to the relatively large variations between the groups within each DBH class, there was not a significant difference detected between crown sections. Categorizing the crowns by proportional height sections does not yield the best method to distinguish differences in its heating value. For Table 4.13, Tukey HSD test was performed but no significant difference was found between or among DBH classes and tree crown sections ($p>0.05$).

4.3.5 Crown Stepwise Regression Variable selection

Separating the crown samples into relative height sections and DBH classes doesn't give enough information to show where the ash content or how HHV varies throughout the tree. The variables here were all different within the sections nested within the DBH classes. Moisture content is used to convert the ash content and HHV to dry basis. The SAS method used here is PROC REG values of alpha were tested at $\alpha = 0.05$.

The ash content regression analysis shows:

$$\text{Ash content } (\%) = 3.09270 - 0.43383\ (\text{SL}) + 0.003337(\text{SM}) - 0.88151(\ln(\text{DBT} + 1)\quad (4.3)$$

where:

SL = section length (m)

SM = section mass (kg)

DBT = double bark thickness (cm)

Pearsons correlation coefficient, r^2, achieved 0.5272 and Mallow's C(p) is 1.878. This is a mild fit for regression models. The section length is the quartered length of the crown section. The crown mass is the dry mass of the crown's section. Both of these of course cannot be directly measured prior felling or harvesting of the tree. However, if the tree is felled, the sections length and total crown mass can be measured and an estimate of the authigenic ash content of the crown can be obtained. The double bark thickness is used to find the last term in the equation, (ln(DBT+1). Because the crown diameters of the C4 were at 0 cm, the term requires the addition of 1 for the natural log transformation. Crown diameters are measured using the DBT and other studies have used this to estimate annual growth. Certain sized DBT diameter is what determines the harvested round wood length limit for most industries.

Volatile matter did not yield a regression model by not selecting any variables at α = 0.01, 0.05, or 0.10. There was not a trend in the subsequent two-way ANOVA comparing volatile matter.

Fixed carbon did yield a regression model with crown ratio (CR), section mass (SM), and the term, D*H, the section diameter multiplied by the section height. The r^2 was only 0.48 with a Mallows Cp of -2.77, which is not a good result. A general trend of increasing fixed carbon in the crown sections is from 15.19% to 16.57%. This trend is similar to the trend found in the ash content parameter. However, both parameters show a slight increase with increasing crown sections both, in the same direction. The small increase in fixed carbon is only 1.38%.

Higher heating value regression model yielded volatile matter and the tree height percentage as significant variables to enter the model at $\alpha = 0.05$, however, the r^2 was calculated at 0.1894 and Mallow's C(p) is 7.87, both of which are indicators of poor performance. In conjunction with previous ANOVA analysis, the HHV in tree crowns is not significantly changing between DBH classes and their differences are specific to the C1-C4 classifications (Appendix B Tables B.1.5 and B.1.6).

4.4 Fuel Quality Analysis: Stemwood Discs

Prior to oven drying, cutting, and lab analysis, the disc samples were measured in the field to collect the physical properties. Decreasing diameter in stemwood correlates to an increasing trend in microfibril angle (MFA), modulus of rupture (MOR), and modulus of elasticity (MOE) (Megraw, 1985). This analysis will determine if similar results occur with ash content and HHV.

4.4.1 Stemwood Ash content

The ash analysis was conducted with the 100 stemwood discs, categorized (D1-D5) for ash and energy content. For the entire population the ash content of the disc samples was 0.33% (SD=0.07). The mean changes for the groups of DBH classes and disc sample sections. Table 4.14 and 4.15 shows the difference in the DBH class and stemwood section ash percentage means, respectively. Two-way ANOVA was used to assess the different categories in the DBH classes, crown sections and their interaction (Table B.1.2). Only the DBH factor was significantly different, however, no trend was noticed ($p<0.0099$). The proportional heights of the stemwood discs appear to have little effect on the authigenic ash content; however the larger DBH class stemwood discs had the least amount of ash on average.

Table 4.14 Ash content summary statistics of disc samples between DBH classes.

Ash % (d.b.)					
DBH Class	Mean	SD	Minimum	Maximum	N
11.43	0.363_{a}	0.10	0.24	0.72	25
13.97	$0.328_{a,b}$	0.06	0.23	0.46	25
16.51	$0.349_{a,b}$	0.04	0.26	0.43	25
19.05	0.298_{b}	0.06	0.21	0.38	25

*values with the same letters within the same row are not significantly different (p=0.05).

Table 4.15 Ash content summary statistics of stemwood disc samples between sections .

Ash % (d.b.)					
Disc Section	Mean	SD	Minimum	Maximum	N
D1	0.359	0.10	0.26	0.72	20
D2	0.325	0.07	0.23	0.55	20
D3	0.308	0.06	0.21	0.40	20
D4	0.328	0.06	0.23	0.46	20
D5	0.353	0.05	0.27	0.43	20

4.4.2 Stemwood Higher Heating value

A two-way ANOVA was conducted on the stemwood to assess HHV by DBH blocks, stemwood disc sections (D1-D5), and the interaction between these terms. However, no significant difference was found for the DBH block (p=0.2999), sections (p=0.2768), or the interaction term (p=0.3779). A follow up ANOVA by comparing all sections within the DBH classes to one another also did not yield a significant difference between any of the groups. For the entire population, the HHV of the disc samples was 20.798 MJ/kg (SD=0.398). Table 4.16 and table 4.17 display the stemwood summary statistics by DBH and stemwood sections, respectively.

Table 4.16 Higher heating value summary statistics of disc samples between DBH classes.

Higher Heating Value (MJ/kg)					
DBH Class	Mean	SD	Minimum	Maximum	N
11.43	20.928	0.440	20.554	22.535	25
13.97	20.769	0.274	20.240	21.448	25
16.51	20.736	0.571	20.232	23.279	25
19.05	20.757	0.206	20.247	21.190	25

Table 4.17 Higher Heating Value summary statistics of disc samples between sections.

Higher Heating value (MJ/kg)					
Crown Section	Mean	SD	Minimum	Maximum	N
D1	20.878	0.497	20.240	22.535	20
D2	20.757	0.239	20.247	21.190	20
D3	20.669	0.246	20.232	21.089	20
D4	20.765	0.299	20.308	21.737	20
D5	20.919	0.582	20.558	23.379	20

The heating value changes did not yield a marginal trend for DBH classes or disc sample sections. Categorizing the sections by relative height groups yield similar results from previous analysis on the crown samples, which does not yield a significant difference in the stem wood ash percentage or higher heating value.

Table 4.18 Tukey HSD test of stem wood disc section HHV (MJ/kg)

Higher Heating value (MJ/kg)					
DBH Class	D1	D2	D3	D4	D5
11.43	21.289	20.903	20.756	20.892	20.800
13.97	20.890	20.740	20.594	20.839	20.781
16.51	20.620	20.656	20.567	20.594	21.246
19.05	20.713	20.729	20.761	20.733	20.851

4.5 Ultimate Analysis Results

Ultimate analysis measures the chemical composition of the biomass sample in terms of percentage of carbon, hydrogen, nitrogen, and sulfur. Oxygen is measured based on percent difference. For this analysis, the top five ash and HHV samples among both the crown and stemwood samples were analyzed in a CHNS Ultimate analyzer (VarioMicro Select Elementar, Germany). Duplicates of each sample were tested to produce an average.

4.5.1 Regression Analysis: Crown sections

Every crown sample (80 total) underwent CHNS ultimate analysis to compare the difference between and among the DBH class and section factors. A two way ANOVA was used to determine the differences in nitrogen, carbon, hydrogen, sulfur and oxygen. The DBH classes did not yield any significant differences in the crown. The only variables which showed a significant difference in the analysis was nitrogen and hydrogen with respect to the crown sections (C1-C4). Sulfur was minimal due to the small amount of ash content however it was shown to only occur in the C4 crown section with a mean of 0.018% (n=20). Sulfur was minimal and excluded from this study; carbon, hydrogen, nitrogen, and oxygen were compared.

Table 4.19 Two-way ANOVA Tukey results from the CHNSO measurements: Nitrogen

Nitrogen by crown section (% d.b.)				
Crown Section (n=20)	C1	C2	C3	C4
N	0.05_{c}	$0.094_{b,c}$	0.18_{b}	0.37_{a}
Nitrogen by DBH class (% d.b.)				
DBH class (n=20)	11.43	13.97	16.51	19.05
N	0.16_{a}	0.18_{a}	0.19_{a}	0.13_{a}

*values with the same letters within the same row are not significantly different (p>0.05).

Stepwise regression conducted on the percent nitrogen yielded the ash content (d.b.) and the DBT as significant variables in the model ($\alpha = 0.05$). The model $r^2 = 0.72$ and has a large C(p) with 2470, which is unusually large. Both ash and DBT follow similar trends in the crown. However, it does not intuitively follow logic to use either variable in predicting the nitrogen yield of the crown samples. Nitrogen in the samples is related to the amount of nitrogen available in the soil for growing purposes and can change with fertilizer inputs. The amount of nitrogen available to the 20 trees used here is beyond the scope of this study.

Hydrogen was also significantly different in the crown sections and not different in the DBH classes similar to nitrogen. However, there was not a defined trend as with the nitrogen variability. Table 4.20 displays the two-way ANOVA (α=0.05) tukey results where the crown sections were different from another with a P-value = 0.02. The DBH classes were not significantly different wish a P-value = 0.53. The two-way ANOVA tables for the CHNOS analysis are in Appendix B, Table B.2.1-4, for carbon, nitrogen, hydrogen, and oxygen, respectively.

Table 4.20 Two-way ANOVA Tukey results from the CHNSO measurements: Hydrogen

Hydrogen by crown section (% d.b.)				
Crown Section (n=20)	C1	C2	C3	C4
H	$6.64_{a,b}$	$6.63_{a,b}$	6.56_{b}	6.70_{a}
Hydrogen by DBH class (% d.b.)				
DBH class (n=20)	11.43	13.97	16.51	19.05
H	6.64_{a}	6.64_{a}	6.66_{a}	6.59_{a}

*values with the same letters within the same row are not significantly different (p>0.05).

Stepwise regression for C, H, and O selected similar variables for the models. Carbon percentage selected N, O, H, and DBT, while H selected C, O, N and DBT. C, H, and O models reached an $r^2 = 0.99$, 0.98, and 0.99 respectively. This is a result of the mass difference in the samples used to find the oxygen percentage. The ultimate analysis results (Appendix F) is comparable to other woody biomass results and within a few percentage points of the same pine wood sawdust used in Abdoulmoumine, (2014).

Figure 4.9 shows the scatterplot of the measured HHV of the crown samples based on the percent carbon and the corresponding value of the Boie and Dulong calculations of an estimated HHV. Dulong calculations consistently underestimate the HHV of crown samples with a mean absolute error (MAE) of 2.66 MJ/kg and a root mean square error (RMSE) of 2.80 MJ/kg. This is partially due to the high amount of oxygen content in the sample. The Boie equation estimates the crown sample HHV much better with a mean absolute error of 0.82 MJ/kg and a RMSE of 1.09 MJ/kg. The Boie equation estimated HHV overestimates 8 samples once the carbon content surpassed 49.55%. Only tree 13 section C3 was perfectly predicted by the Boie equation at 20.714 MJ/kg.

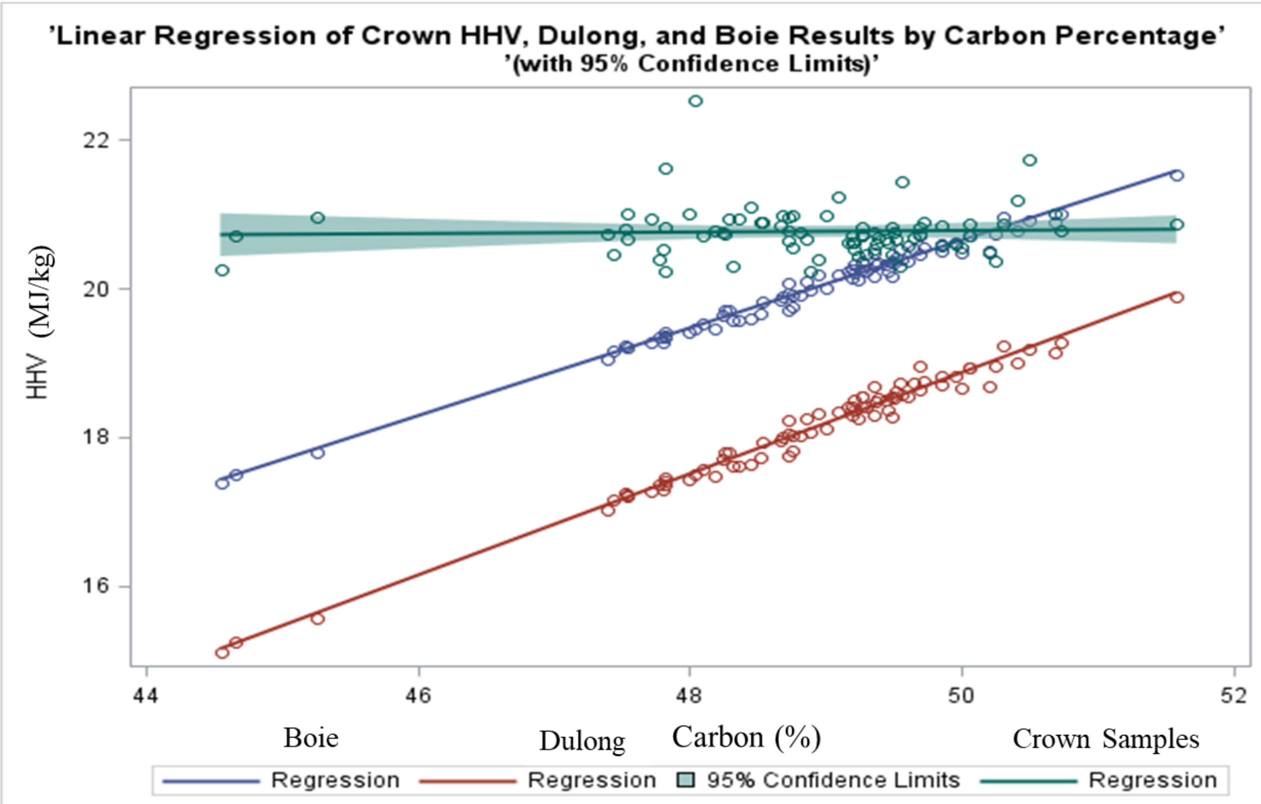

Figure 4.9 Crown section HHV (MJ/kg) plotted with carbon percentage

4.5.2 Regression Analysis: Stemwood Discs

A randomly selected set of 30 stemwood discs were used to evaluate the differences of stemwood composition. The HHV of the stemwood discs were used to develop a range of values to select the samples. Figure 4.10 displays the change in HHV based on the measured carbon content and the estimates obtained by the Dulong and Boie equations.

The Dulong equation and Boie equation for ultimate analysis represent a level of certainty when predicting the heating value of a feedstock with a given elemental composition. Carbon content and the formation of carbon bonds in combustion of the sample result in a larger heating value. Dulong calculations consistently underestimate the HHV of stemwood samples with a MAE of 4.60 MJ/kg and a RMSE of 4.89 MJ/kg. This is partially due to the high amount of oxygen content in the sample. The Boie equation estimates the stemwood sample HHV much better with a MAE of 2.62 MJ/kg and a RMSE of 2.84 MJ/kg. Prior to the C% less than 50%, both the Boie and Dulong equation underestimate the HHV in the stemwood sections. Past the 50% carbon point, the Boie equations does the best job at estimating HHV. Neither prediction equation estimated any stemwood sample HHV perfectly.

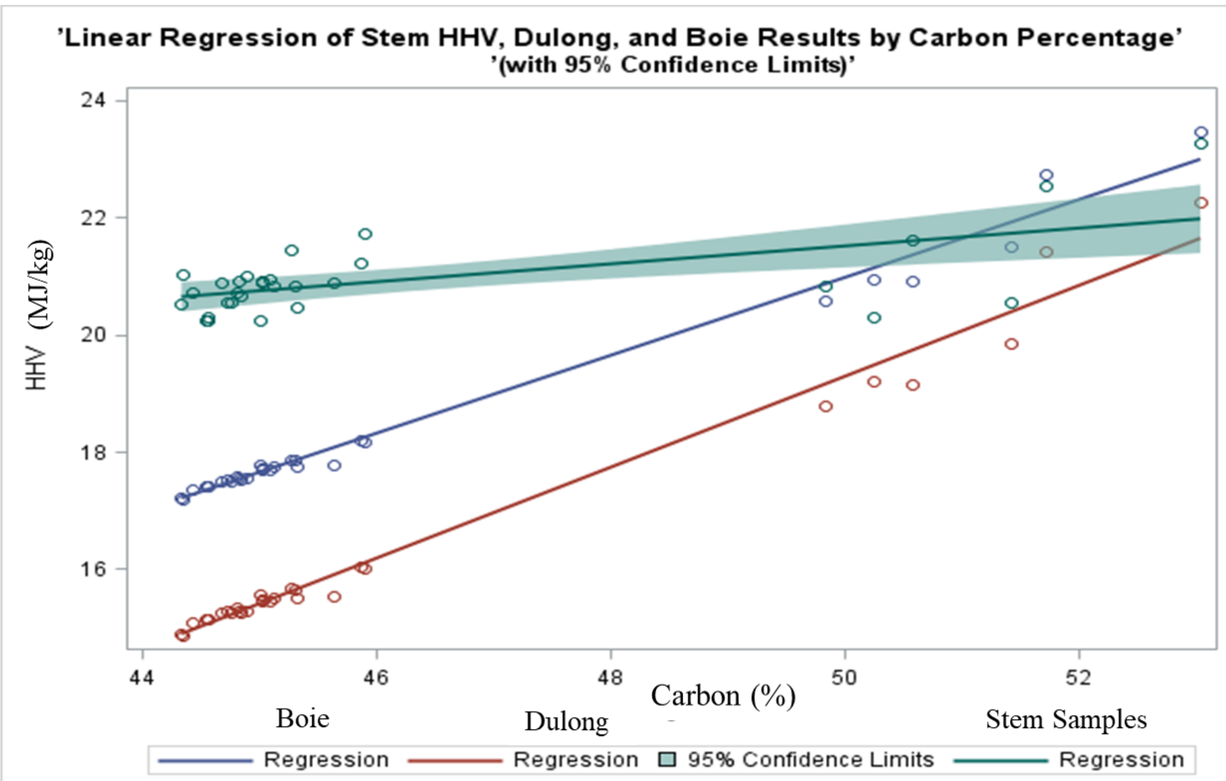

Figure 4.10 Stemwood HHV (MJ/kg) plotted with carbon percentage

Chapter 5: Conclusions

5.1 Objective #1

The first objective was to investigate the effect of within tree variability, i.e. across tree heights and diameters, between crown and stemwood on fuel quality parameters, specifically proximate analysis and higher heating value. The results presented for this objective can serve as a baseline for understanding the fuel quality variability between tree components, which is useful for bioenergy feedstocks. Distinctions between the crown and stemwood in the ash and HHV were both significantly different, $p<0.001$. The ash content in the crown was significantly higher (mean = 1.71%) and also significantly higher in HHV (mean = 21.234 MJ/kg) compared to stemwood ash (mean = 0.33%) and HHV (mean = 20.797 MJ/kg). The crown's sections showed significant changes in ash content increasing from the first section, C1 at 0.80% to the fourth section, C4 at 1.68%. C1 and C2 crown sections yielded authigenic ash of <1% and a HHV greater than all the stemwood sections measured within the same tree.

The HHV and ash content of stemwood did not significantly vary between stemwood sections. HHV was not significantly different for the crown samples sections or DBH classes. The stemwood sections, the change in relative height and actual height did not yield any differences between the ash and HHV. There is not enough evidence to show significant changes in fuel quality regarding ash and HHV along the height of bark-free clean stemwood.

5.2 Objective #2

The second objective was to determine the effect among individual trees, i.e. across DBH classes, on fuel quality parameters, specifically ash content and higher heating value. The results presented for this objective will serve as whole tree understanding for the changes in fuel quality on a per tree or DBH class size basis. Ash content was significantly less for the largest DBH class 19.05 cm (7.5 in.) in both stemwood and crown. Comparisons among the stemwood showed the ash content significantly decreased between the DBH classes from 0.363% (d.b.) in the smallest DBH class (11.7 cm) to 0.298 % (d.b.) in the largest DBH class, 19.05 cm. Only the ash content was affected by the DBH classes; the was no significant effect of DBH on the change in HHV.

Ash and HHV regression models for each tree yielded different results for significant variable selection. However, regression on the separate DBH classes all chose the DBT as a significant variable for ash and HHV. Regression analysis for ash content however, selected height as a second significant variable for the 11.43 cm and 16.51 cm class. Using all the samples in the crown without grouping by DBH class in regression analysis for ash content yielded a model with the natural log of diameter +1, crown section mass, and the crown section length. The ash content of the crown was minimal and did not pose a significant negative effect on HHV in the crown samples.

5.2 Objective #3

The third objective was to investigate the effect of chemical composition of carbon hydrogen, oxygen, nitrogen, and sulfur on the higher heating value for loblolly pine crown and stemwood. The results of this objective can be used to the differences in using chemical composition to estimate HHV. Ultimate analysis yielded that both Dulong and Boie equations are adequate in predicting the HHV of stemwood sections when the C% surpasses 50%. For all ranges of C% in the measured samples, the Boie equation is the better of the two in estimating HHV for both the crown and stemwood samples. However, using strictly carbon content or other physical inputs did not yield a model to accurately estimate the HHV of stemwood or crown samples due to their variability by section or DBH classes.

5.3 Future Recommendations

Crown residues of loblolly pine trees qualify as a feedstock comparable to the stemwood of loblolly pines. Elevated ash content in the crown is authigenic and updated harvesting equipment to reduce soil contamination could be used to create more feedstocks. The range of height and diameter ratios varied with the tree's ages and DBH classes, as well as the other growing factors such as competition, annual rain fall, and sunlight. A similar follow up analysis of loblolly pines are with controlled and maintained growing inputs would allow verification of fuel quality properties.

Further research in this area would only need 3 sections of the crown to find significant or marginal differences. Across the entire tree height range, the variation is minimal. Between all of the sampled sections: crown and stem, and within the DBH blocks, yield statistically the same HHV. The sample's ash content did not produce a negative effect on the sample's HHV. This could be due to the stemwood and crown's chemical composition having the most effect on these properties, regardless of their height location or DBT within the tree.

Direct combustion of biomass which only possesses authigenic ash content do not show a significant decrease in HHV, and therefore remain adequate feedstocks for heating and cofiring with other fuels. For processes which are sensitive around the ash content of the feedstock, such as pyrolysis, clean stemwood without bark and without soil contamination is the best option, however, even the small amount of authigenic ash content can be enough to deactivate the catalyst (Pradhan, 2015). New harvesting mechanisms could make a whole tree harvest operation viable which will assist in reducing the feedstock's ash content and overall production cost.If the process is for direct combustion and the process can withstand ash percentages as high as 2%, unmerchantable stemwood with crown residues can be used to produce process heat within the appropriate fuel quality standards.

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Appendices

Appendix A. ANOVA results for crown and stem samples in physical measurements

Table A.1.1 Tree height one-way ANOVA

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	3	729.050000	243.016667	7.22	0.0028
Error	16	538.600000	33.662500		
Corrected Total	19	1267.650000			

R-Square	**Coeff Var**	**Root MSE**	**Height Mean**
0.575119	11.50038	5.801939	50.45000

Table A.2.1 Sample height ANOVA of stemwood discs by section with DBH classes and interaction.

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	19	14941.03097	786.37005	44.02	<.0001
Error	80	1429.24712	17.86559		
Corrected Total	99	16370.27809			

R-Square	**Coeff Var**	**Root MSE**	**Height Mean**
0.912693	29.93527	4.226771	14.11970

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
Section	4	14516.89414	3629.22353	203.14	<.0001
DBH	3	212.68131	70.89377	3.97	0.0109
DBH * Section	12	211.45553	17.62129	0.99	0.4692

Table A.2.2 Height means for the stemwood samples and the total crown length in Figure 4.2

Stemwood disc section heights (ft.)

Diameter Class	D1	D2	D3	D4	D5	Crown Length
7.5	0.00±0.00	4.50±0.00	8.12±2.70	11.40±1.12	12.26±1.55	23.44±4.94
6.5	0.00±0.00	4.50±0.00	7.20±2.31	11.28±2.88	12.48±2.03	14.22±4.76
5.5	0.00±0.00	4.50±0.00	5.38±2.55	9.92±2.56	10.10±2.57	18.56±4.76
4.5	0.00±0.00	4.50±0.00	5.06±2.11	10.57±3.99	8.83±1.72	14.58±4.52

Table A.3.1 Sample height of crown sections by section with DBH classes and interaction.

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	4014.247469	267.616498	7.24	<.0001
Error	64	2366.878000	36.982469		
Corrected Total	79	6381.125469			

R-Square	**Coeff Var**	**Root MSE**	**Height Mean**
0.629081	13.83592	6.081321	43.95313

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	2075.775594	691.925198	18.71	<.0001
Section	3	1875.972656	625.324219	16.91	<.0001
DBH * Section	9	62.499219	6.944358	0.19	0.9947

Table A.3.2 Sample DBT of crown sections by section with DBH classes and interaction.

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	74.38046875	4.95869792	55.02	<.0001
Error	64	5.76800000	0.09012500		
Corrected Total	79	80.14846875			

R-Square	**Coeff Var**	**Root MSE**	**DBT Mean**
0.928034	23.58042	0.300208	1.273125

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	1.50609375	0.50203125	5.57	0.0019
Section	3	72.03765625	24.01255208	266.44	<.0001
DBH * Section	9	0.83671875	0.09296875	1.03	0.4252

Table A.3.3 Sample mass of crown sections by section with DBH classes and interaction.

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	2986.707875	199.113858	3.30	0.0004
Error	64	3856.904000	60.264125		
Corrected Total	79	6843.611875			

R-Square	**Coeff Var**	**Root MSE**	**CrownMass Mean**
0.436423	60.97592	7.762997	12.73125

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	1678.403375	559.467792	9.28	<.0001
Section	3	1020.334375	340.111458	5.64	0.0017
DBH * Section	9	287.970125	31.996681	0.53	0.8467

Table A.3.4 Tree Total Crown Mass with DBH class comparison.

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	3	6713.61350	2237.87117	3.88	0.0294
Error	16	9239.86400	577.49150		
Corrected Total	19	15953.47750			

R-Square	**Coeff Var**	**Root MSE**	**Total Crown Mass Mean**
0.420824	47.18911	24.03105	50.92500

Table A.3.5 Sample DBT of stemwood disc sections by section with DBH classes and interaction.

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	19	218.0411000	11.4758474	76.15	<.0001
Error	80	12.0560000	0.1507000		
Corrected Total	99	230.0971000			

R-Square	**Coeff Var**	**Root MSE**	**DBT Mean**
0.947605	7.577610	0.388201	5.123000

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	53.5307	17.8435667	118.40	<.0001
Section	4	157.2256	39.3064000	260.83	<.0001
DBH * Section	12	7.2848	0.6070667	4.03	<.0001

Table A.3.6 Sample density of stemwood disc sections by section with DBH classes and interaction.

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	19	0.313771	0.016514	7.205	<.0001
Error	80	0.183360	0.002292		
Corrected Total	99	0.497131			

R-Square	**Coeff Var**	**Root MSE**	**Density Mean**
0.6312	0.1257	0.04787	0.5637

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	0.046691	0.015564	6.79	<.0001
Section	4	0.262226	0.065557	28.60	<.0001
DBH * Section	12	0.004854	0.000405	0.18	0.999

Table A.3.7 Sample age based on rings of stemwood disc sections by section with DBH classes and interaction.

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	19	3236.20	170.326	13.400	<.0001
Error	80	1016.80	12.710		
Corrected Total	99	4253.00			
R-Square	**Coeff Var**	**Root MSE**	**Density Mean**		
0.947605	7.577610	0.388201	0.5637		
Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	253.32	84.440	6.64	<.0001
Section	4	2965.70	741.425	58.33	<.0001
DBH * Section	12	17.18	1.432	0.11	1.000

Appendix B. ANOVA results for crown and stemwood samples in proximate analysis, higher heating value, and ultimate analysis

Table B.1.1 Crown samples testing ash content

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	12.20196	0.813464	4.85	<.0001
Error	64	10.7358	0.167747		
Corrected Total	79	22.93776			

R-Square	**Coeff Var**	**Root MSE**	**Ash Mean**
0.531959	35.02836	0.409569	1.169250

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	1.52584500	0.50861500	3.03	0.0356
Section	3	9.22021500	3.07340500	18.32	<.0001
DBH* section	9	1.45589500	0.16176611	0.96	0.4776

Table B.1.2 Crown samples testing volatile matter

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	0.00470016	0.00031334	1.38	0.1847
Error	64	0.01453344	0.00022708		
Corrected Total	79	0.01923360			

R-Square	**Coeff Var**	**Root MSE**	**VM Mean**
0.244372	2.088330	0.015069	0.721598

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	0.00096762	0.00032254	1.42	0.2450
Section	3	0.00176507	0.00058836	2.59	0.0604
DBH* section	9	0.00196747	0.00021861	0.96	0.4789

Table B.1.3 Crown samples testing fixed carbon

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	0.00439119	0.00029275	2.00	0.0288
Error	64	0.00935873	0.00014623		
Corrected Total	79	0.01374992			

R-Square	**Coeff Var**	**Root MSE**	**FC Mean**
0.319361	7.644647	0.012093	0.158183

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	0.00159819	0.00053273	3.64	0.0172
Section	3	0.00214434	0.00071478	4.89	0.0040
DBH* section	9	0.00064866	0.00007207	0.49	0.8741

Table B.1.4 Crown samples testing HHV

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	1.68149860	0.11209991	0.87	0.6001
Error	64	8.25441160	0.12897518		
Corrected Total	79	9.93591020			

R-Square	**Coeff Var**	**Root MSE**	**HHV Mean**
0.169234	1.691952	0.359131	21.22585

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	0.25164750	0.08388250	0.65	0.5856
Section	3	0.81233890	0.27077963	2.10	0.1090
DBH* section	9	0.61751220	0.06861247	0.53	0.8459

Table B.1.5 Stemwood disc samples testing ash content

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	19	0.1173	0.00617	1.23	0.258
Error	80	0.4026	0.00503		
Corrected Total	99	0.5199			

R-Square	**Coeff Var**	**Root MSE**	**Ash Mean**
0.225673	21.20042	0.000709	0.003346

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	0.06106800	0.02035600	4.05	0.0099
Section	4	0.03645400	0.00911350	1.81	0.1348
DBH* section	12	0.01980200	0.00165017	0.33	0.9820

Table B.1.6 Stemwood disc samples testing HHV

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	19	3.430952	0.180576	1.16	0.3123
Error	80	12.45323	0.155665		
Corrected Total	99	15.88418			

R-Square	**Coeff Var**	**Root MSE**	**HHV Mean**
0.216050	1.896794	394.4911	20797.78

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	0.58019712	0.19339904	1.24	0.2999
Section	4	0.81009406	0.20252352	1.30	0.2768
DBH* section	12	2.04066098	0.17005508	1.09	0.3779

Table B.2.1 Two-way ANOVA testing Crown sections for carbon

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	15.6414750	1.0427650	0.70	0.7780
Error	64	95.7475200	1.4960550		
Corrected Total	79	111.3889950			
R-Square	**Coeff Var**	**Root MSE**	**C Mean**		
0.140422	2.501947	1.223133	48.88725		
Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	6.49433500	2.16477833	1.45	0.2374
Section	3	3.46961500	1.15653833	0.77	0.5133
DBH* section	9	5.67752500	0.63083611	0.42	0.9188

Table B.2.2 Two-way ANOVA testing Crown sections for nitrogen

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	1.07186000	0.07145733	6.78	<.0001
Error	64	0.67496000	0.01054625		
Corrected Total	79	1.74682000			
R-Square	**Coeff Var**	**Root MSE**	**N Mean**		
0.613606	61.67864	0.102695	0.166500		
Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	0.05001000	0.01667000	1.58	0.2027
Section	3	0.94467000	0.31489000	29.86	<.0001
DBH* section	9	0.07718000	0.00857556	0.81	0.6060

Table B.2.3 Two-way ANOVA testing Crown sections for hydrogen

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	0.30339500	0.02022633	1.10	0.3756
Error	64	1.17796000	0.01840563		
Corrected Total	79	1.48135500			
R-Square	**Coeff Var**	**Root MSE**	**H Mean**		
0.204809	2.045724	0.135667	6.631750		
Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	0.04122500	0.01374167	0.75	0.5283
Section	3	0.19196500	0.06398833	3.48	0.0209
DBH* section	9	0.07020500	0.00780056	0.42	0.9176

Table B.2.4 Two-way ANOVA testing Crown sections for oxygen

Source	*DF*	*Sum of Squares*	*Mean Square*	*F Value*	*Pr > F*
Model	15	24.4422000	1.6294800	0.90	0.5658
Error	64	115.6372000	1.8068312		
Corrected Total	79	140.0794000			

R-Square	**Coeff Var**	**Root MSE**	**O Mean**
0.174488	3.033591	1.344184	44.31000

Source	*DF*	*ANOVA SS*	*Mean Square*	*F Value*	*Pr > F*
DBH	3	8.40445000	2.80148333	1.55	0.2101
Section	3	8.60827000	2.86942333	1.59	0.2009
DBH* section	9	7.42948000	0.82549778	0.46	0.8978

Appendix C. Combined Stemwood and Crown sample Regression Results

Summary of Stepwise Selection for Ash									
Tree ID #	Step	Variable Entered	Variable Removed	Number Vars In	Partial R-Square	Model R-Square	C(p)	F Value	Pr > F
3	1	Diameter		1	0.7926	0.7926	1.2002	26.75	0.0013
4	1	Height		1	0.6517	0.6517	1.039	13.1	0.0085
5	1	Diameter		1	0.6836	0.6836	2.7054	15.12	0.006
6	1	Diameter		1	0.807	0.807	1.5964	29.27	0.001
7	1	Diameter		1	0.7004	0.7004	4.038	16.36	0.0049
8	1	Diameter		1	0.6576	0.6576	3.6764	13.45	0.008
11	1	Diameter		1	0.7208	0.7208	10.2243	18.07	0.0038
	2	Height		2	0.1692	0.89	3	9.22	0.0229
12	1	Diameter		1	0.5367	0.5367	3.9414	8.11	0.0248
13	1	Diameter		1	0.541	0.541	1.5607	8.25	0.0239
14	1	Diameter		1	0.6782	0.6782	6.2945	14.75	0.0064
15	1	Diameter		1	0.8594	0.8594	2.4841	42.77	0.0003
17	1	Diameter		1	0.7267	0.7267	1.1173	18.62	0.0035
18	1	Diameter		1	0.8422	0.8422	9.9409	37.36	0.0005
	2	Height		2	0.0944	0.9366	3	8.94	0.0243
21	1	Diameter		1	0.6366	0.6366	1.1877	12.26	0.01
22	1	Diameter		1	0.782	0.782	1.6765	25.11	0.0015
23	1	Diameter		1	0.8698	0.8698	1.7133	46.77	0.0002
24	1	Diameter		1	0.8692	0.8692	2.8505	46.5	0.0002
25	1	Diameter		1	0.8987	0.8987	9.3295	62.13	0.0001
	2	Height		2	0.0589	0.9576	3	8.33	0.0278
26	1	Diameter		1	0.8414	0.8414	2.486	37.15	0.0005
27	1	Diameter		1	0.7416	0.7416	12.2491	20.09	0.0029
	2	Height		2	0.1685	0.9101	3	11.25	0.0153

Table C. 1.1 Individual Tree regression for both crown and stemwood ash analysis for variable selection.

Ash Summary of Stepwise Selection									
Tree ID #	Step	Variable Entered	Variable Removed	Number Vars In	Partial R-Square	Model R-Square	C(p)	F Value	Pr > F
4	1	Diameter		1	0.6489	0.6489	8.6772	79.47	<.0001
4	2	Height		2	0.06	0.7089	2.1841	8.66	0.0053
5	1	Diameter		1	0.627	0.627	2.8788	72.28	<.0001
6	1	Diameter		1	0.5762	0.5762	5.8439	58.47	<.0001
6	2	Height		2	0.0432	0.6195	3.0645	4.77	0.0346
7	1	Diameter		1	0.6517	0.6517	3.0734	80.45	<.0001

Table C.1.2 DBH class regression of ash percentage for both crown and stemwood discs with variable selection.

Summary of Stepwise Selection for HHV									
Tree ID	Step	Variable Entered	Variable Removed	Number Vars In	Partial R-Square	Model R-Square	C(p)	F Value	Pr > F
3	1	Diameter		1	0.6564	0.6564	1.0272	13.37	0.0081
4	1	Height		1	0.7374	0.7374	1.0267	19.66	0.003
5	1	Diameter		1	0.6955	0.6955	2.3943	15.99	0.0052
6	1	Diameter		1	0.7544	0.7544	1.0081	21.5	0.0024
7	1	Diameter		1	0.602	0.602	3.4678	10.59	0.014
8	1	Diameter		1	0.6885	0.6885	1.0008	15.47	0.0057
11	1	Diameter		1	0.5838	0.5838	1.3511	9.82	0.0165
12	1	Diameter		1	0.6287	0.6287	4.0624	11.85	0.0108
13	1	Diameter		1	0.5034	0.5034	1.0225	7.1	0.0323
14	1	Diameter		1	0.7128	0.7128	1.3329	17.37	0.0042
15	1	Diameter		1	0.7239	0.7239	1.4323	18.35	0.0036
17	1	Diameter		1	0.7949	0.7949	1.0048	27.13	0.0012
18	1	Height		1	0.6801	0.6801	4.1223	14.88	0.0062
21	1	Diameter		1	0.5763	0.5763	1.0002	9.52	0.0177
22	1	Diameter		1	0.5299	0.5299	1.0009	7.89	0.0262
23	1	Diameter		1	0.4644	0.4644	1.0813	6.07	0.0432
24	1	Diameter		1	0.4805	0.4805	1.8013	6.47	0.0384
25	1	Diameter		1	0.7892	0.7892	1.1078	26.21	0.0014
26	0								
27	1	Diameter		1	0.7994	0.7994	1.3662	27.89	0.0011

Table C.2.1 Individual Tree regression for both crown and stemwood HHV analysis for variable selection.

Summary of Stepwise Selection for HHV									
DBH ID	Step	Variable Entered	Variable Removed	Number Vars In	Partial R-Square	Model R-Square	C(p)	F Value	Pr > F
4	**1**	Diameter		1	0.4898	0.4898	1.4382	41.29	<.0001
5	**1**	Diameter		1	0.6212	0.6212	0.0281	70.53	<.0001
6	**1**	Diameter		1	0.5784	0.5784	1.8557	59	<.0001
7	**1**	Diameter		1	0.6418	0.6418	0.1328	77.06	<.0001

Table C.2.2 DBH class regression of HHV percentage for both crown and stemwood discs with variable selection.

Appendix D. SAS code for ANOVA Tables

```
/*Author Thomas Loxley
Thesis project*/
/*run crown ash energy model and stem ash energy model program first*/
/*creating the whole tree data set with new id*/
/* calls in the stem information */
proc import datafile = "C:\Users\tal0024\Desktop\stemashenergy.csv"
out = stemashenergy dbms = csv replace;
getnames = yes;
run;
/* sort by DBH class */
proc sort data  = stemashenergy;
by DBH;
run;
/* calculate natural log (ln) of height and diameter,
set treatment when height equals zero,
make D^2*H variable from volume functions
make a D*H variable from partial volume*/
data stemashenergy;
set stemashenergy;
D2H = DBH*DBH*TTH;
logheight = log(height);
if height = 0 then logheight = 0; /*gives the same value of zero for bottom
stem height of D1 */
logDBT = log(DBT+1); /*log in SAS is ln and values less than 1 are negative ,
adding one keeps it continuous*/
DandH = height*DBT;
run;
/* calls in the crown information */
proc import datafile = "C:\Users\tal0024\Desktop\crownashenergy.csv"
out = crownashenergy dbms = csv replace;
getnames = yes;
run;
/* sort by DBH class */
proc sort data  = crownashenergy;
by DBH;
run;
/* calculate natural log (ln) of height and diameter */
data crownashenergy;
set crownashenergy;
DandH = height*DBT;
D2H = DBH*DBH*TTH;
percenttreeht = height/TTH;
logheight = log(height);
logDBT = (log(DBT+1)); /*log in SAS is ln and values less than 1 are negative
, adding one keeps it continuous*/
if DBT = 0 then logDBT=0; /*gives the same value of zero for C4 crown
diameters set to zero */
DandH = height*DBT;
run;
/* puts together whole tree data*/
data wholetree;
set crownashenergy stemashenergy;
```

```
keep X tree section label ID DBH height TTH DBT ash HHV D2H logheight logDBT
percenttreeht DandH ;
run;
proc sort data = wholetree; /* sorts it by the tree */
by tree percenttreeht;
run;
ods rtf file = 'rawdatawholetree.rtf';
proc print data = wholetree;
run;
ods rtf close;
/*ANOVA between crown and disc ash and HHV comparisons.  No extra levels */
ods rtf file = 'wholetreeanovastats.rtf';
proc sort data = wholetree; by X; run;
proc means data = wholetree; class X; var ash; run;
proc means data = wholetree; class X; var HHV; run;
proc anova data = wholetree;class X;model ash = X; means X / tukey;run;
proc anova data  = wholetree;class X;model HHV = X; means X / tukey;run;
/*ANOVA between C1-C4 and D1-D5 crown disc ash and HHV comparisons.  No extra
levels */
proc sort data = wholetree; by label; run;
proc means data = wholetree; class label; var ash; run;
proc means data = wholetree; class label; var HHV; run;
proc anova data = wholetree;class label;model ash = label; means label /
tukey;run;
proc anova data  = wholetree;class label;model HHV = label; means label /
tukey;run;
/*ANOVA between DBH specific ID "DBH_CorD#" C1-C4 and D1-D5 crown disc ash
and HHV comparisons (nested two level) */
proc sort data = wholetree; by ID; run;
proc means data = wholetree; class ID; var ash; run;
proc means data = wholetree; class ID; var HHV; run;
proc anova data = wholetree;class ID;model ash = ID; means ID / tukey;run;
proc anova data  = wholetree;class ID;model HHV = ID; means ID / tukey;run;
/* ANOVA between DBH classes for specific DBH block comparisons in crown and
stem */
proc sort data = wholetree; by DBH; run;
proc means data = wholetree; class DBH; var ash; run;
proc means data = wholetree; class DBH; var HHV; run;
proc anova data = wholetree;class DBH;model ash = DBH; means DBH / tukey;run;
proc anova data = wholetree;class DBH;model HHV = DBH; means DBH / tukey;run;
ods rtf close;

/* Regression model for the whole population of samples in predicting ash and
HHV (0.05 to enter and stay)*/
ods rtf file = 'wholetreeregvariableselectionpopulationregression.rtf';
proc reg data = wholetree;
model Ash =  DBH height TTH DBT DandH D2H percenttreeht logheight logDBT
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data = wholetree;
model HHV =  DBH height TTH DBT Ash DandH D2H percenttreeht logheight logDBT
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
ods rtf close;
```

```
/*Author Thomas Loxley
Thesis project*/
/* import crown data harvest and lab*/
proc import datafile = "C:\Users\tal0024\Desktop\crownashenergy.csv"
out = crownashenergy dbms = csv replace;
getnames = yes;
run;
/* sort by DBH class */
proc sort data  = crownashenergy;
by DBH;
run;
/* calculate natural log (ln) of height and diameter */
data crownashenergy;
set crownashenergy;
DandH = height*DBT;
D2H = DBH*DBH*TTH;
percenttreeht = height/TTH;
logheight = log(height);
logDBT = (log(DBT+1)); /*log in SAS is ln and values less than 1 are negative
, adding one keeps it continuous*/
if DBT = 0 then logDBT=0; /*gives the same value of zero for C4 crown
diameters set to zero */
DandH = height*DBT;
run;
/* print the data set */
ods rtf file = 'rawdatacrown.rtf';
proc print data  = crownashenergy;
run;
ods rtf close;
/* determine summary statistics given different levels of variables */
/* summary stats and anova by ID (DBH and section of tree */
ods rtf file='crownashenergyanovastats.rtf';
proc sort data = crownashenergy; by ID; run;
proc means data = crownashenergy;class id;var ash;run;
proc means data = crownashenergy;class id;var HHV; run;
proc anova data = crownashenergy;class ID;model ash=ID ;means ID / tukey
;run;
proc anova data = crownashenergy;class ID;model HHV=ID  ;means ID / tukey
;run;
/* summary stats and anova by label (section of tree) across all DBH classes
*/
proc sort data = crownashenergy; by label; run;
proc means data = crownashenergy;class label;var ash;run;
proc means data = crownashenergy;class label;var HHV; run;
proc anova data = crownashenergy;class label;model ash=label ;means label /
tukey  ;run;
proc anova data = crownashenergy;class label;model HHV=label ;means label /
tukey  ;run;
/* Summary stats and anova by DBH classes */
proc sort data =  crownashenergy;by DBH;run;
proc means data = crownashenergy ;class DBH;var ash ;run;
proc means data = crownashenergy ;class DBH;var HHV ;run;
proc anova data = crownashenergy;class DBH ;model ash=DBH  ;means DBH / tukey
;run;
proc anova data = crownashenergy;class DBH ;model HHV=DBH  ;means DBH / tukey
;run;
ods rtf close;
```

```
ods rtf file = 'Prox and HHV anova on crown with interactionID check
redo.rtf';
proc sort data = crownashenergy;
by DBH; run;
proc anova data = crownashenergy;
class DBH section; model Ashdb = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = crownashenergy;
class DBH section; model VMdb = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = crownashenergy;
class DBH section; model FCdb = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = crownashenergy;
class DBH section; model HHV = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
ods rtf close;
/* end main summary stats and anovas */
/* List of stem variables:
section DBH height TTH DBT SectionLength CR SectionMass TotalCrownMass
CrownDBT ash DandH D2H percenttreeht logheight logDBT*/
/*Crown Ash simple regression analysis*/
ods rtf file ='crownregressionvariableselection.rtf';
proc reg data  = crownashenergy;
model ash = section DBH height TTH DBT SectionLength CR SectionMass
TotalCrownMass CrownDBT HHV DandH D2H percenttreeht logheight logDBT
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = crownashenergy;
model HHV  = section DBH height TTH DBT SectionLength CR SectionMass
TotalCrownMass CrownDBT ash DandH D2H percenttreeht logheight logDBT
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
ods rtf close;

/*Author Thomas Loxley
Thesis project*/

/* import stem data harvest and lab*/
proc import datafile = "C:\Users\tal0024\Desktop\stemashenergy.csv"
out = stemashenergy dbms = csv replace;
getnames = yes;
run;
/* sort by DBH class */
proc sort data  = stemashenergy;
by DBH;
run;
/* calculate natural log (ln) of height and diameter,
set treatment when height equals zero,
make D^2*H variable from volume functions
make a D*H variable from partial volume*/
data stemashenergy;
set stemashenergy;
D2H = DBH*DBH*TTH;
logheight = log(height);
if height = 0 then logheight = 0; /*gives the same value of zero for bottom
stem height of D1 */
```

```
logDBT = log(DBT+1); /*log in SAS is ln and values less than 1 are negative ,
adding one keeps it continuous*/
DandH = height*DBT;
run;
ods rtf file = 'rawdatastem.rtf';
proc print data  = stemashenergy;
run;
ods rtf close;
/* determine summary statistics given different levels of variables */
/* summary stats and anova by ID (DBH and section of tree */
ods rtf file='stemashenergyanovastats.rtf';
proc sort data = stemashenergy;by ID;run;
proc means data = stemashenergy ;class id;var ash ;run;
proc means data = stemashenergy ;class id;var HHV ;run;
proc anova data = stemashenergy;class ID  ;model ash=ID   ;means ID / tukey
;run;
proc anova data = stemashenergy;class ID  ;model HHV=ID   ;means ID / tukey
;run;
/* summary stats and anova by label (section of tree) across all DBH classes
*/
proc sort data = stemashenergy;by label;run;
proc means data = stemashenergy ;class label;var ash ;run;
proc means data = stemashenergy ;class label;var HHV ;run;
proc anova data = stemashenergy;class label  ;model ash=label   ;means label
/ tukey ;run;
proc anova data = stemashenergy;class label  ;model HHV=label   ;means label
/ tukey ;run;
/* Summary stats and anova by DBH classes */

ods rtf file = 'anova of stem for ash and HHV.rtf';
proc anova data = stemashenergy;
class DBH section ;model ash=DBH section DBH*section   ;means DBH section
DBH*section/ tukey ;run;
proc anova data = stemashenergy;
class DBH section  ;model HHV=DBH section DBH*section  ;means DBH section
DBH*section / tukey ;run;
ods rtf close;
/*List of stem variables:
X tree section label ID DBH height
TTH DBT percenttreeht Density rings
percbark Moisture ash HHV D2H logheight logDBT DandH */
/* simple regression and variable selection */
ods rtf file = 'stemregressionvariableselection.rtf';
proc reg data  = stemashenergy;
model ash = section DBH height  TTH DBT percenttreeht Density rings percbark
Moisture HHV D2H logheight logDBT DandH
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = stemashenergy;
model HHV = section DBH height TTH DBT percenttreeht Density rings percbark
Moisture ash D2H logheight logDBT DandH
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
ods rtf close;
```

Appendix E. SAS Code for CHNS Analysis Results

```
/* Regression and anova analysis for CHNS crown data for al 27 trees */
/* Author: Thomas Loxley */

proc import datafile = "C:\Users\tal0024\Desktop\CHNS crown.csv"
out = CHNS dbms = csv replace;
getnames = yes;
run;
proc sort data = CHNS;
by DBH; run;
proc print data = CHNS;
run;

ods rtf file = 'CHNS anova on crown with interactionID check.rtf';
proc sort data = CHNS;
by DBH; run;
proc anova data = CHNS;
class DBH section; model N = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = CHNS;
class DBH section; model C = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = CHNS;
class DBH section; model H = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = CHNS;
class DBH section; model S = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = CHNS;
class DBH section; model O = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;

ods rtf close;

ods rtf file = 'CHNS regression on crown phys stepwise 0.05.rtf';
proc reg data  = CHNS;
model C = Height TTH DBT
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = CHNS;
model N = Height TTH DBT
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = CHNS;
model H = Height TTH DBT
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = CHNS;
model S = Height TTH DBT
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = CHNS;
model O = Height TTH DBT
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
```

```
ods rtf close;

proc import datafile = "C:\Users\tal0024\Desktop\SIcrownprox.csv"
out = crownprox dbms = csv replace;
getnames = yes;
run;
/* sort both data sets before merging */
proc sort data = crownprox;
by DBH Tree;
run;
proc print data = crownprox;
run;
proc sort  data = CHNS;
by DBH Tree;
run;
proc print data = CHNS; run;
/* create merged data set with prox and ultimate analysis data*/
data crownALL;
      MERGE crownprox CHNS;
      run;
      proc print data = crownALL; run;

ods rtf file = 'CHNS regression on crown with prox stepwise 0.05.rtf';
proc reg data  = crownALL;
model Ashdb = DBH Height TTH DBT SectionLength Crown_Ratio SectionMass VMdb
FCdb HHV N C H S O
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = crownALL;
model VMdb = DBH Height TTH DBT SectionLength Crown_Ratio SectionMass Ashdb
FCdb HHV N C H S O
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = crownALL;
model FCdb = DBH Height TTH DBT SectionLength Crown_Ratio SectionMass VMdb
Ashdb HHV N C H S O
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = crownALL;
model HHV = DBH Height TTH DBT SectionLength Crown_Ratio SectionMass Ashdb
VMdb FCdb N C H O
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = crownALL;
model N = DBH Height TTH DBT SectionLength Crown_Ratio SectionMass VMdb FCdb
HHV C H O Ashdb
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = crownALL;
model C = DBH Height TTH DBT SectionLength Crown_Ratio SectionMass VMdb FCdb
HHV N H O Ashdb
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = crownALL;
model H = DBH Height TTH DBT SectionLength Crown_Ratio SectionMass VMdb FCdb
HHV N C O Ashdb
```

```
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = crownALL;
model O = DBH Height TTH DBT SectionLength Crown_Ratio SectionMass VMdb FCdb
HHV N C H Ashdb
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = crownALL;
model S = DBH Height TTH DBT SectionLength Crown_Ratio SectionMass VMdb FCdb
N C O H Ashdb
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
ods rtf close;
```

```
/* Regression and anova analysis for CHNS stemwood data for 30 randomly
selected samples */
/* Author: Thomas Loxley */
proc import datafile = "C:\Users\tal0024\Desktop\CHNS stemwood.csv"
out = CHNSstem dbms = csv replace;
getnames = yes;
run;
data CHNSstem;
set CHNSstem;
D2H = DBH*DBH*TTH;
logheight = log(height);
if height = 0 then logheight = 0; /*gives the same value of zero for bottom
stem height of D1 */
logDBT = log(DBT+1); /*log in SAS is ln and values less than 1 are negative ,
adding one keeps it continuous*/
DandH = height*DBT;

run;
proc print data = CHNSstem;
run;

ods rtf file='CHNS stemwood summary stats.rtf';
proc means data = CHNSstem ;class DBH;var N ;run;
proc means data = CHNSstem ;class DBH;var C ;run;
proc means data = CHNSstem ;class DBH;var H ;run;
proc means data = CHNSstem ;class DBH;var O ;run;

proc means data = CHNSstem ;class Section;var N ;run;
proc means data = CHNSstem ;class Section;var C ;run;
proc means data = CHNSstem ;class Section;var H ;run;
proc means data = CHNSstem ;class Section;var O ;run;
ods rtf close;

ods rtf file = 'CHNS anova on stemwood with interactionID check.rtf';
proc sort data = CHNSstem;
by DBH; run;
proc anova data = CHNSstem;
class DBH section; model C = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = CHNSstem;
class DBH section; model H = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = CHNSstem;
class DBH section; model N = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
proc anova data = CHNSstem;
class DBH section; model O = DBH section DBH*section ; means DBH section
DBH*section/ tukey;  run;
ods rtf close;

ods rtf file = 'Regression on Stemwood for chns and ash and HHV.rtf';
proc reg data  = CHNSstem;
model HHV  = Section DBH Height TTH DBT Density Rings Bark Ashdb N C H D2H
logheight logDBT DandH
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
```

```
proc reg data  = CHNSstem;
model Ashdb  = Section DBH Height TTH DBT Density Rings Bark  HHV N C H D2H
logheight logDBT DandH
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = CHNSstem;
model N  = Section DBH Height TTH DBT Density Rings Bark  Ashdb HHV C H O D2H
logheight logDBT DandH
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = CHNSstem;
model C  = Section DBH Height TTH DBT Density Rings Bark  Ashdb HHV N H  O
D2H logheight logDBT DandH
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
proc reg data  = CHNSstem;
model H  = Section DBH Height TTH DBT Density Rings Bark  Ashdb HHV N C O D2H
logheight logDBT DandH
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
model O  = Section DBH Height TTH DBT Density Rings Bark  Ashdb HHV N C H D2H
logheight logDBT DandH
/ selection = stepwise slstay  =0.05 slentry = 0.05;
run;
ods rtf close;


      /* Regression and anova analysis for CHNS crown data to compare HHV and
Boie and Dulong */
      /* Author: Thomas Loxley */

      proc import datafile = "C:\Users\tal0024\Desktop\crownboiedulong.csv"
      out = crownBD dbms = csv replace;
      getnames = yes;
      run;
      proc sort data = crownBD;
      by DBH; run;
      proc print data = crownBD;
      run;
      proc reg data  = crownBD;
      m1 : model HHV =  C ;
      m2 : model Boie =  C ;
      m3 : model Dulong =  C ;
      run;
      title1
      'Linear Regression of Crown HHV, Dulong, and Boie Results by Carbon
Percentage';
      title2 '(with 95% Confidence Limits)';
      symbol ci=red cv=blue co=gray value=dot
             interpol=rlclm95 ;
      proc sgplot data=crownBD;
      reg y= Boie x=C;
      reg y = Dulong x=C;
      reg y =HHV x=C / clm clmtransparency=0.4 lineattrs=(pattern=solid);
      run;
      proc import datafile = "C:\Users\tal0024\Desktop\stemboiedulong.csv"
```

```
       out = stemBD dbms = csv replace;
       getnames = yes;
       run;
       proc sort data = stemBD;
       by DBH; run;
       proc print data = stemBD;
       run;
       proc reg data  = stemBD;
       m1 : model HHV =  C ;
       m2 : model Boie =  C ;
       m3 : model Dulong =  C ;
       run;
       title1
       'Linear Regression of Stem HHV, Dulong, and Boie Results by Carbon
Percentage';
       title2 '(with 95% Confidence Limits)';
       symbol ci=red cv=blue co=gray value=dot
              interpol=rlclm95 ;

       proc sgplot data=stemBD;
       reg y= Boie x=C;
       reg y = Dulong x=C;
       reg y =HHV x=C / clm clmtransparency=0.4 lineattrs=(pattern=solid);
       run;
```

Appendix F. Data sets

Whole tree data set used in 4.1 Allometric analysis

X	tree	section	label	ID	DBH	height	TTH	DBT	Ash	HHV	DandH	D2H	percent treeht	log height	log DBT
D	3	1	D1	7_D1	19.05	0.00	18.53	20.32	0.28	20.87	0.0	7651.8	0.00	0.0	3.1
D	3	2	D2	7_D2	19.05	1.37	18.53	18.80	0.24	20.875	25.8	6547.1	0.07	0.9	3.0
D	3	3	D3	7_D3	19.05	3.35	18.53	15.24	0.21	20.928	51.1	4304.2	0.18	1.5	2.8
D	3	4	D4	7_D4	19.05	6.71	18.53	13.46	0.26	21.012	90.3	3358.4	0.36	2.0	2.7
D	3	5	D5	7_D5	19.05	10.06	18.53	10.92	0.31	20.985	109.9	2210.7	0.54	2.4	2.5
C	3	1	C1	7_C1	19.05	12.18	18.53	8.19	0.45	21.609	99.7	1243.5	0.66	2.6	2.2
C	3	2	C2	7_C2	19.05	14.30	18.53	5.46	0.85	20.943	78.1	552.7	0.77	2.7	1.9
C	3	3	C3	7_C3	19.05	16.41	18.53	2.73	0.85	20.678	44.8	138.2	0.89	2.9	1.3
C	3	4	C4	7_C4	19.05	18.53	18.53	0.00	0.77	21.783	0.0	0.0	1.00	3.0	0.0
D	4	1	D1	4_D1	11.43	0.00	11.28	14.48	0.42	20.77	0.0	2363.9	0.00	0.0	2.7
D	4	2	D2	4_D2	11.43	1.37	11.28	11.94	0.34	20.881	16.4	1607.2	0.12	0.9	2.6
D	4	3	D3	4_D3	11.43	2.32	11.28	9.65	0.29	21.089	22.4	1050.6	0.21	1.2	2.4
D	4	4	D4	4_D4	11.43	4.63	11.28	9.14	0.35	21.737	42.4	943.0	0.41	1.7	2.3
D	4	5	D5	4_D5	11.43	7.01	11.28	7.62	0.43	21.028	53.4	654.8	0.62	2.1	2.2
C	4	1	C1	4_C1	11.43	8.08	11.28	5.72	1.21	21.89	46.2	368.3	0.72	2.2	1.9
C	4	2	C2	4_C2	11.43	9.14	11.28	3.81	0.78	21.658	34.8	163.7	0.81	2.3	1.6
C	4	3	C3	4_C3	11.43	10.21	11.28	1.91	0.92	21.692	19.5	40.9	0.91	2.4	1.1
C	4	4	C4	4_C4	11.43	11.28	11.28	0.00	1.14	21.701	0.0	0.0	1.00	2.5	0.0
D	5	1	D1	6_D1	16.51	0.00	14.30	20.32	0.43	20.563	0.0	5902.5	0.00	0.0	3.1
D	5	2	D2	6_D2	16.51	1.37	14.30	16.51	0.36	20.827	22.6	3896.6	0.10	0.9	2.9
D	5	3	D3	6_D3	16.51	3.63	14.30	14.73	0.39	21	53.4	3102.5	0.25	1.5	2.8
D	5	4	D4	6_D4	16.51	7.22	14.30	10.67	0.38	20.885	77.1	1626.9	0.51	2.1	2.5
D	5	5	D5	6_D5	16.51	10.97	14.30	7.11	0.39	21.046	78.0	723.1	0.77	2.5	2.1
C	5	1	C1	6_C1	16.51	11.80	14.30	5.33	1.18	20.699	63.0	406.7	0.83	2.5	1.8
C	5	2	C2	6_C2	16.51	12.63	14.30	3.56	1.1	21.712	44.9	180.8	0.88	2.6	1.5
C	5	3	C3	6_C3	16.51	13.46	14.30	1.78	1.27	21.445	23.9	45.2	0.94	2.7	1.0

X	tree	section	label	ID	DBH	height	TTH	DBT	Ash	HHV	DandH	D2H	percent treeht	log height	log DBT
C	5	4	C4	6_C4	16.51	14.30	14.30	0.00	1.82	21.151	0.0	0.0	1.00	2.7	0.0
D	6	1	D1	6_D1	16.51	0.00	15.45	19.05	0.35	20.574	0.0	5608.1	0.00	0.0	3.0
D	6	2	D2	6_D2	16.51	1.37	15.45	16.00	0.39	20.456	21.9	3957.0	0.09	0.9	2.8
D	6	3	D3	6_D3	16.51	2.93	15.45	13.46	0.32	20.781	39.4	2800.5	0.19	1.4	2.7
D	6	4	D4	6_D4	16.51	5.85	15.45	11.68	0.3	20.665	68.4	2109.6	0.38	1.9	2.5
D	6	5	D5	6_D5	16.51	8.90	15.45	10.41	0.35	20.67	92.7	1675.9	0.58	2.3	2.4
C	6	1	C1	6_C1	16.51	10.54	15.45	7.81	0.59	20.895	82.3	942.7	0.68	2.4	2.2
C	6	2	C2	6_C2	16.51	12.18	15.45	5.21	0.75	21.53	63.4	419.0	0.79	2.6	1.8
C	6	3	C3	6_C3	16.51	13.82	15.45	2.60	0.97	21.654	36.0	104.7	0.89	2.7	1.3
C	6	4	C4	6_C4	16.51	15.45	15.45	0.00	1.02	21.24	0.0	0.0	1.00	2.8	0.0
D	7	1	D1	6_D1	16.51	0.00	16.86	19.05	0.37	20.654	0.0	6116.9	0.00	0.0	3.0
D	7	2	D2	6_D2	16.51	1.37	16.86	16.76	0.35	20.539	23.0	4736.9	0.08	0.9	2.9
D	7	3	D3	6_D3	16.51	4.60	16.86	13.46	0.26	20.459	62.0	3054.6	0.27	1.7	2.7
D	7	4	D4	6_D4	16.51	9.20	16.86	10.16	0.31	20.722	93.5	1739.9	0.55	2.3	2.4
D	7	5	D5	6_D5	16.51	13.96	16.86	5.84	0.39	20.675	81.6	575.3	0.83	2.7	1.9
C	7	1	C1	6_C1	16.51	14.68	16.86	4.38	1.11	21.169	64.3	323.6	0.87	2.8	1.7
C	7	2	C2	6_C2	16.51	15.41	16.86	2.92	1.13	20.865	45.0	143.8	0.91	2.8	1.4
C	7	3	C3	6_C3	16.51	16.13	16.86	1.46	1.41	21.037	23.6	36.0	0.96	2.8	0.9
C	7	4	C4	6_C4	16.51	16.86	16.86	0.00	1.24	21.528	0.0	0.0	1.00	2.9	0.0
D	8	1	D1	7_D1	19.05	0.00	17.68	20.57	0.38	20.733	0.0	7483.1	0.00	0.0	3.1
D	8	2	D2	7_D2	19.05	1.37	17.68	18.80	0.35	20.621	25.8	6245.6	0.08	0.9	3.0
D	8	3	D3	7_D3	19.05	3.29	17.68	16.26	0.32	20.538	53.5	4671.7	0.19	1.5	2.8
D	8	4	D4	7_D4	19.05	6.58	17.68	12.70	0.35	20.623	83.6	2851.3	0.37	2.0	2.6
D	8	5	D5	7_D5	19.05	10.00	17.68	10.67	0.36	20.69	106.7	2011.9	0.57	2.4	2.5
C	8	1	C1	7_C1	19.05	11.92	17.68	8.00	0.43	21.096	95.4	1131.7	0.67	2.6	2.2
C	8	2	C2	7_C2	19.05	13.84	17.68	5.33	0.75	21.557	73.8	503.0	0.78	2.7	1.8
C	8	3	C3	7_C3	19.05	15.76	17.68	2.67	0.91	21.3	42.0	125.7	0.89	2.8	1.3
C	8	4	C4	7_C4	19.05	17.68	17.68	0.00	1.57	21.37	0.0	0.0	1.00	2.9	0.0
D	11	1	D1	6_D1	16.51	0.00	16.31	19.30	0.41	20.767	0.0	6076.6	0.00	0.0	3.0
D	11	2	D2	6_D2	16.51	1.37	16.31	16.76	0.37	20.988	23.0	4582.7	0.08	0.9	2.9

X	tree	section	label	ID	DBH	height	TTH	DBT	Ash	HHV	DandH	D2H	percent treeht	log height	log DBT
D	11	3	D3	6_D3	16.51	3.78	16.31	14.48	0.33	20.361	54.7	3418.1	0.23	1.6	2.7
D	11	4	D4	6_D4	16.51	7.56	16.31	11.94	0.36	20.391	90.2	2324.0	0.46	2.1	2.6
D	11	5	D5	6_D5	16.51	11.43	16.31	10.16	0.37	20.559	116.1	1683.3	0.70	2.5	2.4
C	11	1	C1	6_C1	16.51	12.65	16.31	7.62	0.8	21.063	96.4	946.8	0.78	2.6	2.2
C	11	2	C2	6_C2	16.51	13.87	16.31	5.08	1.24	21.59	70.5	420.8	0.85	2.7	1.8
C	11	3	C3	6_C3	16.51	15.09	16.31	2.54	2.23	21.09	38.3	105.2	0.93	2.8	1.3
C	11	4	C4	6_C4	16.51	16.31	16.31	0.00	3.37	21.208	0.0	0.0	1.00	2.9	0.0
D	12	1	D1	4_D1	11.43	0.00	14.02	13.97	0.72	20.903	0.0	2736.3	0.00	0.0	2.7
D	12	2	D2	4_D2	11.43	1.37	14.02	11.94	0.55	20.827	16.4	1998.2	0.10	0.9	2.6
D	12	3	D3	4_D3	11.43	3.72	14.02	9.91	0.4	20.601	36.8	1375.8	0.27	1.6	2.4
D	12	4	D4	4_D4	11.43	8.96	14.02	8.13	0.41	20.72	72.8	926.3	0.64	2.3	2.2
D	12	5	D5	4_D5	11.43	11.28	14.02	5.08	0.34	20.845	57.3	361.8	0.80	2.5	1.8
C	12	1	C1	4_C1	11.43	11.96	14.02	3.81	1.48	20.926	45.6	203.5	0.85	2.6	1.6
C	12	2	C2	4_C2	11.43	12.65	14.02	2.54	0.99	21.251	32.1	90.5	0.90	2.6	1.3
C	12	3	C3	4_C3	11.43	13.34	14.02	1.27	1.69	21.083	16.9	22.6	0.95	2.7	0.8
C	12	4	C4	4_C4	11.43	14.02	14.02	0.00	1.73	21.207	0.0	0.0	1.00	2.7	0.0
D	13	1	D1	5_D1	13.97	0.00	15.79	16.76	0.34	21.448	0.0	4437.1	0.00	0.0	2.9
D	13	2	D2	5_D2	13.97	1.37	15.79	15.24	0.3	20.95	20.9	3667.0	0.09	0.9	2.8
D	13	3	D3	5_D3	13.97	3.66	15.79	11.43	0.28	20.714	41.8	2062.7	0.23	1.5	2.5
D	13	4	D4	5_D4	13.97	7.32	15.79	8.89	0.29	20.756	65.0	1247.8	0.46	2.1	2.3
D	13	5	D5	5_D5	13.97	10.97	15.79	6.35	0.27	20.901	69.7	636.6	0.70	2.5	2.0
C	13	1	C1	5_C1	13.97	12.18	15.79	4.76	0.99	20.791	58.0	358.1	0.77	2.6	1.8
C	13	2	C2	5_C2	13.97	13.38	15.79	3.18	1	21.304	42.5	159.2	0.85	2.7	1.4
C	13	3	C3	5_C3	13.97	14.58	15.79	1.59	1.42	21.631	23.2	39.8	0.92	2.7	1.0
C	13	4	C4	5_C4	13.97	15.79	15.79	0.00	3.09	21.671	0.0	0.0	1.00	2.8	0.0
D	14	1	D1	5_D1	13.97	0.00	17.07	16.76	0.27	20.933	0.0	4796.9	0.00	0.0	2.9
D	14	2	D2	5_D2	13.97	1.37	17.07	13.97	0.26	20.889	19.2	3331.2	0.08	0.9	2.7
D	14	3	D3	5_D3	13.97	3.81	17.07	11.68	0.38	20.761	44.5	2330.2	0.22	1.6	2.5
D	14	4	D4	5_D4	13.97	7.65	17.07	10.16	0.33	20.835	77.7	1761.9	0.45	2.2	2.4
D	14	5	D5	5_D5	13.97	11.58	17.07	8.89	0.35	21.097	103.0	1349.0	0.68	2.5	2.3

X	tree	section	label	ID	DBH	height	TTH	DBT	Ash	HHV	DandH	D2H	percent treeht	log height	log DBT
C	14	1	C1	5_C1	13.97	12.95	17.07	6.67	0.28	20.794	86.4	758.8	0.76	2.6	2.0
C	14	2	C2	5_C2	13.97	14.33	17.07	4.45	0.76	20.637	63.7	337.2	0.84	2.7	1.7
C	14	3	C3	5_C3	13.97	15.70	17.07	2.22	1.58	21.234	34.9	84.3	0.92	2.8	1.2
C	14	4	C4	5_C4	13.97	17.07	17.07	0.00	2.25	21.442	0.0	0.0	1.00	2.9	0.0
D	15	1	D1	4_D1	11.43	0.00	14.23	13.46	0.29	20.624	0.0	2579.6	0.00	0.0	2.7
D	15	2	D2	4_D2	11.43	1.37	14.23	11.43	0.29	20.976	15.7	1859.6	0.10	0.9	2.5
D	15	3	D3	4_D3	11.43	3.17	14.23	9.65	0.24	20.611	30.6	1326.1	0.22	1.4	2.4
D	15	4	D4	4_D4	11.43	6.34	14.23	8.89	0.29	20.692	56.4	1125.0	0.45	2.0	2.3
D	15	5	D5	4_D5	11.43	9.60	14.23	7.11	0.34	20.652	68.3	720.0	0.67	2.4	2.1
C	15	1	C1	4_C1	11.43	10.76	14.23	5.33	0.87	20.885	57.4	405.0	0.76	2.5	1.8
C	15	2	C2	4_C2	11.43	11.92	14.23	3.56	1	21.386	42.4	180.0	0.84	2.6	1.5
C	15	3	C3	4_C3	11.43	13.08	14.23	1.78	1.15	20.931	23.2	45.0	0.92	2.6	1.0
C	15	4	C4	4_C4	11.43	14.23	14.23	0.00	1.5	21.513	0.0	0.0	1.00	2.7	0.0
D	17	1	D1	5_D1	13.97	0.00	12.19	16.00	0.45	20.841	0.0	3121.9	0.00	0.0	2.8
D	17	2	D2	5_D2	13.97	1.37	12.19	13.46	0.31	20.748	18.5	2209.5	0.11	0.9	2.7
D	17	3	D3	5_D3	13.97	1.95	12.19	11.43	0.37	20.772	22.3	1592.8	0.16	1.1	2.5
D	17	4	D4	5_D4	13.97	3.93	12.19	10.41	0.23	20.657	40.9	1322.2	0.32	1.6	2.4
D	17	5	D5	5_D5	13.97	5.94	12.19	9.91	0.43	20.779	58.9	1196.4	0.49	1.9	2.4
C	17	1	C1	5_C1	13.97	7.51	12.19	7.43	0.72	20.573	55.8	673.0	0.62	2.1	2.1
C	17	2	C2	5_C2	13.97	9.07	12.19	4.95	0.65	21	44.9	299.1	0.74	2.3	1.8
C	17	3	C3	5_C3	13.97	10.63	12.19	2.48	1.21	21.206	26.3	74.8	0.87	2.5	1.2
C	17	4	C4	5_C4	13.97	12.19	12.19	0.00	1.88	21.585	0.0	0.0	1.00	2.6	0.0
D	18	1	D1	6_D1	16.51	0.00	12.80	18.29	0.3	20.543	0.0	4281.5	0.00	0.0	3.0
D	18	2	D2	6_D2	16.51	1.37	12.80	15.75	0.3	20.471	21.6	3174.8	0.11	0.9	2.8
D	18	3	D3	6_D3	16.51	2.90	12.80	14.22	0.35	20.232	41.2	2590.0	0.23	1.4	2.7
D	18	4	D4	6_D4	16.51	5.18	12.80	12.95	0.3	20.308	67.1	2148.2	0.40	1.8	2.6
D	18	5	D5	6_D5	16.51	8.78	12.80	10.92	0.3	23.279	95.9	1527.1	0.69	2.3	2.5
C	18	1	C1	6_C1	16.51	9.78	12.80	8.19	0.88	22.01	80.1	859.0	0.76	2.4	2.2
C	18	2	C2	6_C2	16.51	10.79	12.80	5.46	1	21.027	58.9	381.8	0.84	2.5	1.9
C	18	3	C3	6_C3	16.51	11.80	12.80	2.73	1.56	21.113	32.2	95.4	0.92	2.5	1.3

X	tree	section	label	ID	DBH	height	TTH	DBT	Ash	HHV	DandH	D2H	percent treeht	log height	log DBT
C	18	4	C4	6_C4	16.51	12.80	12.80	0.00	2.28	21.395	0.0	0.0	1.00	2.6	0.0
D	21	1	D1	7_D1	19.05	0.00	17.31	21.84	0.34	20.674	0.0	8260.9	0.00	0.0	3.1
D	21	2	D2	7_D2	19.05	1.37	17.31	19.56	0.24	20.711	26.8	6622.4	0.08	0.9	3.0
D	21	3	D3	7_D3	19.05	4.11	17.31	14.48	0.21	20.536	59.6	3628.9	0.24	1.6	2.7
D	21	4	D4	7_D4	19.05	8.20	17.31	11.43	0.24	20.69	93.7	2261.8	0.47	2.2	2.5
D	21	5	D5	7_D5	19.05	12.44	17.31	7.37	0.28	20.639	91.6	939.3	0.72	2.6	2.1
C	21	1	C1	7_C1	19.05	13.66	17.31	5.52	0.8	20.903	75.4	528.4	0.79	2.7	1.9
C	21	2	C2	7_C2	19.05	14.87	17.31	3.68	1.14	21.194	54.8	234.8	0.86	2.8	1.5
C	21	3	C3	7_C3	19.05	16.09	17.31	1.84	1.67	21.072	29.6	58.7	0.93	2.8	1.0
C	21	4	C4	7_C4	19.05	17.31	17.31	0.00	1.21	21.247	0.0	0.0	1.00	2.9	0.0
D	22	1	D1	7_D1	19.05	0.00	18.29	19.56	0.38	20.798	0.0	6995.4	0.00	0.0	3.0
D	22	2	D2	7_D2	19.05	1.37	18.29	17.53	0.37	21.19	24.0	5617.4	0.08	0.9	2.9
D	22	3	D3	7_D3	19.05	3.29	18.29	14.48	0.38	20.848	47.7	3833.4	0.18	1.5	2.7
D	22	4	D4	7_D4	19.05	6.58	18.29	12.19	0.32	20.631	80.3	2718.4	0.36	2.0	2.6
D	22	5	D5	7_D5	19.05	10.00	18.29	10.16	0.35	20.924	101.6	1887.8	0.55	2.4	2.4
C	22	1	C1	7_C1	19.05	12.07	18.29	7.62	0.65	20.193	92.0	1061.9	0.66	2.6	2.2
C	22	2	C2	7_C2	19.05	14.14	18.29	5.08	0.68	21.614	71.8	471.9	0.77	2.7	1.8
C	22	3	C3	7_C3	19.05	16.22	18.29	2.54	0.88	20.778	41.2	118.0	0.89	2.8	1.3
C	22	4	C4	7_C4	19.05	18.29	18.29	0.00	1.07	21.071	0.0	0.0	1.00	3.0	0.0
D	23	1	D1	5_D1	13.97	0.00	13.41	16.00	0.26	20.989	0.0	3434.1	0.00	0.0	2.8
D	23	2	D2	5_D2	13.97	1.37	13.41	13.72	0.26	20.727	18.8	2523.0	0.10	0.9	2.7
D	23	3	D3	5_D3	13.97	3.11	13.41	10.92	0.24	20.431	34.0	1599.8	0.23	1.4	2.5
D	23	4	D4	5_D4	13.97	6.25	13.41	10.16	0.46	21.226	63.5	1384.4	0.47	2.0	2.4
D	23	5	D5	5_D5	13.97	9.45	13.41	8.38	0.41	20.558	79.2	942.2	0.70	2.3	2.2
C	23	1	C1	5_C1	13.97	10.44	13.41	6.29	0.85	21.98	65.6	530.0	0.78	2.4	2.0
C	23	2	C2	5_C2	13.97	11.43	13.41	4.19	0.84	20.957	47.9	235.6	0.85	2.5	1.6
C	23	3	C3	5_C3	13.97	12.42	13.41	2.10	1.16	21.877	26.0	58.9	0.93	2.6	1.1
C	23	4	C4	5_C4	13.97	13.41	13.41	0.00	1.55	20.954	0.0	0.0	1.00	2.7	0.0
D	24	1	D1	4_D1	11.43	0.00	10.67	15.24	0.28	21.614	0.0	2477.7	0.00	0.0	2.8
D	24	2	D2	4_D2	11.43	1.37	10.67	12.70	0.34	21.002	17.4	1720.6	0.13	0.9	2.6

X	tree	section	label	ID	DBH	height	TTH	DBT	Ash	HHV	DandH	D2H	percent treeht	log height	log DBT
D	24	3	D3	4_D3	11.43	2.19	10.67	11.68	0.28	20.927	25.6	1456.4	0.21	1.2	2.5
D	24	4	D4	4_D4	11.43	4.41	10.67	9.65	0.37	20.718	42.6	993.8	0.41	1.7	2.4
D	24	5	D5	4_D5	11.43	6.64	10.67	8.13	0.38	20.72	54.0	704.8	0.62	2.0	2.2
C	24	1	C1	4_C1	11.43	7.65	10.67	6.10	1.01	21.075	46.6	396.4	0.72	2.2	2.0
C	24	2	C2	4_C2	11.43	8.66	10.67	4.06	1.49	21.015	35.2	176.2	0.81	2.3	1.6
C	24	3	C3	4_C3	11.43	9.66	10.67	2.03	1.47	21.424	19.6	44.0	0.91	2.4	1.1
C	24	4	C4	4_C4	11.43	10.67	10.67	0.00	1.94	21.326	0.0	0.0	1.00	2.5	0.0
D	25	1	D1	5_D1	13.97	0.00	15.39	14.99	0.35	20.24	0.0	3456.8	0.00	0.0	2.8
D	25	2	D2	5_D2	13.97	1.37	15.39	13.21	0.32	20.388	18.1	2685.2	0.09	0.9	2.7
D	25	3	D3	5_D3	13.97	2.53	15.39	12.19	0.36	20.29	30.8	2288.0	0.16	1.3	2.6
D	25	4	D4	5_D4	13.97	5.03	15.39	10.67	0.33	20.722	53.7	1751.8	0.33	1.8	2.5
D	25	5	D5	5_D5	13.97	7.62	15.39	9.40	0.34	20.571	71.6	1359.5	0.50	2.2	2.3
C	25	1	C1	5_C1	13.97	9.56	15.39	7.05	0.63	21.351	67.4	764.7	0.62	2.4	2.1
C	25	2	C2	5_C2	13.97	11.51	15.39	4.70	0.77	21.022	54.1	339.9	0.75	2.5	1.7
C	25	3	C3	5_C3	13.97	13.45	15.39	2.35	1.1	21.115	31.6	85.0	0.87	2.7	1.2
C	25	4	C4	5_C4	13.97	15.39	15.39	0.00	1.19	21.341	0.0	0.0	1.00	2.8	0.0
D	26	1	D1	4_D1	11.43	0.00	16.15	14.48	0.29	22.535	0.0	3386.2	0.00	0.0	2.7
D	26	2	D2	4_D2	11.43	1.37	16.15	12.19	0.33	20.831	16.7	2401.3	0.08	0.9	2.6
D	26	3	D3	4_D3	11.43	3.17	16.15	10.16	0.32	20.554	32.2	1667.5	0.20	1.4	2.4
D	26	4	D4	4_D4	11.43	6.34	16.15	9.40	0.4	20.592	59.6	1426.8	0.39	2.0	2.3
D	26	5	D5	4_D5	11.43	9.60	16.15	8.13	0.4	20.754	78.0	1067.2	0.59	2.4	2.2
C	26	1	C1	4_C1	11.43	11.24	16.15	6.10	0.47	20.974	68.5	600.3	0.70	2.5	2.0
C	26	2	C2	4_C2	11.43	12.88	16.15	4.06	0.67	21.108	52.3	266.8	0.80	2.6	1.6
C	26	3	C3	4_C3	11.43	14.52	16.15	2.03	0.81	21.14	29.5	66.7	0.90	2.7	1.1
C	26	4	C4	4_C4	11.43	16.15	16.15	0.00	1.15	21.593	0.0	0.0	1.00	2.8	0.0
D	27	1	D1	7_D1	19.05	0.00	19.81	21.84	0.27	20.491	0.0	9453.5	0.00	0.0	3.1
D	27	2	D2	7_D2	19.05	1.37	19.81	19.30	0.23	20.247	26.5	7382.8	0.07	0.9	3.0
D	27	3	D3	7_D3	19.05	5.18	19.81	16.26	0.22	20.953	84.2	5235.5	0.26	1.8	2.8
D	27	4	D4	7_D4	19.05	10.36	19.81	12.45	0.28	20.709	129.0	3068.9	0.52	2.4	2.6
D	27	5	D5	7_D5	19.05	15.70	19.81	9.91	0.28	21.015	155.5	1944.1	0.79	2.8	2.4

X	tree	section	label	ID	DBH	height	TTH	DBT	Ash	HHV	DandH	D2H	percent treeht	log height	log DBT
C	27	1	C1	7_C1	19.05	16.73	19.81	7.43	0.61	21.123	124.3	1093.6	0.84	2.9	2.1
C	27	2	C2	7_C2	19.05	17.75	19.81	4.95	1	21.129	87.9	486.0	0.90	2.9	1.8
C	27	3	C3	7_C3	19.05	18.78	19.81	2.48	1.15	21.111	46.5	121.5	0.95	3.0	1.2
C	27	4	C4	7_C4	19.05	19.81	19.81	0.00	1.76	21.288	0.0	0.0	1.00	3.0	0.0

Crown sample data sets used for proximate analysis and HHV in 4.3 Fuel Quality: Crown Sections: A

Obs	tree	label	ID	DBH	height	TTH	DBT	Section Length	CR	Section Mass	Total Crown Mass	Crown DBT
1	4	C1	4_C1	11.43	8.07	11.27	10.54	1.07	0.38	7.76	15.24	10.54
2	4	C2	4_C2	11.43	9.14	11.27	7.90	1.07	0.38	1.81	15.24	10.54
3	4	C3	4_C3	11.43	10.20	11.27	5.28	1.07	0.38	2.54	15.24	10.54
4	4	C4	4_C4	11.43	11.27	11.27	2.64	1.07	0.38	3.13	15.24	10.54
5	12	C1	4_C1	11.43	11.95	14.01	4.95	0.69	0.2	1.13	4.85	4.95
6	12	C2	4_C2	11.43	12.64	14.01	3.71	0.69	0.2	1.91	4.85	4.95
7	12	C3	4_C3	11.43	13.32	14.01	2.49	0.69	0.2	0.68	4.85	4.95
8	12	C4	4_C4	11.43	14.01	14.01	1.24	0.69	0.2	1.13	4.85	4.95
9	15	C1	4_C1	11.43	10.75	14.22	7.24	1.16	0.33	5.85	14.79	7.24
10	15	C2	4_C2	11.43	11.91	14.22	5.44	1.16	0.33	3.63	14.79	7.24
11	15	C3	4_C3	11.43	13.06	14.22	3.63	1.16	0.33	2.77	14.79	7.24
12	15	C4	4_C4	11.43	14.22	14.22	1.80	1.16	0.33	2.54	14.79	7.24
13	24	C1	4_C1	11.43	7.64	10.66	7.87	1.00	0.38	6.40	17.19	7.87
14	24	C2	4_C2	11.43	8.65	10.66	5.92	1.00	0.38	3.76	17.19	7.87
15	24	C3	4_C3	11.43	9.65	10.66	3.94	1.00	0.38	3.63	17.19	7.87
16	24	C4	4_C4	11.43	10.66	10.66	1.98	1.00	0.38	3.40	17.19	7.87
17	26	C1	4_C1	11.43	11.23	16.14	8.00	1.64	0.41	0.59	13.02	8.00
18	26	C2	4_C2	11.43	12.87	16.14	5.99	1.64	0.41	6.12	13.02	8.00
19	26	C3	4_C3	11.43	14.50	16.14	4.01	1.64	0.41	2.86	13.02	8.00
20	26	C4	4_C4	11.43	16.14	16.14	2.01	1.64	0.41	3.45	13.02	8.00
21	13	C1	5_C1	13.97	12.16	15.77	6.10	1.20	0.31	2.54	12.61	6.10
22	13	C2	5_C2	13.97	13.37	15.77	4.57	1.20	0.31	3.76	12.61	6.10
23	13	C3	5_C3	13.97	14.57	15.77	3.05	1.20	0.31	4.22	12.61	6.10
24	13	C4	5_C4	13.97	15.77	15.77	1.52	1.20	0.31	2.09	12.61	6.10

Obs	tree	label	ID	DBH	height	TTH	DBT	Section Length	CR	Section Mass	Total Crown Mass	Crown DBT
25	14	C1	5_C1	13.97	12.94	17.05	8.51	1.37	0.32	6.89	19.10	8.51
26	14	C2	5_C2	13.97	14.31	17.05	6.38	1.37	0.32	4.85	19.10	8.51
27	14	C3	5_C3	13.97	15.68	17.05	4.27	1.37	0.32	4.76	19.10	8.51
28	14	C4	5_C4	13.97	17.05	17.05	2.13	1.37	0.32	2.59	19.10	8.51
29	17	C1	5_C1	13.97	7.50	12.18	9.65	1.56	0.51	13.15	36.29	9.65
30	17	C2	5_C2	13.97	9.06	12.18	7.24	1.56	0.51	4.94	36.29	9.65
31	17	C3	5_C3	13.97	10.62	12.18	4.83	1.56	0.51	13.20	36.29	9.65
32	17	C4	5_C4	13.97	12.18	12.18	2.41	1.56	0.51	4.99	36.29	9.65
33	23	C1	5_C1	13.97	10.43	13.40	8.00	0.99	0.3	4.67	10.21	8.00
34	23	C2	5_C2	13.97	11.42	13.40	5.99	0.99	0.3	1.09	10.21	8.00
35	23	C3	5_C3	13.97	12.41	13.40	4.01	0.99	0.3	3.04	10.21	8.00
36	23	C4	5_C4	13.97	13.40	13.40	2.01	0.99	0.3	1.41	10.21	8.00
37	25	C1	5_C1	13.97	9.55	15.38	9.02	1.94	0.5	10.48	27.71	9.02
38	25	C2	5_C2	13.97	11.49	15.38	6.76	1.94	0.5	7.62	27.71	9.02
39	25	C3	5_C3	13.97	13.44	15.38	4.52	1.94	0.5	5.81	27.71	9.02
40	25	C4	5_C4	13.97	15.38	15.38	2.26	1.94	0.5	3.81	27.71	9.02
41	5	C1	6_C1	16.51	11.79	14.28	6.99	0.83	0.54	6.12	13.56	6.99
42	5	C2	6_C2	16.51	12.62	14.28	5.23	0.83	0.54	2.90	13.56	6.99
43	5	C3	6_C3	16.51	13.45	14.28	3.51	0.83	0.54	3.13	13.56	6.99
44	5	C4	6_C4	16.51	14.28	14.28	1.75	0.83	0.54	1.41	13.56	6.99
45	6	C1	6_C1	16.51	10.53	15.44	10.54	1.64	0.42	12.79	33.07	10.54
46	6	C2	6_C2	16.51	12.16	15.44	7.90	1.64	0.42	8.35	33.07	10.54
47	6	C3	6_C3	16.51	13.80	15.44	5.28	1.64	0.42	9.03	33.07	10.54
48	6	C4	6_C4	16.51	15.44	15.44	2.64	1.64	0.42	2.90	33.07	10.54
49	7	C1	6_C1	16.51	14.67	16.84	5.72	0.72	0.17	1.72	6.53	5.72
50	7	C2	6_C2	16.51	15.39	16.84	4.29	0.72	0.17	0.77	6.53	5.72

Obs	tree	label	ID	DBH	height	TTH	DBT	Section Length	CR	Section Mass	Total Crown Mass	Crown DBT
51	7	C3	6_C3	16.51	16.12	16.84	2.87	0.72	0.17	1.45	6.53	5.72
52	7	C4	6_C4	16.51	16.84	16.84	1.42	0.72	0.17	2.59	6.53	5.72
53	11	C1	6_C1	16.51	12.64	16.29	9.78	1.22	0.3	8.89	34.70	9.78
54	11	C2	6_C2	16.51	13.85	16.29	7.34	1.22	0.3	11.11	34.70	9.78
55	11	C3	6_C3	16.51	15.07	16.29	4.90	1.22	0.3	10.52	34.70	9.78
56	11	C4	6_C4	16.51	16.29	16.29	2.44	1.22	0.3	4.17	34.70	9.78
57	18	C1	6_C1	16.51	9.77	12.79	10.54	1.00	0.31	9.48	22.45	10.54
58	18	C2	6_C2	16.51	10.78	12.79	7.90	1.00	0.31	5.22	22.45	10.54
59	18	C3	6_C3	16.51	11.78	12.79	5.28	1.00	0.31	4.58	22.45	10.54
60	18	C4	6_C4	16.51	12.79	12.79	2.64	1.00	0.31	3.18	22.45	10.54
61	3	C1	7_C1	19.05	12.16	18.51	10.54	2.12	0.46	18.01	41.37	10.54
62	3	C2	7_C2	19.05	14.28	18.51	7.90	2.12	0.46	6.53	41.37	10.54
63	3	C3	7_C3	19.05	16.40	18.51	5.28	2.12	0.46	10.98	41.37	10.54
64	3	C4	7_C4	19.05	18.51	18.51	2.64	2.12	0.46	5.85	41.37	10.54
65	8	C1	7_C1	19.05	11.91	17.66	10.54	1.92	0.43	13.56	50.44	10.54
66	8	C2	7_C2	19.05	13.82	17.66	7.90	1.92	0.43	19.91	50.44	10.54
67	8	C3	7_C3	19.05	15.74	17.66	5.28	1.92	0.43	8.57	50.44	10.54
68	8	C4	7_C4	19.05	17.66	17.66	2.64	1.92	0.43	8.39	50.44	10.54
69	21	C1	7_C1	19.05	13.64	17.30	7.24	1.22	0.28	4.40	19.96	7.24
70	21	C2	7_C2	19.05	14.86	17.30	5.44	1.22	0.28	3.49	19.96	7.24
71	21	C3	7_C3	19.05	16.08	17.30	3.63	1.22	0.28	6.85	19.96	7.24
72	21	C4	7_C4	19.05	17.30	17.30	1.80	1.22	0.28	5.22	19.96	7.24
73	22	C1	7_C1	19.05	12.06	18.27	10.03	2.07	0.45	18.10	45.54	10.03
74	22	C2	7_C2	19.05	14.13	18.27	7.52	2.07	0.45	11.61	45.54	10.03
75	22	C3	7_C3	19.05	16.20	18.27	5.03	2.07	0.45	10.89	45.54	10.03
76	22	C4	7_C4	19.05	18.27	18.27	2.51	2.07	0.45	4.94	45.54	10.03

Obs	tree	label	ID	DBH	height	TTH	DBT	Section Length	CR	Section Mass	Total Crown Mass	Crown DBT
77	27	C1	7_C1	19.05	16.71	19.79	9.02	1.03	0.21	7.53	23.36	9.02
78	27	C2	7_C2	19.05	17.74	19.79	6.76	1.03	0.21	9.25	23.36	9.02
79	27	C3	7_C3	19.05	18.76	19.79	4.52	1.03	0.21	5.17	23.36	9.02
80	27	C4	7_C4	19.05	19.79	19.79	2.26	1.03	0.21	1.41	23.36	9.02

Crown sample data sets used for proximate analysis and HHV in 4.3 Fuel Quality: Crown Sections: B

Obs	X	Tree	Section	ID	DBH	MC (%, w.b.)	MC sd	VM (%, d.b.)	VM sd	Ash (%, d.b.)	Ash sd	FC (%, d.b.)	HHV	HHV sd
1	C	4	1	4_C1	11.43	12.36	0.11	69.64	27.17	1.214	0.057	0.168	21.890	0.016
2	C	4	2	4_C2	11.43	9.88	0.14	73.77	121.78	0.781	0.005	0.156	21.658	0.013
3	C	4	3	4_C3	11.43	10.42	0.20	70.95	73.68	0.918	0.071	0.177	21.692	0.011
4	C	4	4	4_C4	11.43	11.80	0.04	71.55	174.84	1.143	0.035	0.155	21.701	0.016
5	C	12	1	4_C1	11.43	10.50	0.13	73.34	120.91	1.479	0.195	0.147	20.926	0.038
6	C	12	2	4_C2	11.43	9.54	0.04	72.25	107.83	0.994	0.058	0.172	21.251	0.006
7	C	12	3	4_C3	11.43	8.96	0.05	71.23	51.47	1.695	0.094	0.181	21.083	0.006
8	C	12	4	4_C4	11.43	9.16	0.16	70.97	48.98	1.728	0.436	0.181	21.207	0.005
9	C	15	1	4_C1	11.43	10.77	0.15	72.21	42.21	0.866	0.309	0.162	20.885	0.013
10	C	15	2	4_C2	11.43	11.14	0.09	72.30	295.04	0.997	0.152	0.156	21.386	0.001
11	C	15	3	4_C3	11.43	11.46	0.09	70.39	5.47	1.146	0.052	0.170	20.931	0.017
12	C	15	4	4_C4	11.43	9.99	0.18	72.05	10.25	1.502	0.097	0.165	21.513	0.006
13	C	24	1	4_C1	11.43	8.76	0.12	72.52	7.79	1.012	0.108	0.177	21.075	0.020
14	C	24	2	4_C2	11.43	9.86	0.15	72.04	10.87	1.489	0.061	0.166	21.015	0.009
15	C	24	3	4_C3	11.43	10.30	0.17	73.51	100.91	1.475	0.044	0.147	21.424	0.011
16	C	24	4	4_C4	11.43	7.87	0.09	73.88	83.14	1.942	0.018	0.163	21.326	0.013
17	C	26	1	4_C1	11.43	9.86	0.10	74.19	25.38	0.471	0.186	0.155	20.974	0.014

Obs	X	Tree	Section	ID	DBH	MC (%, w.b.)	MC sd	VM (%, d.b.)	VM sd	Ash (%, d.b.)	Ash sd	FC (%, d.b.)	HHV	HHV sd
18	C	26	2	4_C2	11.43	9.36	0.06	73.83	73.11	0.666	0.048	16.79	21.108	0.009
19	C	26	3	4_C3	11.43	10.24	0.07	73.93	99.63	0.812	0.043	15.56	21.140	0.017
20	C	26	4	4_C4	11.43	9.37	0.08	71.75	59.49	1.149	0.144	17.70	21.593	0.021
21	C	13	1	5_C1	13.97	8.52	0.07	74.20	222.43	0.988	0.166	15.51	20.791	0.003
22	C	13	2	5_C2	13.97	10.05	0.05	72.08	50.39	0.998	0.090	14.68	21.304	0.017
23	C	13	3	5_C3	13.97	9.68	0.11	70.37	1.16	1.420	0.110	17.22	21.631	0.013
24	C	13	4	5_C4	13.97	8.05	0.18	73.24	147.94	3.090	0.130	18.11	21.671	0.010
25	C	14	1	5_C1	13.97	10.49	0.06	74.60	34.12	0.281	0.133	18.14	20.794	0.023
26	C	14	2	5_C2	13.97	10.98	0.14	72.42	35.76	0.761	0.255	16.15	20.637	0.002
27	C	14	3	5_C3	13.97	10.97	0.11	72.42	136.27	1.582	0.118	15.56	21.234	0.011
28	C	14	4	5_C4	13.97	9.61	0.04	70.78	84.13	2.255	0.076	17.01	21.442	0.009
29	C	17	1	5_C1	13.97	10.43	0.09	75.06	196.22	0.723	0.045	16.45	20.573	0.007
30	C	17	2	5_C2	13.97	11.60	0.10	72.20	28.44	0.649	0.190	17.71	21.000	0.031
31	C	17	3	5_C3	13.97	16.60	0.31	68.76	248.47	1.172	0.032	16.61	20.551	0.012
32	C	17	4	5_C4	13.97	10.18	0.03	70.42	183.53	1.878	0.091	14.71	21.585	0.014
33	C	23	1	5_C1	13.97	9.99	0.13	72.03	9.33	0.847	0.094	16.31	21.980	0.016
34	C	23	2	5_C2	13.97	9.69	0.12	74.31	89.45	0.842	0.122	15.48	20.957	0.004
35	C	23	3	5_C3	13.97	10.30	0.17	71.71	71.97	1.161	0.069	16.15	21.877	0.010
36	C	23	4	5_C4	13.97	7.87	0.09	74.76	166.98	1.547	0.115	15.02	20.954	0.006
37	C	25	1	5_C1	13.97	11.11	0.13	73.50	19.32	0.631	0.033	17.74	21.351	0.026
38	C	25	2	5_C2	13.97	12.21	0.22	72.15	38.00	0.773	0.006	16.29	21.022	0.010
39	C	25	3	5_C3	13.97	12.68	0.08	70.77	28.01	1.101	0.148	16.87	21.115	0.027
40	C	25	4	5_C4	13.97	9.34	0.14	74.13	173.68	1.195	0.105	18.53	21.341	0.003
41	C	5	1	6_C1	16.51	11.45	0.13	72.75	17.08	1.181	0.046	15.62	20.699	0.007
42	C	5	2	6_C2	16.51	14.74	0.17	68.29	22.68	1.099	0.057	14.62	21.712	0.016
43	C	5	3	6_C3	16.51	11.86	0.11	70.08	153.93	1.266	0.081	15.83	21.445	0.024
44	C	5	4	6_C4	16.51	8.97	0.08	71.53	44.66	1.824	0.063	15.03	21.151	0.020
45	C	6	1	6_C1	16.51	11.79	0.07	73.37	154.68	0.588	0.099	17.36	20.895	0.004

Obs	X	Tree	Section	ID	DBH	MC (%, w.b.)	MC sd	VM (%, d.b.)	VM sd	Ash (%, d.b.)	Ash sd	FC (%, d.b.)	HHV	HHV sd
46	C	6	2	6_C2	16.51	11.92	0.06	72.51	56.70	0.747	0.064	13.80	21.530	0.020
47	C	6	3	6_C3	16.51	13.85	0.19	71.21	50.18	0.973	0.084	15.55	21.654	0.006
48	C	6	4	6_C4	16.51	10.39	0.13	72.98	75.35	1.022	0.070	13.47	21.240	0.023
49	C	7	1	6_C1	16.51	9.57	0.07	72.57	62.28	1.106	0.299	17.53	21.169	0.013
50	C	7	2	6_C2	16.51	8.52	0.06	72.98	18.71	1.135	0.063	17.14	20.865	0.034
51	C	7	3	6_C3	16.51	8.73	0.09	73.30	46.62	1.412	0.059	15.16	21.037	0.024
52	C	7	4	6_C4	16.51	9.55	0.07	72.88	234.09	1.240	0.091	16.82	21.528	0.023
53	C	11	1	6_C1	16.51	13.74	0.10	71.11	37.53	0.802	0.010	15.83	21.063	0.008
54	C	11	2	6_C2	16.51	13.61	0.12	69.83	204.79	1.238	0.036	14.75	21.590	0.019
55	C	11	3	6_C3	16.51	11.48	0.13	70.78	56.97	2.226	0.099	14.86	21.090	0.021
56	C	11	4	6_C4	16.51	8.69	0.06	71.46	233.85	3.366	0.305	15.45	21.208	0.007
57	C	18	1	6_C1	16.51	12.51	0.19	72.37	61.31	0.880	0.141	15.33	22.010	0.007
58	C	18	2	6_C2	16.51	12.52	0.30	70.67	193.97	0.996	0.011	14.62	21.027	0.003
59	C	18	3	6_C3	16.51	10.64	0.20	69.25	52.85	1.555	0.105	15.86	21.113	0.025
60	C	18	4	6_C4	16.51	9.39	0.07	71.64	160.50	2.276	0.222	16.79	21.395	0.030
61	C	3	1	7_C1	19.05	17.10	0.04	69.71	26.76	0.453	0.174	17.68	21.609	0.011
62	C	3	2	7_C2	19.05	10.90	0.06	74.13	101.59	0.850	0.071	14.25	20.943	0.028
63	C	3	3	7_C3	19.05	12.52	0.15	73.91	189.96	0.851	0.029	14.83	20.678	0.029
64	C	3	4	7_C4	19.05	9.32	0.08	72.86	93.14	0.774	0.057	13.98	21.783	0.011
65	C	8	1	7_C1	19.05	13.78	0.10	71.40	55.99	0.435	0.145	15.61	21.096	0.021
66	C	8	2	7_C2	19.05	14.36	0.12	69.49	76.13	0.750	0.083	16.75	21.557	0.019
67	C	8	3	7_C3	19.05	11.89	0.10	72.18	152.43	0.909	0.054	17.36	21.300	0.019
68	C	8	4	7_C4	19.05	10.19	0.06	72.75	202.77	1.569	0.116	16.56	21.370	0.016
69	C	21	1	7_C1	19.05	11.72	0.15	71.69	41.39	0.796	0.057	16.33	20.903	0.040
70	C	21	2	7_C2	19.05	10.11	0.14	73.56	127.96	1.142	0.099	14.35	21.194	0.057
71	C	21	3	7_C3	19.05	11.34	0.08	70.22	34.61	1.665	0.197	15.33	21.072	0.009
72	C	21	4	7_C4	19.05	10.40	0.04	71.58	84.57	1.209	0.052	15.52	21.247	0.010
73	C	22	1	7_C1	19.05	9.71	0.29	75.61	56.97	0.646	0.081	16.49	20.193	0.009

Obs	X	Tree	Section	ID	DBH	MC (%, w.b.)	MC sd	VM (%, d.b.)	VM sd	Ash (%, d.b.)	Ash sd	FC (%, d.b.)	HHV	HHV sd
74	C	22	2	7_C2	19.05	17.34	0.35	69.12	28.68	0.676	0.105	14.24	21.614	0.028
75	C	22	3	7_C3	19.05	12.36	0.15	71.15	26.69	0.883	0.103	15.81	20.778	0.028
76	C	22	4	7_C4	19.05	9.26	0.30	72.99	42.89	1.073	0.263	18.55	21.071	0.021
77	C	27	1	7_C1	19.05	10.75	0.10	73.45	23.91	0.607	0.083	16.70	21.123	0.002
78	C	27	2	7_C2	19.05	11.36	0.07	73.20	93.60	1.000	0.041	12.74	21.129	0.010
79	C	27	3	7_C3	19.05	9.14	0.04	73.34	90.50	1.151	0.205	14.12	21.111	0.008
80	C	27	4	7_C4	19.05	8.82	0.16	72.69	74.97	1.758	0.033	12.73	21.288	0.005

Stemwood sample data sets used in ash content and HHV 4.4 stemwood categorical analysis

Obs	Tree	Section	ID	DBH	Height	TTH	DBT	Tree Ht %	Density	Rings	Bark %	M C %	Ash (%, d.b.)	Ash SD	HHV (d.b.)	HHV SD
1	4	1	4_D1	11.43	0.00	11.28	15.75	0	0.55	17	0.24	5.86	0.42%	0.01%	20.77	0.026
2	4	2	4_D2	11.43	1.37	11.28	13.21	0.12	0.61	15	0.18	6.73	0.34%	0.04%	20.881	0.056
3	4	3	4_D3	11.43	2.32	11.28	10.92	0.21	0.52	12	0.16	6.13	0.29%	0.05%	21.089	0.106
4	4	4	4_D4	11.43	4.63	11.28	10.41	0.41	0.54	11	0.15	6.37	0.35%	0.04%	21.737	0.010
5	4	5	4_D5	11.43	7.01	11.28	8.89	0.62	0.5	9	0.14	6.8	0.43%	0.04%	21.028	0.044
6	12	1	4_D1	11.43	0.00	14.02	15.24	0	0.6	23	0.21	5.62	0.72%	0.11%	20.903	0.084
7	12	2	4_D2	11.43	1.37	14.02	13.21	0.1	0.59	19	0.18	5.57	0.55%	0.08%	20.827	0.182
8	12	3	4_D3	11.43	3.72	14.02	11.18	0.27	0.49	16	0.16	4.68	0.40%	0.03%	20.601	0.014
9	12	4	4_D4	11.43	8.96	14.02	9.40	0.64	0.49	12	0.13	6.16	0.41%	0.08%	20.72	0.075
10	12	5	4_D5	11.43	11.28	14.02	6.35	0.8	0.42	9	0.19	6.86	0.34%	0.01%	20.845	0.373
11	15	1	4_D1	11.43	0.00	14.23	14.73	0	0.71	29	0.14	5.24	0.29%	0.03%	20.624	0.055
12	15	2	4_D2	11.43	1.37	14.23	12.70	0.1	0.71	25	0.08	5.22	0.29%	0.10%	20.976	0.238
13	15	3	4_D3	11.43	3.17	14.23	10.92	0.22	0.6	21	0.07	5.57	0.24%	0.02%	20.611	0.099
14	15	4	4_D4	11.43	6.34	14.23	10.16	0.45	0.6	17	0.1	5.65	0.29%	0.11%	20.692	0.095
15	15	5	4_D5	11.43	9.60	14.23	8.38	0.67	0.58	12	0.11	5.81	0.34%	0.03%	20.652	0.177
16	24	1	4_D1	11.43	0.00	10.67	16.51	0	0.66	32	0.17	4.81	0.28%	0.02%	21.614	0.435
17	24	2	4_D2	11.43	1.37	10.67	13.97	0.13	0.63	30	0.11	5.11	0.34%	0.01%	21.002	0.048
18	24	3	4_D3	11.43	2.19	10.67	12.95	0.21	0.59	25	0.14	5.38	0.28%	0.02%	20.927	0.040
19	24	4	4_D4	11.43	4.42	10.67	10.92	0.41	0.54	21	0.14	5.48	0.37%	0.05%	20.718	0.111
20	24	5	4_D5	11.43	6.64	10.67	9.40	0.62	0.5	16	0.1	5.86	0.38%	0.02%	20.72	0.113
21	26	1	4_D1	11.43	0.00	16.15	15.75	0	0.77	32	0.17	5.15	0.29%	0.01%	22.535	0.042
22	26	2	4_D2	11.43	1.37	16.15	13.46	0.08	0.65	26	0.12	5.43	0.33%	0.07%	20.831	0.117
23	26	3	4_D3	11.43	3.17	16.15	11.43	0.2	0.59	23	0.1	5.75	0.32%	0.04%	20.554	0.124
24	26	4	4_D4	11.43	6.34	16.15	10.67	0.39	0.55	18	0.12	5.84	0.40%	0.01%	20.592	0.206
25	26	5	4_D5	11.43	9.60	16.15	9.40	0.59	0.55	15	0.09	5.42	0.40%	0.04%	20.754	0.235
26	13	1	5_D1	13.97	0.00	15.79	18.03	0	0.67	31	0.16	5.13	0.34%	0.03%	21.448	0.117

Obs	Tree	Section	ID	DBH	Height	TTH	DBT	Tree Ht %	Density	Rings	Bark %	M C %	Ash (%, d.b.)	Ash SD	HHV (d.b.)	HHV SD
27	13	2	5_D2	13.97	1.37	15.79	16.51	0.09	0.62	28	0.17	5.46	0.30%	0.04%	20.95	0.077
28	13	3	5_D3	13.97	3.66	15.79	12.70	0.23	0.58	24	0.12	5.7	0.28%	0.02%	20.714	0.052
29	13	4	5_D4	13.97	7.32	15.79	10.16	0.46	0.58	20	0.12	6.17	0.29%	0.03%	20.756	0.108
30	13	5	5_D5	13.97	10.97	15.79	7.62	0.7	0.51	14	0.12	6.31	0.27%	0.03%	20.901	0.054
31	14	1	5_D1	13.97	0.00	17.07	18.03	0	0.67	38	0.15	4.64	0.27%	0.03%	20.933	0.055
32	14	2	5_D2	13.97	1.37	17.07	15.24	0.08	0.65	33	0.09	5.14	0.26%	0.02%	20.889	0.067
33	14	3	5_D3	13.97	3.81	17.07	12.95	0.22	0.6	26	0.07	5.93	0.38%	0.03%	20.761	0.102
34	14	4	5_D4	13.97	7.65	17.07	11.43	0.45	0.57	21	0.1	6.18	0.33%	0.02%	20.835	0.035
35	14	5	5_D5	13.97	11.58	17.07	10.16	0.68	0.58	14	0.09	6.38	0.35%	0.04%	21.097	0.091
36	17	1	5_D1	13.97	0.00	12.19	17.27	0	0.58	27	0.18	5.11	0.45%	0.06%	20.841	0.054
37	17	2	5_D2	13.97	1.37	12.19	14.73	0.11	0.57	24	0.14	5.45	0.31%	0.05%	20.748	0.050
38	17	3	5_D3	13.97	1.95	12.19	12.70	0.16	0.5	22	0.17	5.76	0.37%	0.03%	20.772	0.033
39	17	4	5_D4	13.97	3.93	12.19	11.68	0.32	0.51	20	0.11	6.11	0.23%	0.17%	20.657	0.037
40	17	5	5_D5	13.97	5.94	12.19	11.18	0.49	0.47	18	0.09	6.24	0.43%	0.04%	20.779	0.115
41	23	1	5_D1	13.97	0.00	13.41	17.27	0	0.63	26	0.13	4.58	0.26%	0.08%	20.989	0.087
42	23	2	5_D2	13.97	1.37	13.41	14.99	0.1	0.61	22	0.14	4.49	0.26%	0.01%	20.727	0.059
43	23	3	5_D3	13.97	3.11	13.41	12.19	0.23	0.49	19	0.11	5.47	0.24%	0.05%	20.431	0.120
44	23	4	5_D4	13.97	6.25	13.41	11.43	0.47	0.47	16	0.08	5.34	0.46%	0.05%	21.226	0.110
45	23	5	5_D5	13.97	9.45	13.41	9.65	0.7	0.44	12	0.15	5.41	0.41%	0.06%	20.558	0.180
46	25	1	5_D1	13.97	0.00	15.39	16.26	0	0.68	28	0.15	4.71	0.35%	0.13%	20.24	0.110
47	25	2	5_D2	13.97	1.37	15.39	14.48	0.09	0.64	25	0.12	4.68	0.32%	0.02%	20.388	0.027
48	25	3	5_D3	13.97	2.53	15.39	13.46	0.16	0.62	20	0.11	4.64	0.36%	0.03%	20.29	0.332
49	25	4	5_D4	13.97	5.03	15.39	11.94	0.33	0.6	18	0.12	5.38	0.33%	0.03%	20.722	0.038
50	25	5	5_D5	13.97	7.62	15.39	10.67	0.5	0.53	14	0.14	5.71	0.34%	0.02%	20.571	0.126
51	5	1	6_D1	16.51	0.00	14.30	21.59	0	0.53	23	0.2	5.88	0.43%	0.02%	20.563	0.121
52	5	2	6_D2	16.51	1.37	14.30	17.78	0.1	0.54	20	0.17	5.49	0.36%	0.07%	20.827	0.118
53	5	3	6_D3	16.51	3.63	14.30	16.00	0.25	0.52	18	0.16	5.42	0.39%	0.04%	21	0.037
54	5	4	6_D4	16.51	7.22	14.30	11.94	0.51	0.48	14	0.13	6.11	0.38%	0.05%	20.885	0.007

Obs	Tree	Section	ID	DBH	Height	TTH	DBT	Tree Ht %	Density	Rings	Bark %	M C %	Ash (%, d.b.)	Ash SD	HHV (d.b.)	HHV SD
55	5	5	6_D5	16.51	10.97	14.30	8.38	0.77	0.43	10	0.18	6.91	0.39%	0.02%	21.046	0.039
56	6	1	6_D1	16.51	0.00	15.45	20.32	0	0.59	25	0.3	5.44	0.35%	0.03%	20.574	0.078
57	6	2	6_D2	16.51	1.37	15.45	17.27	0.09	0.59	22	0.21	5.61	0.39%	0.05%	20.456	0.117
58	6	3	6_D3	16.51	2.93	15.45	14.73	0.19	0.51	18	0.17	5.81	0.32%	0.07%	20.781	0.085
59	6	4	6_D4	16.51	5.85	15.45	12.95	0.38	0.48	16	0.13	6.18	0.30%	0.04%	20.665	0.054
60	6	5	6_D5	16.51	8.90	15.45	11.68	0.58	0.44	13	0.15	6.28	0.35%	0.05%	20.67	0.145
61	7	1	6_D1	16.51	0.00	16.86	20.32	0	0.6	26	0.13	4.72	0.37%	0.16%	20.654	0.071
62	7	2	6_D2	16.51	1.37	16.86	18.03	0.08	0.63	24	0.12	5.08	0.35%	0.02%	20.539	0.076
63	7	3	6_D3	16.51	4.60	16.86	14.73	0.27	0.56	21	0.12	5.4	0.26%	0.05%	20.459	0.204
64	7	4	6_D4	16.51	9.20	16.86	11.43	0.55	0.51	15	0.1	6.15	0.31%	0.04%	20.722	0.090
65	7	5	6_D5	16.51	13.96	16.86	7.11	0.83	0.5	13	0.1	6.65	0.39%	0.05%	20.675	0.193
66	11	1	6_D1	16.51	0.00	16.31	20.57	0	0.54	32	0.14	5.03	0.41%	0.02%	20.767	0.087
67	11	2	6_D2	16.51	1.37	16.31	18.03	0.08	0.58	29	0.15	4.85	0.37%	0.04%	20.988	0.053
68	11	3	6_D3	16.51	3.78	16.31	15.75	0.23	0.49	24	0.14	5.37	0.33%	0.01%	20.361	0.562
69	11	4	6_D4	16.51	7.56	16.31	13.21	0.46	0.51	19	0.11	5.36	0.36%	0.02%	20.391	0.185
70	11	5	6_D5	16.51	11.43	16.31	11.43	0.7	0.45	14	0.11	5.98	0.37%	0.04%	20.559	0.045
71	18	1	6_D1	16.51	0.00	12.80	19.56	0	0.62	30	0.2	5.19	0.30%	0.08%	20.543	0.041
72	18	2	6_D2	16.51	1.37	12.80	17.02	0.11	0.58	26	0.17	5.59	0.30%	0.11%	20.471	0.162
73	18	3	6_D3	16.51	2.90	12.80	15.49	0.23	0.51	22	0.16	5.7	0.35%	0.06%	20.232	0.168
74	18	4	6_D4	16.51	5.18	12.80	14.22	0.4	0.47	16	0.14	6.13	0.30%	0.01%	20.308	0.019
75	18	5	6_D5	16.51	8.78	12.80	12.19	0.69	0.51	13	0.09	5.84	0.30%	0.01%	23.279	0.428
76	3	1	7_D1	19.05	0.00	18.53	21.59	0	0.59	31	0.18	5.75	0.28%	0.01%	20.87	0.052
77	3	2	7_D2	19.05	1.37	18.53	20.07	0.07	0.58	26	0.14	5.84	0.24%	0.09%	20.875	0.092
78	3	3	7_D3	19.05	3.35	18.53	16.51	0.18	0.49	23	0.11	5.7	0.21%	0.14%	20.928	0.069
79	3	4	7_D4	19.05	6.71	18.53	14.73	0.36	0.49	19	0.14	6.49	0.26%	0.06%	21.012	0.111
80	3	5	7_D5	19.05	10.06	18.53	12.19	0.54	0.49	16	0.13	6.39	0.31%	0.06%	20.985	0.084
81	8	1	7_D1	19.05	0.00	17.68	21.84	0	0.69	31	0.12	4.57	0.38%	0.02%	20.733	0.026
82	8	2	7_D2	19.05	1.37	17.68	20.07	0.08	0.7	26	0.14	4.34	0.35%	0.02%	20.621	0.119

Obs	Tree	Section	ID	DBH	Height	TTH	DBT	Tree Ht %	Density	Rings	Bark %	M C %	Ash (%, d.b.)	Ash SD	HHV (d.b.)	HHV SD
83	8	3	7_D3	19.05	3.29	17.68	17.53	0.19	0.67	22	0.09	4.59	0.32%	0.04%	20.538	0.158
84	8	4	7_D4	19.05	6.58	17.68	13.97	0.37	0.57	19	0.09	5.5	0.35%	0.02%	20.623	0.174
85	8	5	7_D5	19.05	10.00	17.68	11.94	0.57	0.54	17	0.11	5.63	0.36%	0.02%	20.69	0.057
86	21	1	7_D1	19.05	0.00	17.31	23.11	0	0.64	36	0.18	4.43	0.34%	0.08%	20.674	0.105
87	21	2	7_D2	19.05	1.37	17.31	20.83	0.08	0.6	32	0.2	4.26	0.24%	0.04%	20.711	0.035
88	21	3	7_D3	19.05	4.11	17.31	15.75	0.24	0.52	22	0.14	5.02	0.21%	0.09%	20.536	0.006
89	21	4	7_D4	19.05	8.20	17.31	12.70	0.47	0.52	19	0.11	5.33	0.24%	0.05%	20.69	0.098
90	21	5	7_D5	19.05	12.44	17.31	8.64	0.72	0.5	14	0.12	5.82	0.28%	0.12%	20.639	0.100
91	22	1	7_D1	19.05	0.00	18.29	20.83	0	0.61	29	0.15	4.53	0.38%	0.07%	20.798	0.138
92	22	2	7_D2	19.05	1.37	18.29	18.80	0.08	0.6	26	0.12	4.86	0.37%	0.04%	21.19	0.082
93	22	3	7_D3	19.05	3.29	18.29	15.75	0.18	0.53	20	0.09	4.94	0.38%	0.05%	20.848	0.027
94	22	4	7_D4	19.05	6.58	18.29	13.46	0.36	0.52	17	0.08	4.7	0.32%	0.03%	20.631	0.154
95	22	5	7_D5	19.05	10.00	18.29	11.43	0.55	0.48	15	0.09	5.28	0.35%	0.01%	20.924	0.052
96	27	1	7_D1	19.05	0.00	19.81	23.11	0	0.63	32	0.15	5.18	0.27%	0.04%	20.491	0.195
97	27	2	7_D2	19.05	1.37	19.81	20.57	0.07	0.66	29	0.1	4.86	0.23%	0.03%	20.247	0.387
98	27	3	7_D3	19.05	5.18	19.81	17.53	0.26	0.63	26	0.08	4.89	0.22%	0.02%	20.953	0.098
99	27	4	7_D4	19.05	10.36	19.81	13.72	0.52	0.55	21	0.06	5.61	0.28%	0.02%	20.709	0.133
100	27	5	7_D5	19.05	15.70	19.81	11.18	0.79	0.49	14	0.14	6.21	0.28%	0.02%	21.015	0.086

CHNS Data on Crown section samples

Tree	Section	DBH	Height	TTH	DBT	N [%]	C [%]	H [%]	S [%]	O [%]	HHV	Boie	Dulong
3	1	19.05	12.16	18.51	10.54	0.01	50.05	6.79	0.00	43.16	20.870	20.703	18.941
4	1	11.43	8.07	11.27	10.54	0.12	50.73	6.76	0.00	42.39	20.770	20.999	19.265
5	1	16.51	11.79	14.28	6.99	0.10	49.60	6.68	0.00	43.62	20.563	20.374	18.549
6	1	16.51	10.53	15.44	10.54	0.01	49.85	6.71	0.00	43.44	20.574	20.504	18.701
7	1	16.51	14.67	16.84	5.72	0.10	49.51	6.75	0.00	43.64	20.654	20.420	18.614
8	1	19.05	11.91	17.66	10.54	0.01	49.26	6.81	0.00	43.93	20.733	20.357	18.556
11	1	16.51	12.64	16.29	9.78	0.07	48.81	6.61	0.00	44.51	20.767	19.911	18.016
12	1	11.43	11.95	14.01	4.95	0.09	48.52	6.52	0.00	44.88	20.903	19.667	17.726
13	1	13.97	12.16	15.77	6.10	0.03	49.56	6.72	0.00	43.70	21.448	20.385	18.570
14	1	13.97	12.94	17.05	8.51	0.00	48.28	6.65	0.00	45.07	20.933	19.700	17.788
15	1	11.43	10.75	14.22	7.24	0.02	49.19	6.66	0.00	44.13	20.624	20.149	18.295
17	1	13.97	7.50	12.18	9.65	0.08	48.67	6.61	0.00	44.64	20.841	19.849	17.947
18	1	16.51	9.77	12.79	10.54	0.12	49.99	6.62	0.00	43.27	20.543	20.482	18.659
21	1	19.05	13.64	17.30	7.24	0.00	47.54	6.53	0.00	45.93	20.674	19.217	17.225
22	1	19.05	12.06	18.27	10.03	0.01	47.53	6.56	0.00	45.90	20.798	19.240	17.255
23	1	13.97	10.43	13.40	8.00	0.12	49.00	6.61	0.00	44.28	20.989	20.001	18.117
24	1	11.43	7.64	10.66	7.87	0.05	47.82	6.55	0.00	45.58	21.614	19.376	17.406
25	1	13.97	9.55	15.38	9.02	0.01	47.82	6.58	0.00	45.59	20.240	19.410	17.451
26	1	11.43	11.23	16.14	8.00	0.00	48.04	6.54	0.00	45.42	22.535	19.451	17.488
27	1	19.05	16.71	19.79	9.02	0.12	50.20	6.57	0.00	43.10	20.491	20.515	18.686
3	2	19.05	14.28	18.51	7.90	0.03	50.31	6.89	0.00	42.78	20.875	20.950	19.237
4	2	11.43	9.14	11.27	7.90	0.01	51.58	6.89	0.00	41.53	20.881	21.535	19.892
5	2	16.51	12.62	14.28	5.23	0.17	49.26	6.70	0.00	43.88	20.827	20.246	18.408
6	2	16.51	12.16	15.44	7.90	0.03	49.29	6.70	0.00	43.98	20.456	20.242	18.406
7	2	16.51	15.39	16.84	4.29	0.16	49.20	6.78	0.00	43.87	20.539	20.319	18.506

Tree	Section	DBH	Height	TTH	DBT	N [%]	C [%]	H [%]	S [%]	O [%]	HHV	Boie	Dulong
8	2	19.05	13.82	17.66	7.90	0.07	49.20	6.70	0.00	44.03	20.621	20.204	18.362
11	2	16.51	13.85	16.29	7.34	0.21	48.68	6.63	0.00	44.49	20.988	19.898	18.004
12	2	11.43	12.64	14.01	3.71	0.20	49.49	6.70	0.00	43.61	20.827	20.367	18.545
13	2	13.97	13.37	15.77	4.57	0.08	48.72	6.66	0.00	44.55	20.950	19.933	18.051
14	2	13.97	14.31	17.05	6.38	0.08	48.53	6.64	0.00	44.75	20.889	19.822	17.923
15	2	11.43	11.91	14.22	5.44	0.05	48.75	6.63	0.00	44.57	20.976	19.904	18.013
17	2	13.97	9.06	12.18	7.24	0.02	48.24	6.61	0.00	45.14	20.748	19.639	17.713
18	2	16.51	10.78	12.79	7.90	0.12	47.44	6.52	0.00	45.92	20.471	19.171	17.168
21	2	19.05	14.86	17.30	5.44	0.07	48.10	6.56	0.00	45.27	20.711	19.523	17.572
22	2	19.05	14.13	18.27	7.52	0.09	50.40	6.71	0.00	42.81	21.190	20.774	19.003
23	2	13.97	11.42	13.40	5.99	0.01	47.39	6.45	0.00	46.16	20.727	19.041	17.011
24	2	11.43	8.65	10.66	5.92	0.13	47.54	6.51	0.00	45.82	21.002	19.210	17.210
25	2	13.97	11.49	15.38	6.76	0.11	47.78	6.53	0.00	45.59	20.388	19.334	17.353
26	2	11.43	12.87	16.14	5.99	0.07	47.82	6.53	0.00	45.59	20.831	19.345	17.366
27	2	19.05	17.74	19.79	6.76	0.18	44.55	6.16	0.00	49.11	20.247	17.391	15.103
3	3	19.05	16.40	18.51	5.28	0.10	47.71	6.50	0.00	45.69	20.928	19.271	17.278
4	3	11.43	10.20	11.27	5.28	0.06	48.45	6.50	0.00	45.00	21.089	19.597	17.642
5	3	16.51	13.45	14.28	3.51	0.21	48.00	6.49	0.00	45.30	21.000	19.409	17.429
6	3	16.51	13.80	15.44	5.28	0.06	48.19	6.48	0.00	45.28	20.781	19.452	17.476
7	3	16.51	16.12	16.84	2.87	0.13	49.48	6.55	0.00	43.84	20.459	20.159	18.283
8	3	19.05	15.74	17.66	5.28	0.07	47.80	6.49	0.00	45.65	20.538	19.286	17.292
11	3	16.51	15.07	16.29	4.90	0.29	50.24	6.71	0.00	42.77	20.361	20.734	18.956
12	3	11.43	13.32	14.01	2.49	0.33	49.95	6.71	0.00	43.01	20.601	20.612	18.818
13	3	13.97	14.57	15.77	3.05	0.29	50.05	6.76	0.00	42.91	20.714	20.714	18.943
14	3	13.97	15.68	17.05	4.27	0.31	49.50	6.67	0.00	43.52	20.761	20.355	18.524
15	3	11.43	13.06	14.22	3.63	0.10	49.46	6.62	0.00	43.83	20.611	20.226	18.371
17	3	13.97	10.62	12.18	4.83	0.20	48.72	6.46	0.00	44.62	20.772	19.700	17.749
18	3	16.51	11.78	12.79	5.28	0.31	48.89	6.60	0.00	44.21	20.232	19.971	18.078
21	3	19.05	16.08	17.30	3.63	0.23	49.35	6.59	0.00	43.84	20.536	20.162	18.292

Tree	Section	DBH	Height	TTH	DBT	N [%]	C [%]	H [%]	S [%]	O [%]	HHV	Boie	Dulong
22	3	19.05	16.20	18.27	5.03	0.16	49.85	6.77	0.00	43.23	20.848	20.607	18.827
23	3	13.97	12.41	13.40	4.01	0.14	49.23	6.61	0.00	44.03	20.431	20.114	18.244
24	3	11.43	9.65	10.66	3.94	0.14	48.36	6.49	0.00	45.01	20.927	19.567	17.607
25	3	13.97	13.44	15.38	4.52	0.08	48.31	6.52	0.00	45.10	20.290	19.565	17.611
26	3	11.43	14.50	16.14	4.01	0.13	48.75	6.51	0.00	44.62	20.554	19.759	17.825
27	3	19.05	18.76	19.79	4.52	0.28	45.26	6.20	0.00	48.26	20.953	17.788	15.555
3	4	19.05	18.51	18.51	2.64	0.09	50.69	6.68	0.09	42.45	21.012	20.896	19.139
4	4	11.43	11.27	11.27	2.64	0.28	50.50	6.75	0.09	42.40	21.737	20.922	19.177
5	4	16.51	14.28	14.28	1.75	0.34	49.72	6.74	0.04	43.17	20.885	20.554	18.761
6	4	16.51	15.44	15.44	2.64	0.12	49.44	6.70	0.03	43.72	20.665	20.327	18.501
7	4	16.51	16.84	16.84	1.42	0.24	49.69	6.69	0.02	43.37	20.722	20.454	18.639
8	4	19.05	17.66	17.66	2.64	0.26	49.16	6.71	0.01	43.86	20.623	20.239	18.402
11	4	16.51	16.29	16.29	2.44	0.48	48.95	6.71	0.01	43.85	20.391	20.176	18.328
12	4	11.43	14.01	14.01	1.24	0.58	49.27	6.73	0.02	43.40	20.720	20.367	18.544
13	4	13.97	15.77	15.77	1.52	0.44	49.36	6.81	0.01	43.40	20.756	20.480	18.688
14	4	13.97	17.05	17.05	2.13	0.68	49.69	6.84	0.01	42.79	20.835	20.714	18.952
15	4	11.43	14.22	14.22	1.80	0.19	49.64	6.77	0.02	43.39	20.692	20.528	18.740
17	4	13.97	12.18	12.18	2.41	0.45	48.86	6.69	0.00	44.00	20.657	20.104	18.243
18	4	16.51	12.79	12.79	2.64	0.61	49.55	6.75	0.00	43.10	20.308	20.524	18.724
21	4	19.05	17.30	17.30	1.80	0.18	49.38	6.74	0.00	43.71	20.690	20.352	18.534
22	4	19.05	18.27	18.27	2.51	0.22	48.72	6.75	0.00	44.31	20.631	20.081	18.233
23	4	13.97	13.40	13.40	2.01	0.27	49.09	6.70	0.00	43.95	21.226	20.191	18.346
24	4	11.43	10.66	10.66	1.98	0.42	49.19	6.70	0.00	43.70	20.718	20.260	18.420
25	4	13.97	15.38	15.38	2.26	0.27	48.26	6.63	0.01	44.84	20.722	19.716	17.800
26	4	11.43	16.14	16.14	2.01	0.22	49.37	6.71	0.00	43.71	20.592	20.316	18.487
27	4	19.05	19.79	19.79	2.26	0.40	44.66	6.18	0.00	48.76	20.709	17.508	15.234

CHNS Data on Randomly Selected Stemwood samples

Tree	Disc	N	C	H	S	O	HHV	Boie	Dulong
3	2	0.00	44.69	6.23	0.00	49.08	20.88	17.51	15.25
3	3	0.00	44.84	6.21	0.00	48.96	20.93	17.55	15.29
3	5	0.00	44.89	6.18	0.00	48.93	20.99	17.54	15.28
4	5	0.02	44.35	6.10	0.00	49.55	21.03	17.18	14.86
4	2	0.03	45.63	6.10	0.00	48.24	20.88	17.79	15.54
4	4	0.00	45.91	6.31	0.00	47.78	21.74	18.18	16.01
5	4	0.01	45.02	6.25	0.00	48.72	20.89	17.69	15.46
7	2	0.00	44.74	6.24	0.00	49.03	20.54	17.54	15.28
7	3	0.16	45.33	6.17	0.00	48.35	20.46	17.75	15.51
8	3	0.00	44.76	6.21	0.00	49.04	20.54	17.51	15.25
12	1	0.01	45.02	6.27	0.00	48.71	20.90	17.71	15.49
12	2	0.02	49.84	6.77	0.00	43.38	20.83	20.58	18.80
13	1	0.00	45.28	6.30	0.00	48.43	21.45	17.87	15.66
14	4	0.00	45.32	6.28	0.00	48.41	20.84	17.86	15.65
17	4	0.01	44.84	6.19	0.00	48.96	20.66	17.53	15.27
17	1	0.01	45.13	6.26	0.00	48.61	20.84	17.75	15.52
18	3	0.00	44.56	6.20	0.00	49.24	20.23	17.42	15.14
18	4	0.00	44.57	6.20	0.00	49.23	20.31	17.42	15.14
18	5	0.08	53.04	7.87	0.00	39.01	23.28	23.48	22.26
21	2	0.00	44.82	6.25	0.00	48.94	20.71	17.59	15.34
21	3	0.00	44.34	6.13	0.00	49.53	20.54	17.22	14.90
23	4	0.01	45.88	6.34	0.00	47.78	21.23	18.20	16.05
24	4	0.00	44.44	6.21	0.00	49.36	20.72	17.36	15.08
24	1	0.04	50.57	6.75	0.00	42.64	21.61	20.90	19.16
25	1	0.00	45.02	6.32	0.00	48.67	20.24	17.78	15.57
25	3	0.16	50.25	6.88	0.00	42.72	20.29	20.93	19.21
26	1	0.03	51.73	7.77	0.00	40.48	22.54	22.73	21.41

Tree	Disc	N	C	H	S	O	HHV	Boie	Dulong
26	3	0.19	51.42	6.89	0.00	41.51	20.55	21.49	19.84
27	2	0.00	44.55	6.21	0.00	49.24	20.25	17.42	15.15
27	3	0.00	45.10	6.22	0.00	48.69	20.95	17.68	15.44