ABSTRACT

ASHLEY, ELISSA MARIE. Assessing Aboveground Biomass Productivity of American Sycamore Grown as a Short Rotation Coppice for Bioenergy. (Under the direction of Dr. John S. King and Dr. William E. Winner).

With the current climate of energy uncertainty it is imperative that the potential utilization of renewable energy resources be investigated. Ethanol-based biofuels divert from food stocks and are energy intensive to cultivate. Biofuel derived from short rotation coppice species provide a unique opportunity to meet rising energy needs. It is hoped that many of the species currently being considered as bioenergy resources may confer many ecosystem services. Compared to agricultural crops, they are more tolerant of variation in climate, compatible with existing managed and natural uses, and they have higher inherent resource use efficienciecs (King et al. 2013).

American sycamore *(Platanus occidentalis)* is a fast growing and long-lived hardwood tree. It is favored as a shade tree and is resilient to pollution and saline soils, it has previously been used to prevent soil erosion and provide phytoremediation to strip mine sites (Brinks et al.,2011; Davis and Trettin. 2006). While sycamore has been shown to outcompete black locust, cottonwood and sweetgum (Brinks et al.,2011; Davis and Trettin. 2006.; Coyle and Coleman 2005), not much is known about the sustainability of this species. Current projections of increasing drought severity in the southeastern United States (King et al. 2013) highlight the need to study bioenergy systems productivity and sustainability. The current study examined the effects of planting density and simulated drought on aboveground biomass productivity of American sycamore grown as a low-input short rotation coppice culture for four years in Butner, North Carolina. A destructive harvest of a subset of trees

was used to develop allometric regression equations to predict aboveground biomass and partitioning. Harvested trees were also used to determine wood density and energy content.

Energy content and growth efficiency of the wood were not impacted by the planting density, or water reduction treatments, but biomass production, leaf area index, and wood density produced from the trees were significantly affected by the treatments. The highest planting density plot resulted in largest amount of total tree biomass produced, 23.16 Mg ha^{-1}, the greatest leaf area index 11.86 m^2 m^2, and the smallest wood density 598.24 kg m^{-3}. The lowest planting density plot resulted in the smallest amount of total tree biomass produced 8.44 Mg ha^{-1}, the smallest leaf area index 4.36 m^2 m^2, and greatest wood density 684.98 kg m^{-3}. Energy content remained equal at all planting densities. In this low input, marginal land system, American sycamore aboveground productivity has been shown to be capable of being an integral part of securing our energy future.

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Assessing Aboveground Biomass Productivity of American Sycamore Grown as a Short Rotation Coppice Culture for Bioenergy

by
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DEDICATION

To my Grandpa, Eugene Mecham Ashley, the rhyme and reason for my journey to North Carolina and the completion of my Masters of Science in Natural Resources: Thank you for all of the amazing opportunities and support you provided to me throughout my adolescence. It is because of the summers on the Blue Ridge and trips to our national parks that I am where I am today. I am forever grateful for the land ethic that you helped to instill within me. How funny it is that while I used to complain about all the big trees I have now spent many an hour studying them. I love you very much and I hope you have found peace and contentment among your place in the stars.

September 17th 1924- March 12th 2015

BIOGRAPHY

Elissa Marie Ashley, daughter of Charles and Donna Ashley, was born on June 23rd 1991 in Orlando, Florida. Elissa's fascination with Natural Resources began at an early age. Many a summer was spent with family camping where Elissa became a certified Junior Park Ranger in 4 National Parks. Elissa went on to complete her Bachelors of Science at the University of Central Florida. During her time at UCF Elissa was a member of the Marching Knights and Kappa Kappa Psi. Her involvement with Kappa Kappa Psi afforded her the opportunity to develop her leadership skills where she served as the Southeast District President. During these formative years of education Elissa's passion for scientific discovery was ignited. Her work was diverse and ranged from habitat restoration efficacy to identification and capture of arthropods of public health importance. Following her graduation from the University of Central Florida in 2013 Elissa began graduate school at North Carolina State University in pursuit of a Master of Science in Natural Resources.

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Energy uncertainty

Our energy future is dynamic; there are massive fluctuations in the production and consumption of fossil fuels. There is however a general consensus that there will be a dramatic decrease in fossil fuel consumption as supplies decline. Current legislation has begun to explore diversification of our renewable energy portfolio (EIA, 2013). According to the Renewable Fuel Standard located within the *Energy Independence and Security Act of 2007* (EISA) renewable fuel is any fuel that is produced from renewable resources and that is used to replace or reduce a quantity of fossil fuel. Advanced biofuels are renewable fuels other than ethanol-derived renewables, such as the biofuels that come from cellulosic woody biomass. It is perceived that renewable biomass such as planted trees and forest residues will be used to help achieve the production and utilization of 36.0 billion gallons of renewable fuel by 2022. Specifically, advanced biofuels (e.g. non-corn grain, lignocellulose based) are expected to generate 21.0 billion gallons by 2022.

Current biofuel production is focused on utilizing grain ethanol from corn and soybeans. However, it is still unknown whether these feedstocks, which compete with the global food supply, are feasible or even ethical to use for bioenergy (Pimentel and Patzek, 2005). Also, there are serious concerns about the efficiency of the ethanol derived from corn grain. Growing corn grain requires a large input of nitrogen fertilizer. The fixation of nitrogen into a usable form found in fertilizer is an energy and carbon intensive production process

(Worrell and Blok, 1994). Not only is this a carbon intensive process but also it is expensive and inefficient. 80% of the operating cost in bioenergy production is from fertilizer input (Demirbas, 2006), but this does not result in 80% more production. A reduction in the input and energy cost for feedstock will create a production system that results in more economical fuel with a larger net energy return (Johnson, et al., 2007). Fertilizers do however increase the above and belowground production of crops. Increasing the above ground production of biomass feedstocks for biofuels could provide a solution to the expected rise in CO_2 concentrations. These biomass systems have been proven to increase carbon sequestration and offset fossil fuel emissions (Ryan, et al., 2010; Lemus and Lal, 2005).

Using biomass for biofuels results in a production system that releases recently fixed carbon (CO_2), which does not result in a shift of the carbon cycle and therefore can be considered carbon neutral (Johnson, et al., 2007). While biomass and fossil fuels generate comparable amounts of carbon dioxide, fossil fuels do not regenerate and release previously stored carbon. Every time a new plant grows it sequesters the same amount of CO_2 from the atmosphere, which was put out by the utilization of that plant. Traditional fossil fuels release carbon faster than it can be incorporated into organic forms by autotrophic organisms. Fossil fuels are geologically old; biomass is new and can be managed more easily and on a shorter timescale. Because of this stark difference in temporal scale, biomass utilization for bioenergy provides a unique opportunity to create a net sink for CO_2 (Johnson, et al., 2007; Ryan, et al., 2010).

Biomass for bioenergy

Tree species grown as a feedstock for bioenergy may confer many ecosystem services. Inherently, they restore degraded land by building soil organic matter, recycling nutrients, and maintaining vegetative cover (Brinks, et al., 2011). Because they can be grown on marginal lands, this reduces the impact to food and feed production lands (Perlack, et al., 2005). To meet standards as a biofuel and to be considered a viable feedstock, this renewable resource must be economical to produce in large quantities. For it to be sustainable as a substitute for petroleum, it should be manufactured without depleting food supplies, contribute environmental benefits like the reduction of greenhouse gas emissions, and provide more energy than is used to produce it (Johnson, et al., 2007). The U.S. Department of Energy predicts that there has to be a productivity rate of 8-10 dry tons acre^{-1} year^{-1} for long-term feasibility of renewable energy production (Perlack, et al., 2005).

Short rotation coppice (SRC) of woody crops has potential to provide a sustainable supply of biofuel feedstock. SRC species are fast growing and vigorous. After harvest they re-sprout multiple stems from the stump which minimizes planting costs. Harvests occur every 2-5 years and production output remains high for 25-30 years after the first harvest (Perlack, et al., 2005).

The genera *Populus* and *Salix* have been the most widely investigated for SRC (King, et al., 2013; Fischer, et al., 2015). It has been found that within two years of converting cropland to a *Populus* SRC plantation, the system can sequester enough CO_2 to offset the original land conversion (Njakou Djomo, et al., 2013). However, *Populus* generally grows at northern latitudes and is not as widespread in the Southeast of the United States. There are no known studies to determine the level of *Populus* SRC water use and/or sustainability within this region (King, et al., 2013). In times of drought and other physiological stress, plants undergo a penalty to production (Johnson, et al., 2007). When cultivating a species for maximum productivity, as is needed for a biofuel feedstock, tolerance to environmental stress such as drought will be an important consideration (King, et al., 2013).

The United States Southeast is a predominantly rural region with a long and well-developed history of agriculture and forestry (Alvarez, 2007). The climatic conditions of this region are conducive to large-scale production of myriad of agricultural crops. Converting some of the abundant degraded and eroded cropland in this region to SRC forestry can help to stimulate local economies by utilizing an infrastructure and trained workforce already in place.

American sycamore

While hardwood species are generally considered difficult to plant on a wide scale basis (Steinbeck, et al., 1972). American sycamore has shown to be resilient with a high survival rate and resistance to herbivores (Steinbeck, et al., 1972). Sycamore, a native Southeastern species, thrives in a range of climates and site qualities. It has been well established on degraded farmlands (Coyle and Coleman, 2005) and reclaimed surface mine lands, both of which are considered highly disturbed sites (Brinks, et al., 2011). Sycamore has been shown to out-produce black locust (Brinks, et al., 2011), cottonwood (Coyle and Coleman, 2005), and sweetgum (Davis and Trettin, 2006).

It has been shown that planting at high-density results in greater productivity (Olson and Wittwer, 1980; Wittwer, et al., 1978; Steinbeck, et al., 1972). Generally, planting seedlings close together requires a larger initial economic investment. However, within the first year closely spaced sycamore trees were shown to shade out competing vegetation, decreasing the need for weed control (Steinbeck, et al., 1972). While tighter spacing does result in reduced average ground-level diameter growth, it increases stand basal area and volume production, increasing stand-level dry-mass production in young stands (Aspinwall, et al., 2011).

For sycamore to be a good candidate for short rotation coppice, it needs to be sustainable over the long term, giving large yields through multiple rotations (Davis and Trettin, 2006). Studies have shown an increased yield after the initial rotation due to the carbohydrates stored in the rootstocks of the trees (Steinbeck, et al., 1972). In a single growing season prior to the first harvest, sycamore has been shown to produce 17 Mg ha^{-1} on a degraded cropland in South Carolina with no fertilizer input (Coyle and Coleman, 2005).Research on the ecophysiology and productivity of sycamore is limited, and that which has been done was focused on suitability for the pulp and paper industry (Olson and Wittwer, 1980; Steinbeck, et al., 1972; Herrick and Brown, 1967). These studies showed that some of the quality characteristics of the wood change with planting density. Specific gravity of the stem wood increased with the wider spacing, resulting in less-dense wood for more tightly spaced trees

(Olson and Wittwer, 1980). Biofuel harvests focus on stem wood, which makes up a majority of the biomass produced (Brinks, et al., 2011). Stem bark has the highest energy content, but the caloric value decreases with age (Tuskan and De La Cruz, 1982). This suggests that short rotation coppice of sycamore could be ideal for supplying future energy demands.

When investigations began on the viability of hardwood species for utilization in biofuel production, initial researchers derived their knowledge from existing figures that vastly overestimated the potential output and efficiency of these short rotation systems (Tuskan and De La Cruz, 1982). There are no known studies that directly quantify the density of tree spacing and the effect of drought on sycamore that would be used primarily as a fuel source for bioenergy. The bulk of published literature about sycamore was done in the late seventies and early eighties for the pulp and paper industry. While they provide a picture of its considerable productivity, they did not report on the sustainability or water use of the system. Only one study was found that commented on the bioenergy potential of this species (Tuskan and De La Cruz, 1982). However, even this study did not provide anything more than a mention of American sycamore as a bioenergy crop and little subsequent work has been done, leaving severe gaps in our knowledge on this potentially pivotal bioenergy species. The current study provides an indepth analysis of the productivity potential of American sycamore, a native southeastern hardwood, utilized as a short rotation coppice species for bioenergy production on a marginal site in the Piedmont of North Carolina.

CHAPTER 2. IMPACTS OF SPACING AND DROUGHT ON ABOVEGROUND BIOMASS PRODUCTIVITY OF AMERICAN SYCAMORE.

Making the transition from extensively managed natural forests to intensively managed plantations can help to fuel the rising energy demands of the future while minimizing the land area required (Fox, 2000). SRC systems are tolerant of variation in climate (King, et al., 2013), confer ecosystem services and are compatible with existing managed and natural uses (Johnson, et al., 2007). When these low input systems are optimized it should minimize deleterious side effects to the wood characteristics necessary for bioenergy production. Previous research has made significant strides in determining the impact of wood quality as a result of increased planting density. However, the systems that were studied all had inputs of irrigation and fertilizer, or a combination of both (Brinks, et al., 2011; Davis and Trettin, 2006; Coyle and Coleman, 2005; Olson and Wittwer, 1980; Steinbeck, et al., 1972; Herrick and Brown, 1967). A better understanding of optimization, under stress conditions in a low input system, and its effects on biomass production for bioenergy are needed.

Hypothesis and objectives

In the current study, we investigated a low input sycamore plantation with no fertilization or irrigation to determine the effects of planting density and simulated drought on productivity. Bioenergy crops need to be vigorous, sustainable and compatible with the existing landscape. While there will be the initial investment to establish the plantation, short rotation coppice species minimize costs over the long term. This randomized complete block design study quantified the amount of biomass produced at various planting densities and with an imposed drought treatment to quantify what a first rotation of American sycamore can potentially yield in the Piedmont of North Carolina.

In this study the null hypothesis was that planting density and drought treatments would not have an effect aboveground biomass production, leaf area index, growth efficiency, wood density or energy content. The alternative hypothesis was that planting density and drought treatments would have an effect on the overall quanities (aboveground) and quality of biomass produced (leaf area index, growth efficiency, wood density, and energy content).

An allometric approach was used to quantifying above ground biomass. This is useful because the partitioning that exists at the scale of the individual tree can help to understand the relationships that exist at the stand level and to quantify plot level totals without simply being a function of scaling procedures (King, et al., 1999).

MATERIALS AND METHODS

Study site

The study site was located on North Carolina Agricultural Research Service land in Durham County, North Carolina (36° 7' 57.6798"N, 78° 48' 25.704"W). Elevation at this site was about 86 m above sea level (http://www.gpsvisualizer.com/elevation). Between 2010-2014 the average annual precipitation was 912 mm and average temperatures were 20.0 °C in summer, 7.8 °C in winter (National Climate Data Center, http://www1.ncdc.noaa.gov/pub/orders/cdo/477998.pdf accessed 13-Feb-2015). The soil is comprised of Creedmoor sandy loam and Altavista silt loam (fine, mixed, semiactive, thermic Aquic Hapludults (USDA NRCS Web Soil Survey, http://websoilsurvey.sc.egov.usda.gov/ accessed 2/10/2015) (Figure 1).

Experimental design and treatment description

This study was established in January of 2010 to determine the effects of planting density and water availability on stand-level aboveground biomass productivity of American sycamore (*Platanus occidentalis*) grown as a short-rotation coppice culture in the Piedmont of North Carolina. At site establishment improved bare root sycamore seedlings of Piedmont provenance, purchased from the North Carolina Forest Service Tree Seedling Store (http://nc-forestry.stores.yahoo.net/sycimpied1yr.html), were hand planted. There was a single application of glyphosate herbicide within rows. The application of glyphosate, with the addition of mowing for weed control, was repeated 3 - 4 times during the first and second growing seasons. The plots were mowed only once during the third growing season.

Planting density treatments were (1) 0.5 x 2.0m (10,000 trees ha^{-1}), (2) 1.0 x 2.0m (5,000 trees ha^{-1}), (3) 2.0 x 2.0m (2,500 trees ha^{-1}), and (4) 4.0 x 2.0m (1,250 trees ha^{-1}). Water availability treatments were (1) natural precipitation (control) and (2) water reduction. Water reduction treatments were installed during the third growing season. These treatments were composed of gutters that covered approximately 20% of the ground and intercepted natural precipitation off of the plots. Gutters were constructed below the tree canopy but elevated between 30-60 cm above the soil, to move water gravimetrically off of the plot. Gutters were placed 50cm out from the trunk of the tree on both sides leaving an aisle width of 100 cm (Figure 2). The droughted plots were surrounded by back-filled, plastic lined trenches 1 m deep to prevent lateral flow of soil water into/out of the plots, and to contain tree roots within the treatment.

The design of this short-rotation coppice study was set up in a randomized complete block design with a 4x2 factorial of planting density and drought treatments. Each combination of planting density and water treatment was assigned randomly to each replication. The three blocks consisted of eight plots (Figure 3). The design summary is:

3 blocks

4 planting density treatments

2 water reduction treatments

24 tree plots total

Planting density treatments have been maintained from the initial planting, and water availability treatments were applied since the beginning of the fourth growing season.

Measurements

Basal diameter (BD) measurements (mm), taken 10 cm above the ground line, were recorded for every tree in every plot at the initial planting (2010) and at the end of the first, second, and third growing seasons. Height (Ht) measurements (cm) were recorded at planting and at the conclusion of the first and second growing seasons. Diameter at breast height (DBH) (mm) (1.37m) was recorded for every tree at the end of the fourth growing season immediately preceding the first harvest.

Destructive sampling

At the conclusion of the fourth growing season (Jan 27- Feb 24, 2014), three to five trees were selected from each plot to be destructively harvested and later utilized to develop allometric regression equations. These trees were randomly selected from within the interior of each plot to mitigate edge effects. For every destructively measured tree, a diameter at breast height (DBH), and height (Ht) was recorded. Individual trees were separated into stem wood, dead branches and live branches. The fresh weights (kg) of all components were measured in the field. From the stem wood, three subsamples of 10 cm each were collected, representative of the top, middle, and base of the tree. Twenty to thirty 10 cm segments of dead and live branches were collected. To determine water content and calculate dry mass the subsamples from each component were dried to constant weight at 70 °C and weighed. Total dry mass (kg) of each component was calculated by multiplying the fresh weight (kg) by the subsample moisture content (%)(Aspinwall, et al., 2011).

Foliage sampling

A forest floor litter collection was done at the end of the fourth growing season. Forest floor mass was collected from a random $0.25m^2$ area from every plot in the area between the rows of trees. These samples were then dried to constant weight at 70 °C. A subsample of live leaves was collected in September 2014, the fifth growing season, from two coppiced plots and two uncoppiced plots. Special care was taken to retrieve samples from various levels of the canopy. These samples were taken to ensure that any variation in age and canopy closure would be accounted for. Leaf area was estimated using ImageJ, they were then dried to constant weight and a specific leaf area was calculated.

Wood density sampling

From the original subsamples taken from the field and dried in the lab, a 1cm segment from each middle stem wood sample was extracted. To ensure a uniform moisture content, samples were dried to constant mass at 40 °C. This was done to prevent any water absorption by the sample. A dry mass and dry volume were measured for each sample and used to calculate the wood density.

Energy content sampling

From the middle section of the stem subsamples, 0.3 - 0.7 g subsamples were extracted. These were then kept in the drying oven at 40 °C to ensure uniform moisture content and that no ambient moisture was absorbed by the samples. These subsamples were then run through an 1108 oxygen bomb calorimeter (Parr Instrument Company, Illinois) to determine the energy content of the wood. Values were measured according to DIN 51900 (Meng, et al., 2012).

Growth measurement regressions

In order to use our biomass regressions, heights of trees that had not been measured at the end of the third growing season were predicted using density treatment specific regression equations. These were developed from the measured height and basal diameter pairs from the end of the second growing season. The height and basal diameter equation followed the form Ht(cm)= m(BD(mm))+b and had an average R^2 of 0.81 with standard error of 0.03 (Table 1).

Height (Ht) and diameter at breast height (DBH) were taken for a subsample of trees at the end of the fourth growing season. DBH was recorded for every tree in every plot at the end of the fourth growing season. Heights of the trees not measured at the end of the fourth growing season were predicted using density treatment specific equations. They were developed from the Ht -DBH pair regression equations derived from end of the fourth growing season values. They followed the general form Ht (cm)= m ln(DBH (mm))+b, with an average R^2 of 0.75 with standard error of 0.09 (Table 2).

The end of the fourth growing season diameter measurements were not a basal diameter measurement, instead diameter at breast height was measured. To determine the basal diameters for the end of the fourth growing season (in order to be able to apply our biomass regressions), additional measurements were taken in spring of 2015. Original growth trees were measured for a basal diameter and diameter at breast height, and the relationship between basal diameter and diameter at breast height was derived. This equation was then applied to all of the diameter at breast height measurements taken before the harvest to determine the end of fourth growing season basal diameters. BD(mm) = 1.1888 (DBH(mm)) + 8.7885; R^2 = 0.95

Specific leaf area and leaf area index measurements

Individual leaf area from the additional September 2014 collection were measured and then dried to constant weight at 70 °C. The measured leaf area was divided by the dry weight of each leaf to derive specific leaf area ($cm^2\ g^{-1}$). A simple analysis revealed that there was not a significant difference in the age, or location of the leaf in the canopy and its associated specific leaf area (P>0.05). Specific leaf area from all samples were averaged (167.09 $cm^2\ g^{-1}$ (SE 4.69)) and used to calculate the leaf area index for each plot as the average specific leaf area multiplied by the weight of the dried forest floor samples. Leaf mass was later calculated by dividing the leaf area index for each plot by the average specific leaf area resulting in the leaf mass m^{-2}. This number was converted to leaf mass per hectare ($Mg\ ha^{-1}$) for future analysis.

Allometric regression equations to predict aboveground biomass

To predict aboveground biomass for each spacing treatment, allometric regression equations were formed. These equations were developed by regressing the natural logarithm of plant dry weight (kg: stem wood, dead branches, live branches) by the diameter at breast height for each different spacing treatment. The equations were tested for effects of diameter at breast height, tree height, planting density treatment, and water availability treatment. Allometric analysis of the dry mass data collected at the end of the fourth growing season indicated that water availability and height had no significant effect on the model parameters for predicting aboveground biomass for individual trees. These power functions with diameter at breast height as the independent variable were used to calculate individual biomass values for all trees in the treatment plots. All the of the dry plant weight component measurements were summed to the plot level (kg plot^{-1}) and converted to Mg ha^{-1}. To minimize edge effects, the outermost column and row of the 10,000 tree ha^{-1} and 5,000 trees ha^{-1} plots were removed and the conversion to Mg ha^{-1} was adjusted accordingly. These equations were later used to predict the aboveground standing biomass of the plots at the end of the first, second, and third growing seasons from their respective estimated diameter at breast height values: plant dry mass (kg)= $a + b(dbh(cm)) + c\,(dbh(cm))^2$ (Table 3)

Growth efficiency calculation

Utilizing the allometric regression equation for stem wood and derived diameter at breast height measurements for the end of the third growing season stem wood mass was calculated.

To determine growth efficiency for the fourth growing season, the last year of growth before the harvest, the stem wood plot level values (Mg ha^{-1}) and leaf area index of each plot were used. Stem wood from the end of the third growing season was subtracted from stem wood from the end of the fourth growing season; these values were then divided by their respective leaf area indices resulting in a growth efficiency value for each plot.

Wood density calculation

Stem wood subsample dry mass (g) was divided by the dry volume (cm^3), these density values were then converted to kg m^{-3}. Density values for individual samples were next run through a simple linear regression that tested for significance of planting density, water treatment, and block effects. Planting density was the only factor of statistical significance (P<0.0001). Density values were averaged across plots and spacing type.

Statistical analysis

Before conducting any analyses, all of the collected and calculated data were examined for errors and distribution via exploratory analysis. To determine the effect of the planting density treatments, and water treatment further analysis and calculations were conducted using PROC GLM (SAS/STAT software v 9.4, SAS Institute, Inc.) using a significance level of 0.05. Post-hoc analysis of treatments was conducted using Tukey-Highly Significant Difference Test corrections (SAS/STAT software v 9.4, SAS Institute, Inc.) using a significance level alpha=0.05.

Analysis of variance (ANOVA) was used to test for block, spacing, water availability and interactive effects on aboveground biomass. The linear model was:

$$Y_{ijkl} = \mu + R_i + D_j + W_k + R_iD_j + R_iW_k + D_jW_k + \varepsilon_{ijkl}$$

Where Y_{ijkl} is the observed aboveground biomass plot totals (Mg ha^{-1}) for total tree, stem wood, dead branches, live branches, leaf mass; R_i is the effect of the *i*th block (*i*= 1-3); D_j is the effect of the *j*th planting density (*j*= 0.5, 1, 2, or 4m within-row spacing); W_k is the effect of the *k*th water treatment (*k*=reduction or control); R_iD_j is the block x planting density effect; R_iW_k is the block x water treatment effect; D_jW_k is the planting density x water treatment effect; and ε_{ijkl} is the random error associated with the model and is assumed to be distributed $N(0,\sigma^2)$. When spacing effects were significant in the ANOVA Tukey's adjustment was used for comparing planting density means, block means, and block planting density interaction effects. The linear model above was also used to determine which treatment applications had a significant effect on leaf area index, growth efficiency, and wood density.

RESULTS

Growth Measurements

Height measurements revealed that through the first three growing seasons, average height for each of the spacing treatments was not significantly different. In the last growing season, differences in the average height of the different planting density treatments were evident

(Figure 4). Basal diameter measurements on average for the first two growing seasons were not significantly different. In the third and fourth growing season the 1,250 tree ha^{-1} density treatment had the largest basal diameter and the 10,000 ha^{-1} density treatment had the smallest diameters on average. (Figure 5)

Energy content

There was similar energy content for every sample. American sycamore energy content analysis for four samples , each representative of the different planting density treatments, revealed an average 19.15 MJ kg^{-1} with a standard error of 0.07.

Results for further analysis

Average specific leaf area for this site was determined to be 167.2 cm^2 g^{-1}. Leaf area index and leaf mass (Mg ha^{-1}) for each plot were calculated (Table 4). Growth efficiency and wood density based off of the stem wood biomass values were calculated for each plot (Table 4). Leaf area index increased with increased planting density. The lowest planting density (1,250 tree ha^{-1}) resulted in the smallest LAI (4.36 m^2 m^{-2} SE 1.01), closely followed by the other low planting density 2,500 tree ha^{-1} (6.22 m^2 m^{-2} SE 1.15). The two highest density treatments had the highest LAI. The 5,000 tree ha^{-1} treatment produced a LAI of 8.42 m^2 m^{-2} SE 1.04, the highest density treatments (10,000 tree ha^{-1}) had the highest LAI at 11.86 m^2 m^{-2} with a SE of 1.54. The trend for wood density was the opposite of what was seen for leaf area index. As the planting density decreased the wood density increased. The highest planting density treatment (10,000 tree ha^{-1}) had the lowest wood density (598.23 kg m^{-3} SE 1.31), followed closely by the 5,000 tree ha^{-1} with wood density of 622.94 kg m^{-3} SE 11.39. The lower planting density produced the greater wood density values (2,500 tree ha^{-1} 651.8 kg m^{-3} SE 11.24 and 1,250 tree ha^{-1} 684.98 kg m^{-3} SE 10.32). Growth efficiency values did not appear to have any trend (10,000 tree ha^{-1} GE of 1.50 SE 0.12, 5,000 tree ha^{-1} GE of 1.60 SE 0.12, 2,500 tree ha^{-1} GE of 1.35 SE 0.11, and 1,250 tree ha^{-1} GE of 1.11 SE 1.41), All of the previously listed results (Table 5) were later used in a statistical analysis to determine how planting density and water reduction impacted plot level values.

Aboveground biomass plot totals

After dry individual tree biomass values were calculated, based on diameter at breast height, all tree component biomass values (stem wood, dead branches, live branches) were summed to the plot level (kg plot^{-1}). Values were then converted to Mg ha^{-1} (Table 4).

Total tree biomass values (Mg ha^{-1}) were estimated using the biomass regression equations (Table 3). Total tree biomass increased between the second to third and third to fourth growing seasons. (Figure 6). The highest planting density (10,000 trees ha^{-1}) increased 428% between the second and third growing seasons (2.97 to 15.67 Mg ha^{-1}), and 47% (15.67 to 23.16 Mg ha^{-1}) between the third and the fourth growing seasons. The 5,000 tree ha^{-1} underwent a 463% increase in total tree biomass production (2.34 to 13.16 Mg ha^{-1}) between the second and third growing seasons and a 49% (13.16 to 19.62 Mg ha^{-1}) increase between the third and fourth growing season. The 2,500 tree ha^{-1} treatment plots experienced the highest percentage of growth between the second and third growing of 547% (1.18 to 7.63 Mg ha^{-1}) and a 61% increase between the third and fourth growing season (7.63 to 12.31 Mg ha^{-1}). The lowest density plot (1,250 tree ha^{-1}) had a moderate increase in aboveground total tree production between the second and third growing seasons with 448% (0.92 to 5.04 Mg ha^{-1}) but experienced the highest percentage increase, of all the treatments, of total tree biomass production between the third and fourth growing season of 67% (5.04 to 8.44 Mg ha^{-1})(Table 6).

Biomass Partitioning

From the average totals of every component for each planting density, the proportion of biomass was calculated. Average stem wood, dead branches, live branches and leaf mass were summed and then each component was divided by this total mass to derive the percentage value. The 10000 tree ha^{-1} treatment had about 59% biomass in stem wood. Twenty three percent of the biomass produced was leaf mass, 11% was dead branches and 7% was live branches (Figure 7). Similarly 5000 tree ha^{-1} density partitioned most biomass to stem wood, at 57%. Leaf mass comprised 21% of the total biomass, and dead and live branches each made up 11% of the plot biomass produced (Figure 8). The 2500 tree ha^{-1} plots resembled the denser spacing treatment in that the stem wood still made up a majority of the biomass proportion at 52%. The next largest allocation of biomass was to leaf mass at 23% (Figure 9). Unlike the denser planted treatments, live branches makes up a larger proportion of the biomass at 15% followed next by dead branch mass at 10% of total biomass produced. In the widest spacing treatment, 1250 tree ha^{-1}, the stem wood still made up a majority of the biomass produced but it was no longer more than half at 44%. The live branch biomass weight comprised a staggering 31% of the total biomass produced followed next by the leaf mass at 23%. Dead branches were the smallest component of the biomass produced at 2% (Figure 10).

Summary statistics

Planting density and water reduction effects on aboveground biomass production

At the end of the fourth growing season, the 10,000 tree ha^{-1} treatment produced on average the largest amount of total tree biomass (23.16 Mg ha $^{-1}$ SE 0.98), closely followed by the 5,000 tree ha^{-1} plots (19.62 Mg ha $^{-1}$ SE 1.71). The 2,500 tree ha^{-1} plot produced a substantial amount (12.32 Mg ha $^{-1}$ SE 2.70), and the smallest amount of total tree biomass was the 1,250 tree ha^{-1} plots (9.73 Mg ha $^{-1}$ SE 1.54). The 10,000 tree ha^{-1} plot also produced the largest amount of dead branches (3.25 Mg ha $^{-1}$ SE 0.14), but the smallest amount of live branches (1.87 Mg ha $^{-1}$ SE 0.07). In contrast, the 1,250 tree ha^{-1} plot produced the smallest amount of dead branches (0.22 Mg ha $^{-1}$ SE 0.06) and the largest amount of live branches (3.84 Mg ha $^{-1}$ SE 0.60) (Table 8). The application of the ANOVA indicated that the blocking as well as the planting density treatment and a block by planting density interaction each had a significant effect on total tree, stem wood, dead branches, live branches and leaf litter biomass produced (P<0.05). The application of the ANOVA also revealed that the water reduction treatment did not have a significant effect at the 95% confidence level.

Total tree biomass production

The ANOVA of total tree biomass revealed that blocking (*P*=0.0001) and planting density treatment (*P*<0.0001) were significant (Table 9). Because these effects were significant, Tukey's test for honestly significant difference was run. This test indicated that blocking did not have a significant effect (Table 18) planting density did still have a significant effect. Specifically, there was a significant difference between the total tree biomass produced between the 10,000 and 2,500 tree ha^{-1} (*P*=0.0035), 10000 and 1250 tree ha^{-1} (*P*=0.0003), as well as the 5,000 and 1,250 tree ha^{-1} (*P*=0.0026) treatments. There was not a significant difference between the amount of biomass produced between the 10,000 and 5,000 tree ha^{-1}, nor the 2,500 and 1,250 tree ha^{-1} treatments (Table 17).

Stem wood biomass production

The application of the ANOVA analyzing stem wood revealed that blocking and density treatment were significant (Table 10). Further analysis through a Tukey post-hoc comparison of means revealed blocking did not have a significant effect on stem wood biomass produced (Table 18). The planting density treatment, however, did remain a significant effect. There was a significant difference in the comparison of the 10,000 tree ha^{-1} and 2,500 and 1,250 tree ha^{-1} (*P*=0.0003, 0.0002 respectively). The 5,000 tree ha^{-1} density also significantly differed from these treatments (2,500 and 1,250 tree ha^{-1}) (P=0.0378, 0.0006 respectively). The 2,500 and 1,250 tree ha^{-1} and the 10,000 and 5,000 tree ha^{-1} treatment plots did not differ from one another (Table 17).

Dead branch biomass production

Planting density and block were both shown, through the application of the ANOVA, to have a significant effect on dead branch biomass production (Table 11). Tukey's test indicated that blocking was not significant (Table 18). The test did however reveal that there were significant differences between every planting density combination except between the 10,000 and 5,000 tree ha^{-1} planting density treatment (Table 17).

Live branch biomass production

Planting density and blocking were both shown, through application of an ANOVA, to have a significant effect on live-branch biomass production (Table 12). Tukey's test indicated, however, that planting density did not have a significant effect; none of the pairwise comparisons produced any values of significance (Table 17). Although blocking does appear to have had an impact, in that there was a significant difference between the 1st and 3rd block (Table 18).

Leaf biomass production

The original application of the ANOVA model indicated that both planting density and block had a significant effect on the leaf litter biomass produced (Table 13). Tukey's test for significant difference confirmed this analysis. There was a significant difference produced between the 1st and the 3rd block (Table 18). There was also a significant difference between the 10,000 tree ha^{-1} and 2,500 and 1,250 tree ha^{-1} treatments (P=0.0311,0.0035 respectively) (Table 17).

Additional Analysis of Variance

The model listed above was also used to test for block, planting density, and water reduction treatment effects on the leaf area index (Table 14). The ANOVA indicated that both block and planting density had a significant effect on leaf area index measurements (P<0.05). Post hoc analysis of the data through a Tukey test for honestly significant difference indicated only planting density had a significant effect. There was a significant difference between the 10,000 and 2,500 tree ha^{-1} (P=0.0311)(Table 17). After adjustments were made through the Tukey correction, blocking did not have a significant effect (Table 18). When growth efficiency was tested through the ANOVA model there was nothing to note of statistical significance (Table 15). It does not appear in our analysis, at our level of confidence, that treatments had an effect on the growth efficiency. Wood density was tested with the ANOVA and revealed that only planting density had a significant effect on the wood density produced (P<0.05)(Table 16). When planting density treatments were analyzed in the Tukey test, it was determined that there was a significant difference between the 10,000 tree ha^{-1} and 2,500 and 1,250 tree ha^{-1} treatments (*P*=0.0086,0.0002 respectively). There was also a significant difference between the 5,000 and 1,250 tree ha^{-1} (*P*=0.0024). There was not a significant difference between the other combinations (Table 17).

DISCUSSION

Biomass production in the southeastern United States through short rotation forestry of native species like American sycamore provides an opportunity to stimulate the economy by utilizing an already established infrastructure (Alvarez, 2007; Johnson, et al., 2007). However, not much is known about the water use or potential biomass accumulation resulting from the production of sycamore as a short rotation coppice culture; most previous studies focused on suitability for pulp and paper (Coyle and Coleman, 2005; Olson and Wittwer, 1980; Steinbeck, et al., 1972; Herrick and Brown, 1967).

In the low-input sycamore plantation of the current study, the null hypothesis was that planting density and water reduction treatments would not have an effect on the amount of biomass produced, leaf area index, growth efficiency, wood density, or energy content. The alternative hypothesis was that planting density would increase the aboveground biomass, leaf area index, growth efficiency, wood density and energy content. Water reduction treatments would cause a decreased in the aboveground biomass, leaf area index, growth efficiency, wood density and energy content. High-density planting regimes trigger an increase in intraspecific competition, resulting in higher inherent resource use efficiency and larger total amounts of biomass (Burkes, et al.,2003). With this in mind it was expected that the planting density treatments would have an effect and the largest amount of aboveground biomass is produced in the highest density plots. It was determined that planting density treatments *did* have an effect on aboveground biomass produced for the total tree, stem wood, dead branches, leaf mass, leaf area index, and wood density; for these results, the alternative hypothesis was supported. The work in this study has confirmed the expectations about the relationship between planting density and aboveground biomass production, but it has expanded and applied this knowledge by relating it to a rotation length relevant to the optimization of biomass for bioenergy production. However, after post-hoc analysis, the null hypothesis was supported due to planting density treatments not resulting in a significant effect on live branch mass or growth efficiency ($P > 0.05$). At the 95% confidence level, water reduction treatment did not have an effect on aboveground biomass production, leaf area index, growth efficiency or wood density.

Aboveground biomass

In the tightest planting density treatment (10,000 tree ha^{-1}) with the two main years of growth (between the second to third and third to fourth growing seasons) there was an aboveground net primary production (ANPP) of 12.68 and 7.49 Mg ha^{-1} yr^{-1} respectively. In the 5,000 tree ha^{-1} there was a smaller ANPP with 10.82 and 6.45 Mg ha^{-1} yr^{-1}. The 2,500 tree ha^{-1} experience an ANPP of 6.45 and 4.69 Mg ha^{-1} yr^{-1}. The lowest planting density treatment

(1,250 tree ha^{-1}) underwent the smallest ANPP with 4.12 and 3.40 Mg ha^{-1} yr^{-1}. In all planting density treatments the highest level of ANPP occurred between the second and third growing seasons, this all occurred before the first harvest and subsequent coppice. At a similar site, with a similar study of biomass being utilized in SRC, *Populus* produced 1.1 Mg ha^{-1} before the first coppice and 1.3 Mg ha^{-1} at one year past the harvest and subsequent coppice (Stout, et al., 2014). In native hardwood stands of deciduous forests of the southeast ANPP averaged around 9.2 Mg ha^{-1} yr^{-1} and ranged from 5.2 to 11.8 Mg ha^{-1} yr^{-1} (Bolstad, et al., 2001). Compared to other bioenergy systems like *Larix* and *Liriodendron* with 1.0 and 0.9 Mg ha^{-1} yr^{-1} respectively *Platanus* performs very well. However, even at the most productive of 12.68 Mg ha^{-1} yr^{-1}, it does not come close to *Eucalyptus* which has an ANPP of 17.5 Mg ha^{-1} yr^{-1} (King et al. 2013).

Many studies have quantified the effects of increasing planting density and its resulting increase in biomass production (Burkes, et al., 2003; Olson & Wittwer 1980; Wittwer, et al., 1978; Wood, et al., 1977; Saucier, et al., 1972;) results of the current study are consistent with that body of work. As spacing between trees gets smaller, intraspecific competition increases, resulting in changes in biomass partitioning (Burkes, et al., 2003). Considering the different components of the total aboveround biomass (stem wood, dead branches, live branches and leaf mass), partitioning differences between the planting densities was investigated. While absolute leaf mass increased with increasing stand density (Table 5), the proportion of leaf mass produced as a fraction of the total remained relatively constant for the different density treatments; each planting density resulted in about twenty three percent leaf mass (Figure 7-10). Burkes et al. (2003) and Wood et al. (1977) also quantified the relationship bewteen increasing stand density and production of foliage mass and found little change in the proportion of leaf mass produced at the different planting densities. Stem wood had a simlar response to planting density as leaf mass. However, as density of the stand increases, our results show a larger amount (proportion and absolute mass) of stem wood is produced (Table 8). Proportionally the stem wood was always majority of the biomass produced (Figure 7-10), consistent with prevous studies that found stem biomass made up a proportionate majority of the biomass produced (Brinks, et al., 2011; Davis and Trettin, 2006; Coyle and Coleman, 2005) although these studies did not quantify the effect of planting density. Values of stem wood and total aboveground biomass production were comparable to unfertilized sites found in other studies (Francis, 1984; Tuskan and De La Cruz, 1982; Krinard and Kennedy, 1981). Studies that investigate planting density also found that increased density increased stem wood production and that the stem wood made up a majority of the biomass produced, regardless of that planting density (Burkes, et al., 2003; Wood, et al., 1977; Saucier, et al., 1972).

Of the studies that investigate aboveground biomass partitioning, all of them grouped total branch weight (live and dead) together (Brinks, et al., 2011; Davis and Trettin, 2006; Coyle and Coleman, 2005; Wood, et al., 1977; Saucier, et al., 1972). Total branch weight made up about a quarter of the total above ground biomass produced regardless of spacing. This study separated out dead branches and live branches specifically because of biomass processing preferences. When the goal is to get the largest amount of merchantable wood, the differences between live and dead branch weight is consequential. Processing short rotation coppice species for bioenergy uses a silage chopper, much like in corn and other agricultural processing (McAlpine, et al., 1966). While all the aboveground biomass is going to be collected, the dead branches are likely to break off and not make it to further processing, resulting in a loss of merchantable product. There was found to be a vast difference in the proportion of dead branches in the different spacing density treatments. Dead branch biomass increased with increased density (Table 8). However, proportionally, the dead branch weight comprised 10 to 11% of the total biomass produced for the 10000, 5000, and 2500 tree ha^{-1} plots (Figure 7 - 9). At the widest spacing/least dense plot, dead branches only proprotionally made up 2%, a majority of the branch biomass was composed of live branches at 31 % of the total biomass produced. Post-hoc analysis revealed that live branch biomass was not significantly different between the different planting denisties, but was significantly different between the blocks of the field experiment; this could be the result of a differing nutient availabilities. The addition of fertilizers in the Davis and Trettin study (2006) resulted in a significant increase in branch wood produced. There was a significant difference between the amount of live branches produced in the first and third block (Table 18). The third block was noticably wetter and potentially could have had higher nutrient availabiltiy.

This study is unique in the approach to studying water use by American sycamore. While there was not a significant effect of water reduction treatment on any of the parameters studied at the 95% confidence level, there was a signficant effect at the 90% confidence level for total tree (Table 9), stem wood (Table 10), leaf mass (Table 13), and leaf area index (Table 14). Of the other studies on American sycamore, all of the ones that investigated water effects on aboveground productivity did so through irrigation (Brinks, et al., 2011; Davis and Trettin, 2006; Coyle and Coleman, 2005). However, the climatic extremes predicted for the Southeast and much of the terrestrial land surface in the coming decades are of increased drought severity (King, et al., 2013). In the current study, the precipitation reduction treatments were only in effect for a single very wet year. Occurrence of marginally significant (P~=0.1) rainfall reduction effects on sycamore biomass production suggests the potential for decreased producitivity under more severe drought conditions. Dickmann et al. (1985) found a significant decrease in biomass growth of American sycamore under drought conditions.

Leaf area index

Leaf area index is a value that characterizes the tree canopy, with higher values indicating a more dense tree canopy providing a greater surface area to absorb incoming radiation leading to enhanced productivity (Chapin, et al., 2012). Our results indicate that there was a significant difference in LAI between different density treatments (Table 14). As the density of the treatments got higher, so too did the LAI (Table 5). However, it was found in the post-hoc Tukey HSD test that only the 10,000 and 2,500 tree ha^{-1} had a significant impact on the difference in leaf area index (Table 17). The leaf area index found in this study was much higher than the only other study that measured LAI, 4.9 $m^2\ m^{-2}$ (Dickmann, et al., 1985).

Reasons for the high values could be that leaf litter samples were taken from the between the rows of trees and not the inter row. Upon further investigation during the first year following the harvest, after season four, there was a significant difference between the biomass in the row versus inter row. Leaf area index for this site may actually need to be an average of the inter row and row biomass samples. Also, leaf litter samples were not divided into separate age classes and so leaf litter mass could be an over estimation due to the collection of season three leaf litter that had not fully degraded. In young deciduous forests in the United States Southeast LAI averaged 5.8 $m^2\ m^{-2}$ with a range from 2.7 to 8.2 $m^2\ m^{-2}$ (Bolstad, et al., 2001). The highest planting density treatment had the highest LAI (11.86 $m^2\ m^{-2}$) and this is much larger than both the range and average LAI found in the Bolstad study (2001). However, the other planting density treatments and their measured average LAI exist well within the range of values found for native Southeastern deciduous forests (4.36-8.42 $m^2\ m^{-2}$). While the values found specifically for sycamore in this study are slightly higher than the average it was suggested in the Bolstad study that the indices determined could be underestimations due to a high level of disturbance and and multiple changes in species composition. Large leaf area indices are not out of the realm of possibility. American sycamore, across studies, maintained a high leaf area, this allows it to shade out weedy competition and become well established early in a rotation a great trait for a bioenergy species. It was noted through observations of field conditions that higher planting density plots, with larger leaf area indicies, had a much smaller amount of weedy biomass growth in the plots.

Growth efficiency

Growth efficiency is the ability of a tree to convert light energy into wood. It is quantified by determining the amount of stem wood produced per unit leaf area (Burkes, et al., 2003). In the context of this study, it was the amount of stem wood biomass produced during the fourth growing season by the calculated leaf area index. Interestingly, there was no significant effect of spacing density or water reduction on growth efficiency even though we documented widely differing rates of leaf area and biomass production across treatments. Other studies have found that the addition of fertilizers and higher densities increased growth efficiency of stem wood (Burkes, et al., 2003; Albaugh, et al., 1998) . Because of the uncertainty of the leaf area index values found in this study it is possible that this could account for the lack of treatment effect significance.

Wood density

In this sudy it was found that planting density treatment had a significant effect on the wood density. As the planting density decreased (larger spacing between trees) the density of the wood increased (Olson and Wittwer, 1980;Saucier, et al., 1972)(Table 5). This could be a result of increased mechanical stress from greater exposure to wind resulting in a more dense wood. Olson and Wittwer (1980) found that trees at a wider spacing, which had more available nutirents because of lower competition, produced a denser wood. Trees that were tightly packed and competing for nutrients produced a significantly less dense wood. These results suggest that more work is needed to understand the effects of planting density of SRC bioenergy systems on the sustainability of soil resources such as nutrients.

Energy content

The energy content for each treatment was comprable, and due to time limitations, only one sample from each different planting density was tested (Table 5). Tusken and De La Cruz (1982) found that at a 3 x 3m spacing there were differences in the energy content of the different components of stem wood versus stem bark. The only significant difference resulted from different ages of the wood being tested for energy content. Older trees resulted in less energy rich wood. This suggests that in addition to being an optimum biomass rotation age based on aboveground biomass yield, there is also an optimum energy yield rotation age. In our study, at the first harvest of a four year rotation stand wood had about 19.15 MJ kg^{-1} energy content. This is very comprable to that of ceullulosic ethanol based from corn and soybeans (19.9MJ kg^{-1}) and bitumonous coal which is only slightly higher (23.9 MJ kg^{-1} (Rodrigue)). Both cellulosic ethanol and coal production can be environmentally destructive. Co-firing American sycamore with other energy sources, simply utilizing it in biomass pyrolysis, or as a cellulosic feedstock for enthanol production may therefore provide opportunities to fuel rising energy demands of the 21st Century world.

CONCLUSIONS

Growing American sycamore at wider spacing resulted in larger individual trees, but also lower total aboveground biomass. When grown at close spacing it resulted in greater total aboveground biomass produced. There did appear to be a trade off on what can be considered merchantable product. The biomass produced in the 10000 and 5000 tree ha^{-1} density was comparable, except that there was a larger proportion of live branch biomass in the wider of the two spacing treatments. Planting density had minimal impact on wood quality, growth efficiency, and energy content. Since energy content of the wood changes over time, less energy dense wood in older trees, it would be interesting to compare the differences in energy content from the first harvest and the wood produced when the trees coppice before the second rotation begins.

There was no statistically significant, or visible effect on the aboveground biomass produced as a result of the water reduction treatment. Past studies of sycamore sustainability have investigated irrigation and seen the positive response on aboveground biomass. Bioenergy species should require minimal inputs (i.e. no fertilizer, irrigation, or herbicide) while still maintaining a high level of productivity. With predictions of increased drought severity and the energy uncertainty of the future it is necessary for studies that investigate the drought tolerance of bioenergy species and quantify the effects for future short rotation management.

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APPENDIX

Table 1. Regression equations used to calculate end of the third growing season height (Ht)(cm). Based on height and basal diameter (BD)(mm) measurements at the conclusion of the second growing season.
Ht(cm)= m(BD(mm))+b

Density	m	b	R^2
10000 ha^{-1}	5.10	36.54	0.76
5000 ha^{-1}	4.66	37.26	0.74
2500 ha^{-1}	4.97	23.74	0.85
1250 ha^{-1}	5.02	23.98	0.90

Table 2. Regression equations used to calculate end of the fourth growing season height (Ht)(cm). Based on height and diameter at breast height (DBH)(mm) measurements from subset of measurements trees at the conclusion of the fourth growing season.
Ht(cm)= m ln(DBH(mm))+b

Density	m	b	R^2
10000 ha^{-1}	255.98	-313.25	0.92
5000 ha^{-1}	267.71	-425.65	0.43
2500 ha^{-1}	298.50	-607.75	0.87
1250 ha^{-1}	210.01	-314.54	0.80

Table 3. Biomass regression equations used for calculating biomass at the end of the fourth growing season. Developed by regressing the natural log of the components (kg) against the diameter at breast height (DBH)(cm).
log (Component weight(kg))= log(a + b(DBH(cm)) + c(DBH(cm))^2)

Biomass component	Density	a	b	c	R^2
Stem wood	10000 ha^{-1}	-0.17	0.19	-0.01	0.96
	5000 ha^{-1}				
	2500 ha^{-1}				
	1250 ha^{-1}				
Dead branches	10000 ha^{-1}	-0.02	0.02	0.01	0 .78
	5000 ha^{-1}	-0.17	0.06		
	2500 ha^{-1}	-0.07	0.03		
	1250 ha^{-1}	0.04	-0.03		
Live branches	10000 ha^{-1}	-0.03	0.03		0.88
	5000 ha^{-1}		0.05		
	2500 ha^{-1}		0.07		
	1250 ha^{-1}		0.11		
Total tree	10000 ha^{-1}	-0.17	0.22	-0.01	0.96
	5000 ha^{-1}	-0.14			
	2500 ha^{-1}	-0.14			
	1250 ha^{-1}	-0.08			

Table 4. Plot-level leaf area index (LAI), growth efficiency, and wood density.

Density	Water Reduction	Block	Plot	LAI m^2m^{-2}	Growth Efficiency	Wood Density kg m^{-3}
10000 ha^{-1}	Control	1	8	7.87	0.76	593.48
10000 ha^{-1}	Reduced	1	34	10.97	0.47	597.99
10000 ha^{-1}	Reduced	2	4	17.69	0.38	598.08
10000 ha^{-1}	Control	2	12	15.72	0.33	598.32
10000 ha^{-1}	Control	3	20	7.49	0.77	604.39
10000 ha^{-1}	Reduced	3	24	11.43	0.45	597.24
5000 ha^{-1}	Control	1	13	4.96	0.91	625.30
5000 ha^{-1}	Reduced	1	14	7.32	0.63	627.09
5000 ha^{-1}	Control	2	14	7.24	0.48	679.92
5000 ha^{-1}	Reduced	2	27	11.53	0.44	595.39
5000 ha^{-1}	Control	3	1	12.14	0.35	604.55
5000 ha^{-1}	Reduced	3	13	7.36	0.62	605.39
2500 ha^{-1}	Control	1	18	2.74	0.49	701.29
2500 ha^{-1}	Reduced	1	19	2.86	0.22	644.56
2500 ha^{-1}	Control	2	11	6.82	0.68	640.28
2500 ha^{-1}	Reduced	2	34	6.26	0.64	617.67
2500 ha^{-1}	Reduced	3	31	7.76	0.53	672.80
2500 ha^{-1}	Control	3	33	10.88	0.37	634.21
1250 ha^{-1}	Reduced	1	22	6.34	0.26	659.46
1250 ha^{-1}	Control	1	33	1.82	1.24	660.33
1250 ha^{-1}	Control	2	2	0.53	6.11	722.67
1250 ha^{-1}	Reduced	2	13	7.58	0.23	669.87
1250 ha^{-1}	Reduced	3	19	5.33	0.63	715.35
1250 ha^{-1}	Control	3	27	4.53	0.51	682.22

Table 5. Average values and their associated standard error (SE) for leaf area index (LAI) growth efficiency, energy content, and wood density. Averaged over droughted treatments.

Density Treatment	LAI m^2m^{-2}	Growth Efficiency	Energy Content MJ kg^{-1}	Wood Density kg m^{-3}
10000 ha^{-1}	11.86 (1.54)	1.50 (0.07)	19.03	598.25 (1.31)
5000 ha^{-1}	8.42 (1.04)	1.60 (0.07)	19.38	622.94 (11.39)
2500 ha^{-1}	6.22 (1.15)	1.35 (0.06)	19.02	651.80 (11.24)
1250 ha^{-1}	4.36 (1.01)	1.11 (0.85)	19.15	684.98 (10.32)

Table 6. Aboveground net primary productivity averaged over droughted treatments.

Planting Density	2nd	3rd	4th
	Mg ha^{-1} yr^{-1}		
10000 ha^{-1}	2.98	12.69	7.49
5000 ha^{-1}	2.34	10.83	6.46
2500 ha^{-1}	1.18	6.45	4.69
1250 ha^{-1}	0.88	4.12	3.40

Table 7. Plot-level estimates of above ground biomass by tree component.

Density	Water Reduction	Block	Plot	Mg/ha				
				Total Tree	Stem Wood	Dead Branch	Live Branch	Leaf Mass
10000 ha^{-1}	Control	1	8	21.41	16.49	3.00	1.73	4.71
10000 ha^{-1}	Reduced	1	34	20.11	15.58	2.81	1.68	6.57
10000 ha^{-1}	Reduced	2	4	24.92	19.18	3.49	2.00	10.59
10000 ha^{-1}	Control	2	12	22.17	17.06	3.13	1.79	9.41
10000 ha^{-1}	Control	3	20	26.65	20.42	3.76	2.08	4.49
10000 ha^{-1}	Reduced	3	24	23.68	18.28	3.31	1.95	6.85
5000 ha^{-1}	Control	1	13	13.70	9.55	1.64	1.98	2.97
5000 ha^{-1}	Reduced	1	14	17.18	11.93	2.44	2.32	4.38
5000 ha^{-1}	Control	2	14	17.18	11.95	2.26	2.41	4.33
5000 ha^{-1}	Reduced	2	27	24.25	16.72	3.83	3.10	6.91
5000 ha^{-1}	Control	3	1	22.15	15.31	3.48	2.83	7.27
5000 ha^{-1}	Reduced	3	13	23.27	16.11	3.56	3.02	4.41
2500 ha^{-1}	Control	1	18	3.37	2.31	0.26	0.91	1.64
2500 ha^{-1}	Reduced	1	19	4.44	3.05	0.38	1.17	1.72
2500 ha^{-1}	Control	2	11	15.91	10.82	2.22	3.08	4.08
2500 ha^{-1}	Reduced	2	34	14.84	10.17	1.97	2.96	3.75
2500 ha^{-1}	Reduced	3	31	17.33	11.70	2.47	3.34	4.65
2500 ha^{-1}	Control	3	33	18.01	12.24	2.51	3.48	6.51
1250 ha^{-1}	Reduced	1	22	6.55	3.80	0.11	2.61	3.80
1250 ha^{-1}	Control	1	33	7.29	4.24	0.13	2.86	1.09
1250 ha^{-1}	Control	2	2	1.97	1.06	0.05	0.85	0.32
1250 ha^{-1}	Reduced	2	13	7.98	4.63	0.13	3.15	4.54
1250 ha^{-1}	Reduced	3	19	14.03	8.00	0.38	5.50	3.19
1250 ha^{-1}	Control	3	27	12.83	7.31	0.35	5.10	2.71

Table 8. Average values and their associated standard error (SE) for total tree, stem wood, dead branches, live branches, and leaf mass. Averaged over the drought treatment.

Density Treatment	Mg/ha				
	Total Tree	Stem Wood	Dead Branches	Live Branches	Leaf Mass
1000 ha^{-1}	23.16 (0.89)	17.83 (0.67)	3.25 (0.13)	1.87 (0.06)	7.10 (0.92)
5000 ha^{-1}	19.62 (1.56)	13.60 (1.07)	2.87 (0.33)	2.61 (0.17)	5.04 (0.63)
2500 ha^{-1}	12.32 (2.47)	8.38 (1.67)	1.63 (0.39)	2.49 (0.42)	3.72 (0.69)
1250 ha^{-1}	8.44 (1.65)	4.84 (0.94)	0.19 (0.05)	3.34 (0.64)	2.61 (0.60)

Table 9. F-tests of fixed effects of planting density and water reduction treatments on each block for Total Tree biomass (significant *P*-values indicated in bold).

Total Tree					
Source	DF	Type III SS	Mean Square	F Value	Pr>F
Block	2	256.06	128.03	57.54	**0.0001**
Density	3	809.86	269.95	121.34	**<.0001**
Water	1	10.59	10.59	4.76	0.0719
Block*Density	6	116.2	19.37	8.7	**0.0093**
Block*Water	2	17.65	8.82	3.97	0.0796
Density*Water	3	19.55	6.52	2.93	0.1217
Error	6	13.35	2.22		

Table 10. F-tests of fixed effects of planting density and water reduction treatments on each block for Stem Wood biomass (significant *P*-values indicated in bold).

Stem wood					
Source	DF	Type III SS	Mean Square	F Value	Pr>F
Block	2	113.45	56.72	61.06	**0.0001**
Density	3	588.88	196.29	211.29	**<.0001**
Water	1	4.5	5.5	4.84	0.0701
Block*Density	6	48.99	8.16	8.79	**0.0091**
Block*Water	2	8.1	4.05	4.36	0.0677
Density*Water	3	8.65	2.88	3.1	0.1106
Error	6	5.57	0.93		

Table 11. F-tests of fixed effects of planting density and water reduction treatments on each block for Dead Branch biomass (significant *P*-values indicated in bold).

Dead Branches					
Source	DF	Type III SS	Mean Square	F Value	Pr>F
Block	2	5.38	2.69	33.87	**0.0005**
Density	3	34.31	11.44	143.89	**<.0001**
Water	1	0.18	0.18	2.29	0.181
Block*Density	6	2.74	0.46	5.75	0.0257
Block*Water	2	0.28	0.14	1.8	0.2441
Density*Water	3	0.84	0.28	3.51	0.089
Error	6	0.48	0.079		

Table 12. F-tests of fixed effects of planting density and water reduction treatments on each block for Live Branch biomass (significant *P*-values indicated in bold).

Live Branches					
Source	DF	Type III SS	Mean Square	F Value	Pr>F
Block	2	9.37	4.69	22.24	**0.0017**
Density	3	6.58	2.19	10.4	**0.0086**
Water	1	0.57	0.57	2.71	0.1511
Block*Density	6	9.85	1.64	7.79	**0.0123**
Block*Water	2	0.64	0.32	1.52	0.293
Density*Water	3	0.68	0.23	1.07	0.4285
Error	6	1.26	0.21		

Table 13. F-tests of fixed effects of planting density and water reduction treatments on each block for leaf biomass (significant *P*-values indicated in bold).

Leaf Mass					
Source	DF	Type III SS	Mean Square	F Value	Pr>F
Block	2	19.99	9.99	9.06	**0.0154**
Density	3	67.17	22.39	20.3	**0.0015**
Water	1	5.83	5.83	5.29	0.0612
Block*Density	6	26.53	4.42	4.01	0.0577
Block*Water	2	6.52	3.26	2.95	0.128
Density*Water	3	9.13	3.04	2.76	0.134
Error	6	6.62	1.1		

Table 14. F-tests of fixed effects of planting density and water reduction treatments on each block for Leaf Area Index (significant *P*-values indicated in bold).

Leaf Area Index					
Source	DF	Type III SS	Mean Square	F Value	Pr>F
Block	2	55.79	27.9	9.08	**0.0153**
Density	3	187.34	62.45	20.32	**0.0015**
Water	1	16.15	16.15	5.26	0.0617
Block*Density	6	74.19	12.36	4.02	0.0572
Block*Water	2	18.17	9.08	2.96	0.1279
Density*Water	3	25.57	8.52	2.77	0.133
Error	6	18.44	3.07		

Table 15. F-tests of fixed effects of planting density and water reduction treatments on each block for Growth Efficiency (significant *P*-values indicated in bold).

Growth Efficiency					
Source	DF	Type III SS	Mean Square	F Value	Pr>F
Block	2	1.86	0.93	0.71	0.5306
Density	3	4.24	1.41	1.07	0.4298
Water	1	2.34	2.34	1.77	0.2312
Block*Density	6	6.87	1.15	0.87	0.5664
Block*Water	2	2.44	1.22	0.92	0.4466
Density*Water	3	5.28	1.76	1.33	0.3485
Error	6	7.92	1.32		

Table 16. F-tests of fixed effects of planting density and water reduction treatments on each block for Wood Density (significant *P*-values indicated in bold).

Wood Density					
Source	DF	Type III SS	Mean Square	F Value	Pr>F
Block	2	10.09	5.04	0.01	0.9914
Density	3	25175	8391.71	14.33	**0.0038**
Water	1	889.02	889.02	1.52	0.264
Block*Density	6	4950.73	825.12	1.41	0.344
Block*Water	2	3181.96	1590.98	2.72	0.1446
Density*Water	3	577.37	192.46	0.33	0.8054
Error	6	3514.47	585.74		

Table 17. Results of the ANOVA post hoc Tukey HSD test showing the interactions and statistical significance (*p*-values) between contrasting planting density treatments (10000,5000, 2500, 1250 tree ha^{-1}) for different tree components and derived values. (significant *p* values in bold)

		10000 ha^{-1}	5000 ha^{-1}	2500 ha^{-1}
Total Tree	5000 ha^{-1}	0.5640		
	2500 ha^{-1}	**0.0035**	0.0591	
	1250 ha^{-1}	**0.0003**	**0.0026**	0.4890
Stem Wood	5000 ha^{-1}	0.1125		
	2500 ha^{-1}	**0.0003**	**0.0379**	
	1250 ha^{-1}	**0.0002**	**0.0006**	0.2232
Dead Branches	5000 ha^{-1}	0.7828		
	2500 ha^{-1}	**0.0039**	**0.0305**	
	1250 ha^{-1}	**0.0002**	**0.0002**	**0.0100**
Live Branches	5000 ha^{-1}	0.6270		
	2500 ha^{-1}	0.7410	0.9974	
	1250 ha^{-1}	0.1069	0.6332	0.5170
Leaf Mass	5000 ha^{-1}	0.2828		
	2500 ha^{-1}	**0.0311**	0.6439	
	1250 ha^{-1}	**0.0035**	0.1622	0.7514
Leaf Area Index	5000 ha^{-1}	0.2828		
	2500 ha^{-1}	**0.0311**	0.6439	
	1250 ha^{-1}	**0.0035**	0.1622	0.7514
Wood Density	5000 ha^{-1}	0.3650		
	2500 ha^{-1}	0.0086	0.2393	
	1250 ha^{-1}	**0.0002**	**0.0024**	0.1458

Table 18. Results of the ANOVA post hoc Tukey HSD test showing the interactions and statistical significance (p-values) between different blocks for different tree components and derived values. (significant p values in bold)

		1	2
Total Tree	2	0.4209	
	3	0.0736	0.5559
Stem Wood	2	0.5273	
	3	0.1677	0.7132
Dead Branches	2	0.4900	
	3	0.2431	0.8798
Live Branches	2	0.5495	
	3	**0.0139**	0.1230
Leaf Mass	2	0.2040	
	3	0.3744	0.9153
Leaf Area Index	2	0.2040	
	3	0.3744	0.9153

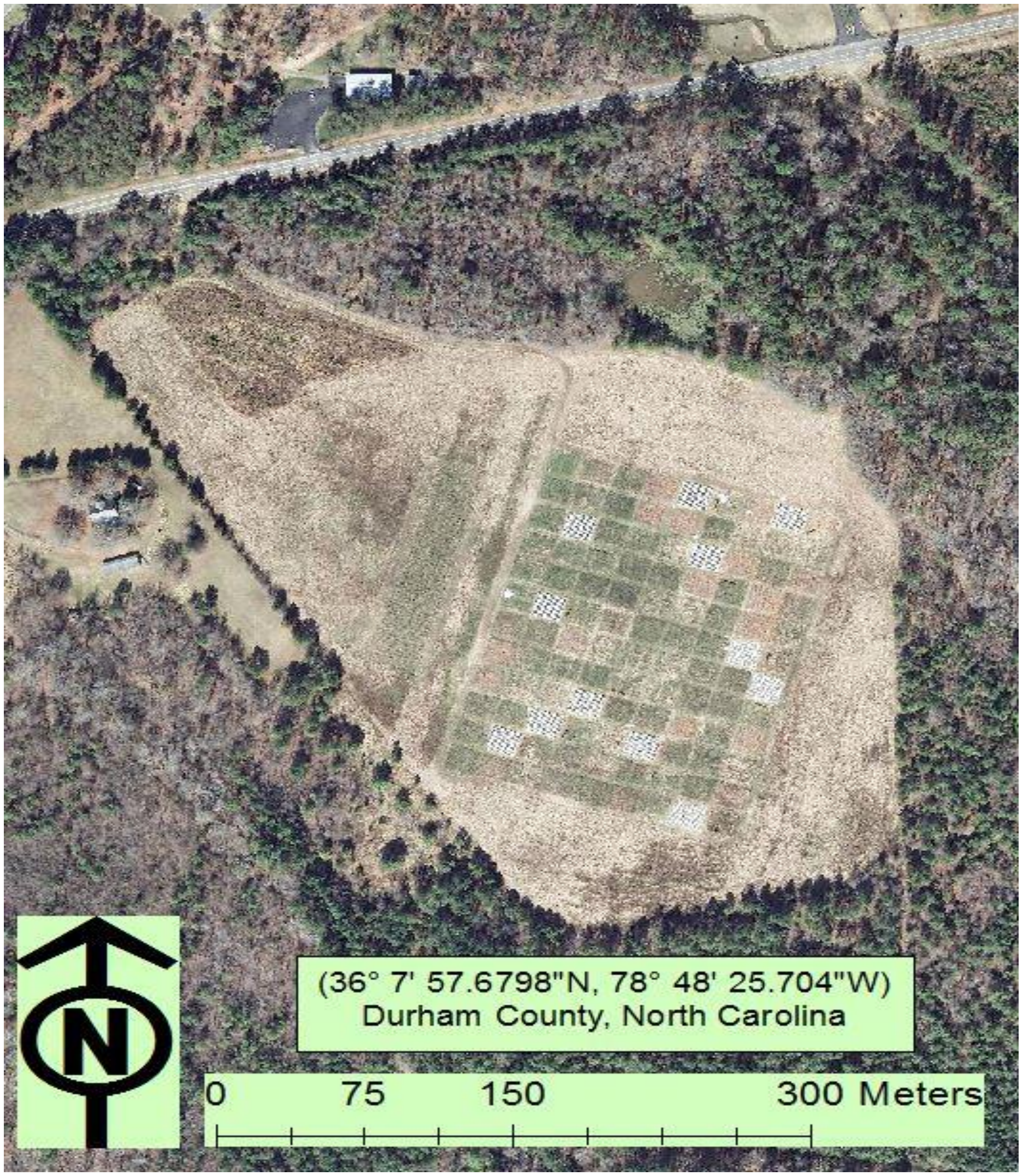

Figure 1. Aerial view of the study site from Google earth.

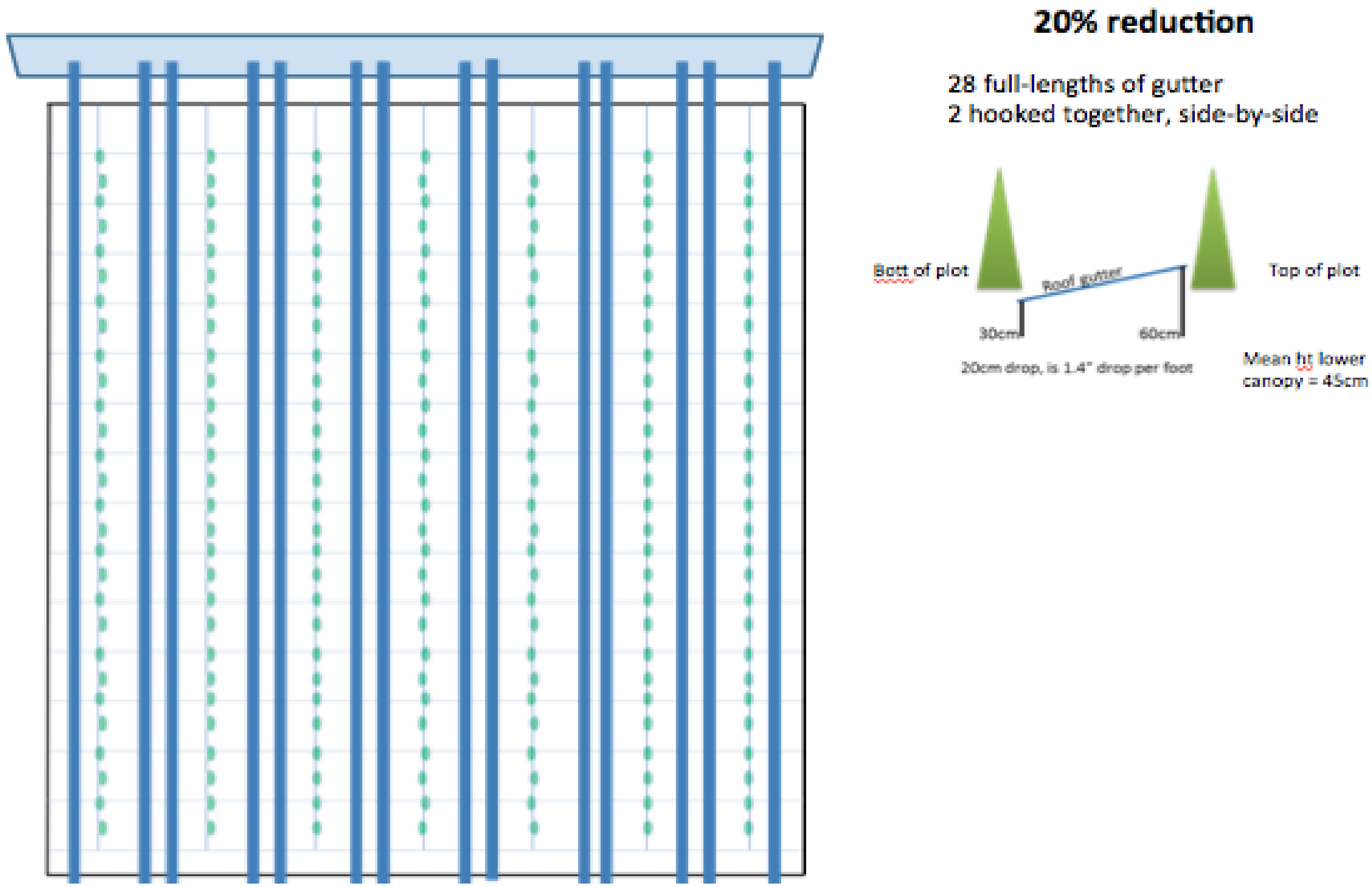

Figure 2. Schematic of gutter system put in place to impose the droughted treatment at the study site.

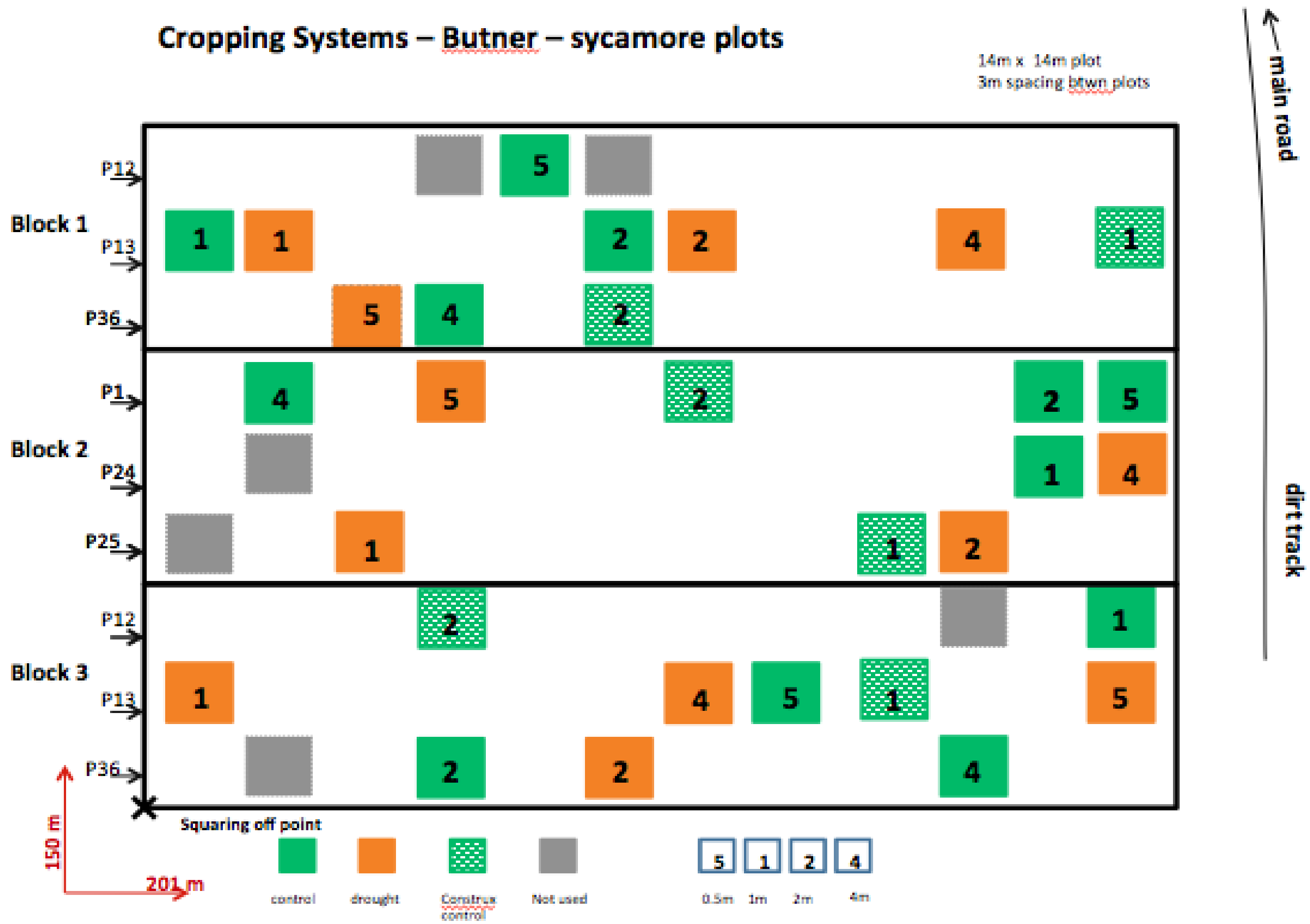

Figure 3. Randomized Complete Block Design schematic for study site

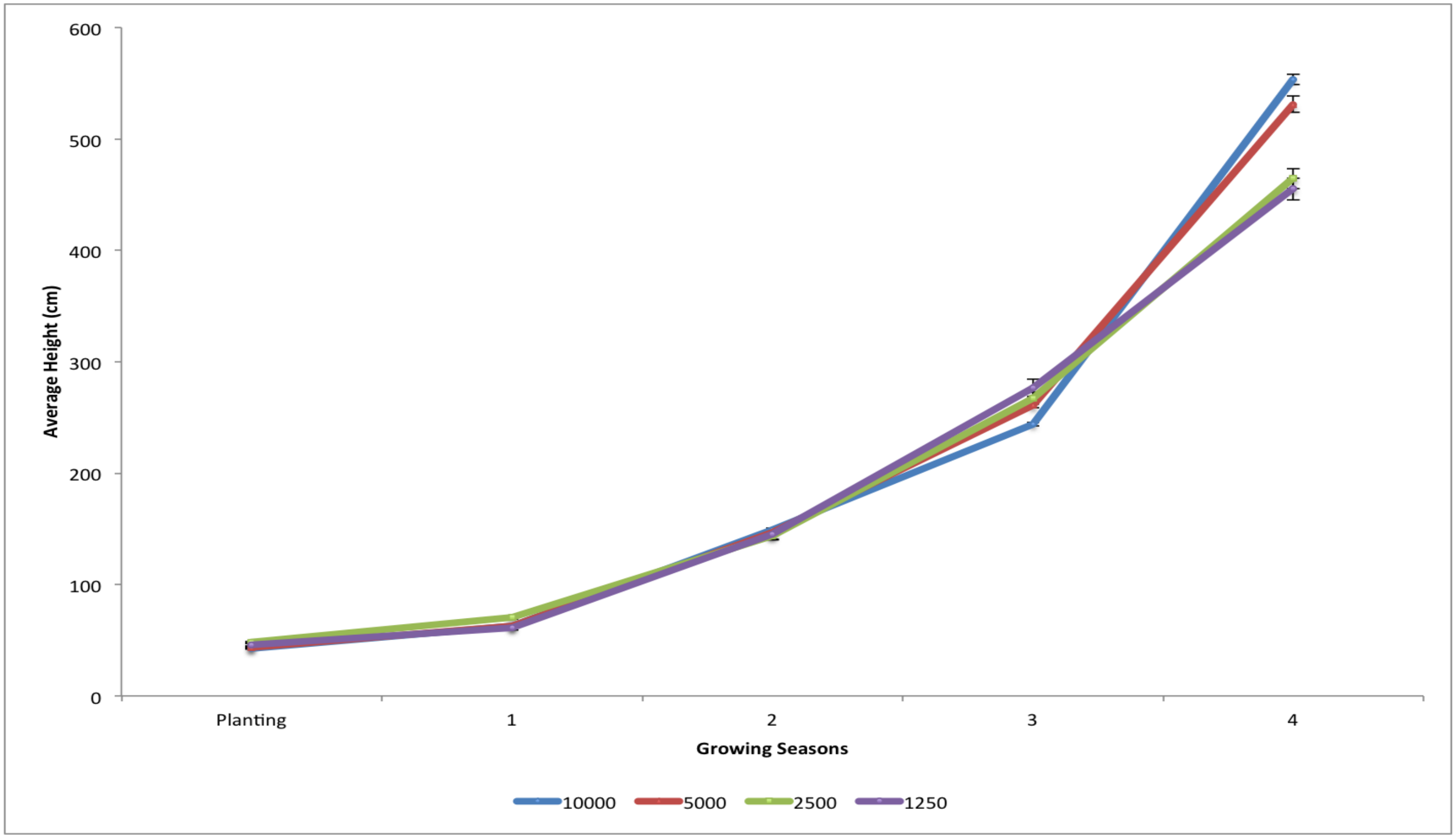

Figure 4. Average height measurements (with standard error bars) for different planting densities through out the first rotation

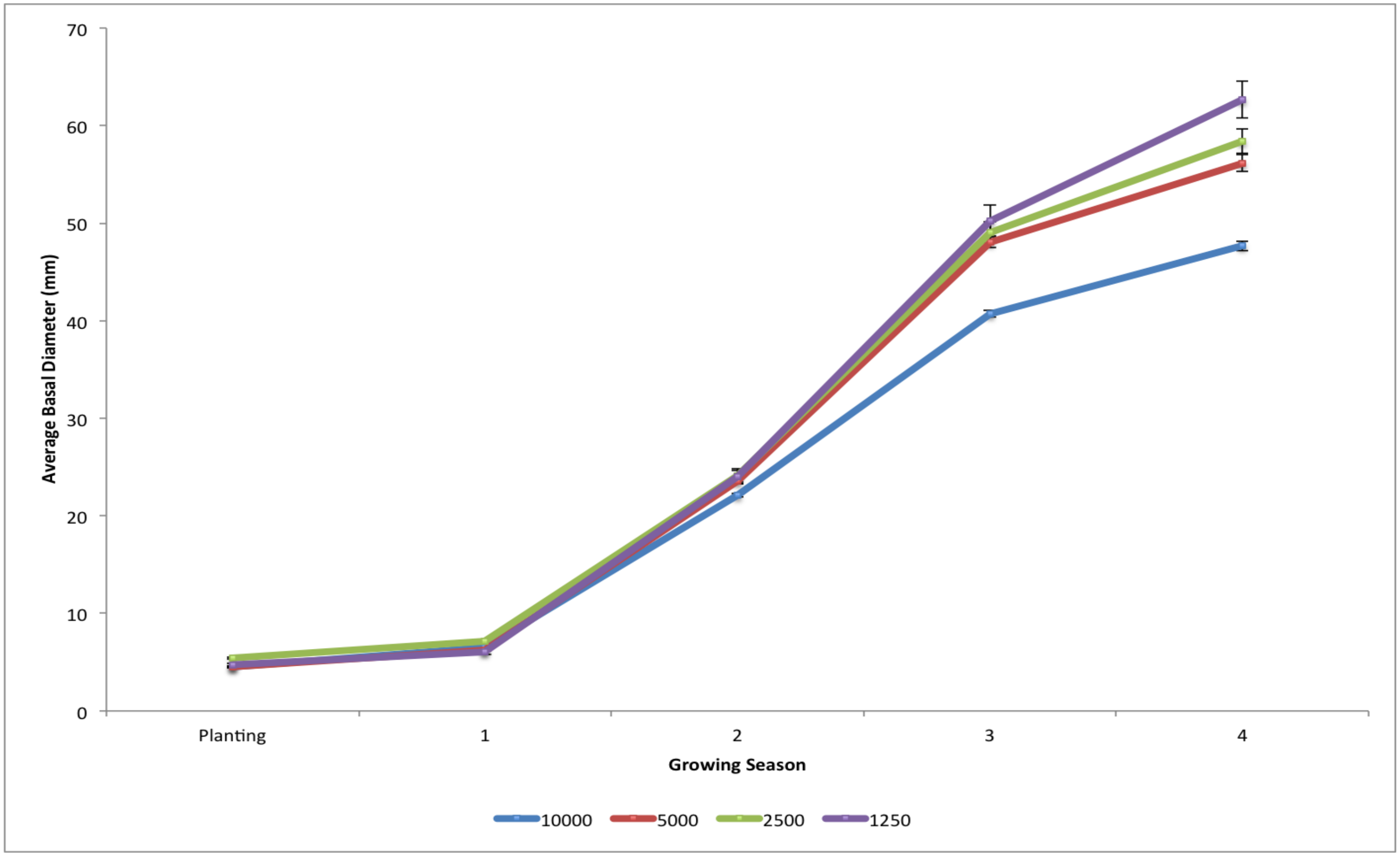

Figure 5. Average basal diameter measurements (with standard error bars) for different planting densities through out the first rotation

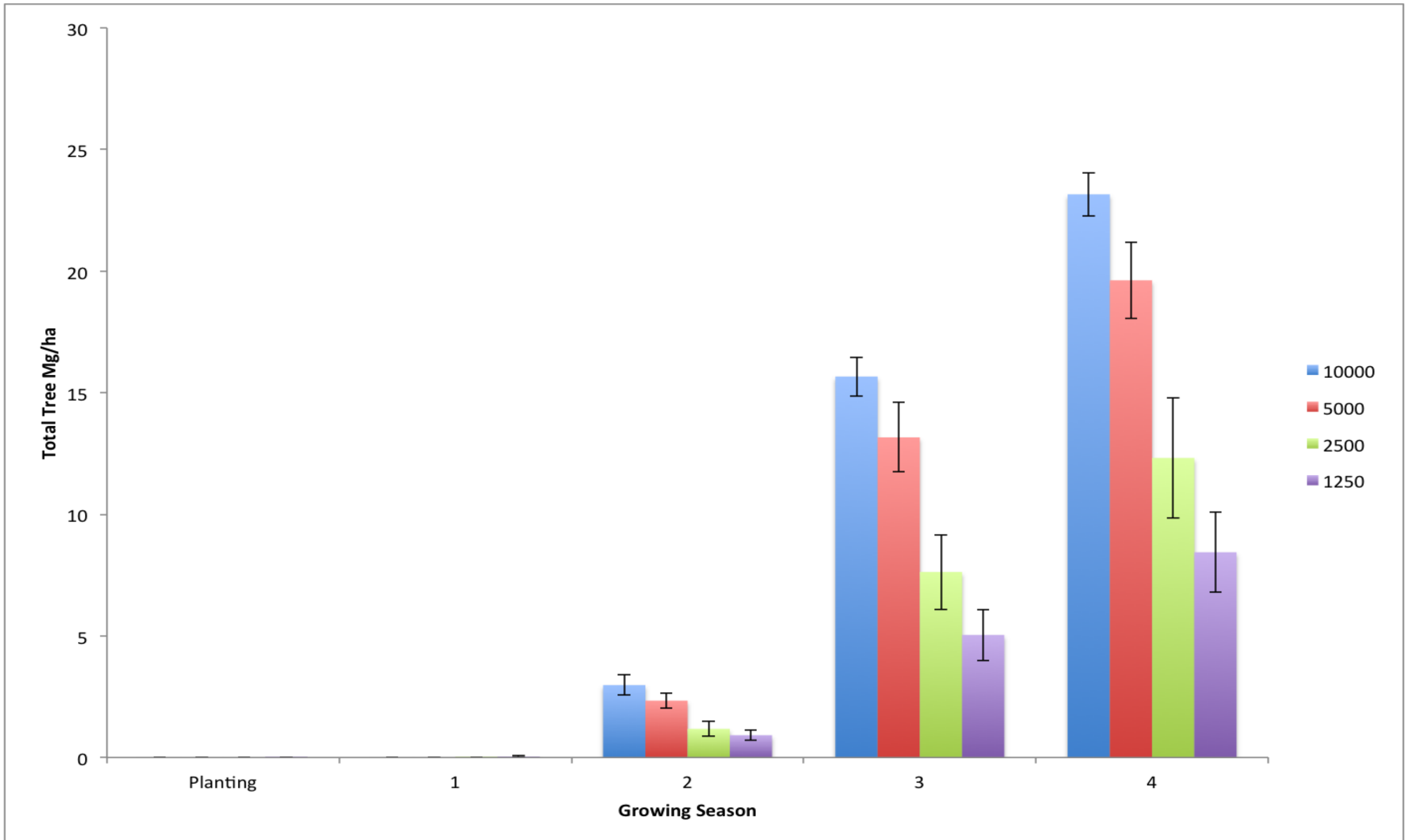

Figure 6. Average total tree biomass productivity (Mg ha^{-1} produced)(with standard error bars) at the conclusion of each growing season.

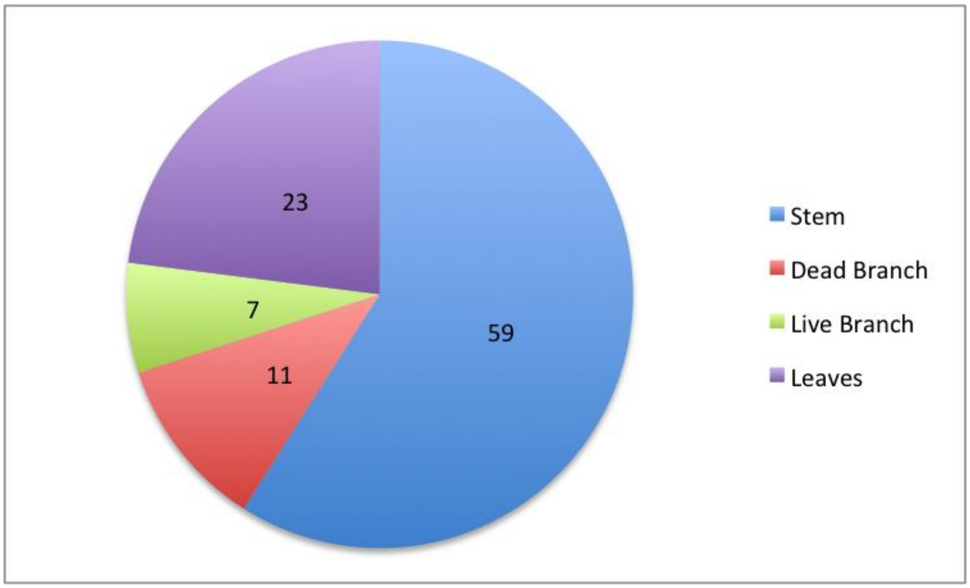

Figure 7. Biomass partitioning pie chart, each section represents the proportion of the weight that component comprises.

10000 tree ha^{-1}

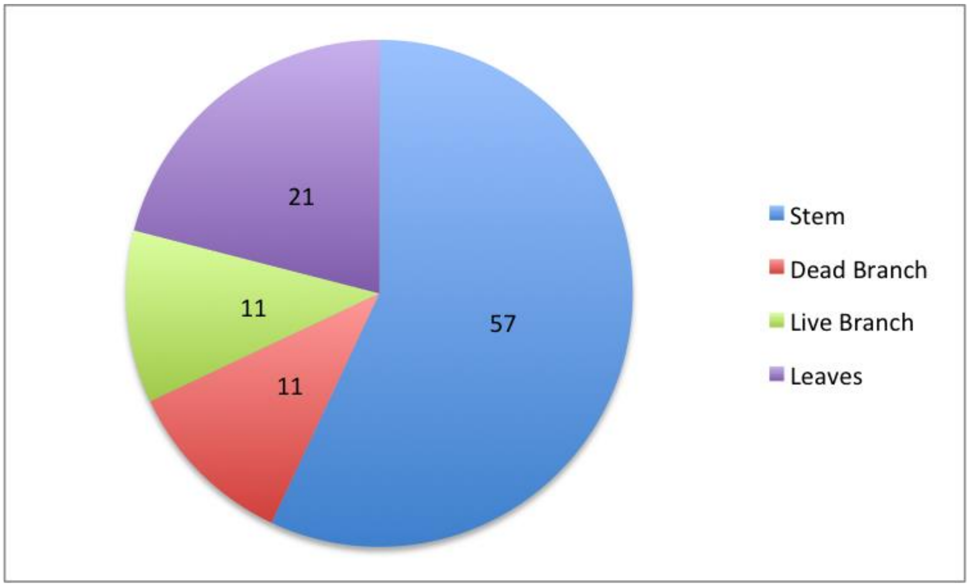

Figure 8. Biomass partitioning pie chart, each section represents the proportion of the weight that component comprises.

5000 tree ha^{-1}

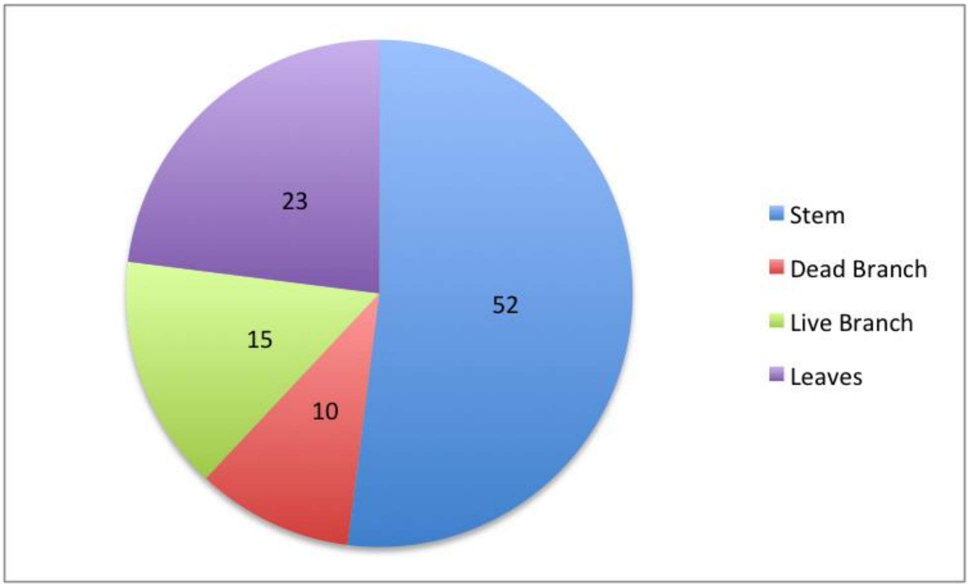

Figure 9. Biomass partitioning pie chart, each section represents the proportion of the weight that component comprises.

2500 tree ha^{-1}

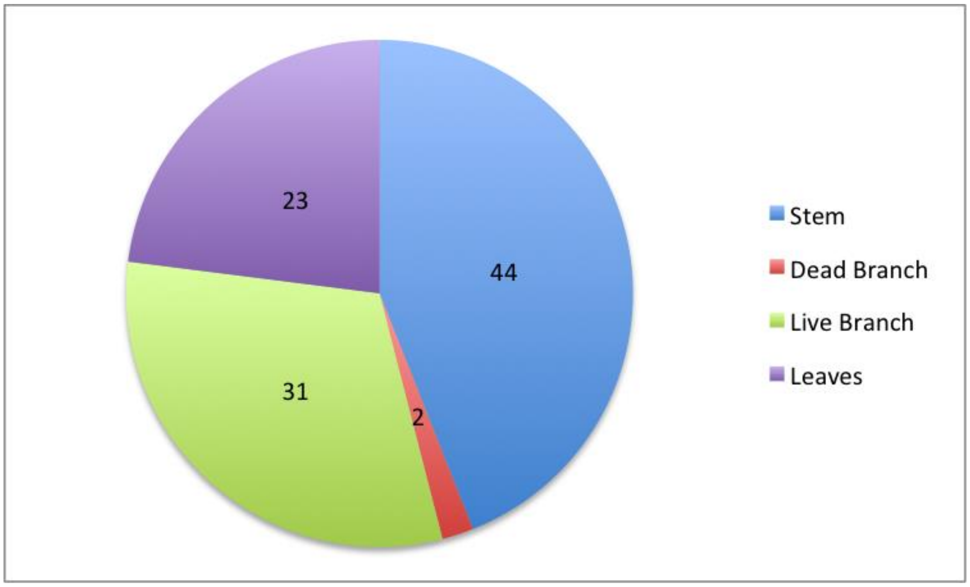

Figure 10. Biomass partitioning pie chart, each section represents the proportion of the weight that component comprises.

1250 tree ha^{-1}

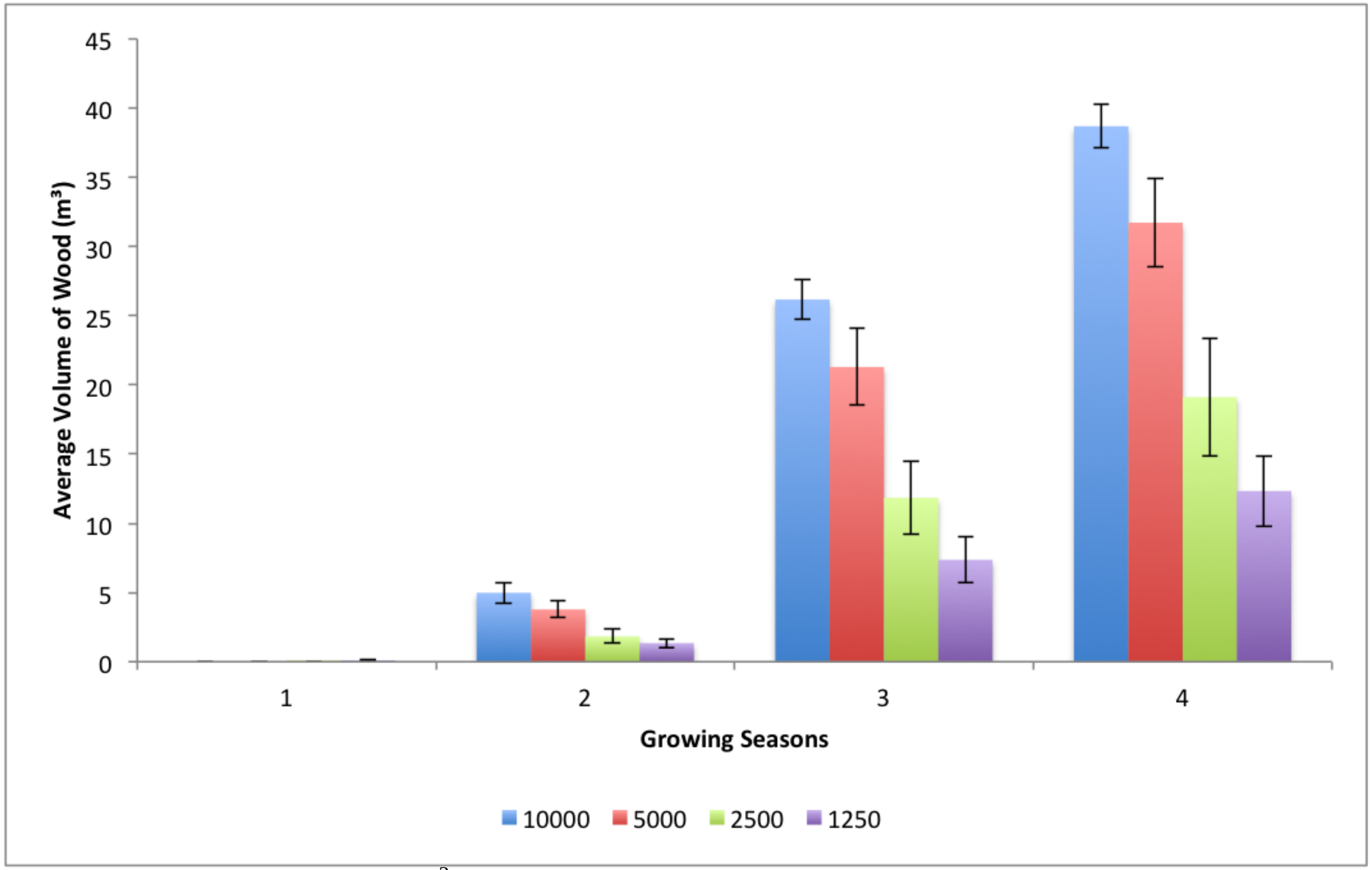

Figure 11. Average Volume of wood (m^3 produced)(with standard error bars) at the conclusion of each growing season.