ABSTRACT

BOONE, JAMESON DAVID. Productivity of Coppiced Sycamore as a Potential Short Rotation Wood-Energy Crop (SRWC). (Under the direction of Dr. John S. King).

Rising energy needs and climate change require the United States to develop sustainable, alternative solutions for energy production. Bioenergy developed from woody crops may be a partial solution (English et al. 2006). Early bioenergy research focused on corn ethanol, but there are many ethical concerns around growing a food crop for energy (Lee and Lavoie 2013). Second generation fuels produced from trees grown on low quality sites may offer a more sustainable solution. Productivity rates for woody crops of 8-10 Mg ha^{-1} yr^{-1} are needed for economic sustainability (English et al. 2006). Coppiced *Platanous occidentalis* in the upper Piedmont of North Carolina produced on average over 9 Mg ha^{-1} yr^{-1} at a high planting density of 10,000 ha^{-1}. These trees had high growth efficiencies of 1.95 Mg ha^{-1} yr^{-1} LAI^{-1} in the third growing season. The study found that coppiced sycamore produced more biomass (27.11 SE 0.75) Mg ha^{-1} after three years than the previous rotation had after four years (23.16 SE 0.89). The high productivity rates with no silvicultural inputs (fertilization, weed control, pesticides or irrigation) after coppicing show that sycamore has excellent potential as a short rotation woody crop (SRWC). Coppiced sycamore is competitive with other, more widely studied, coppiced species grown in high-density plantations for bioenergy (Dillen et al. 2013, Henderson et al. 2010).

Productivity of Coppiced Sycamore as a Potential Short Rotation Woody-Energy Crop (SRWC)

by
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BIOGRAPHY

Jameson Boone was born on December 5th, 1992 in San Jose, California to Joanne Evelyn Boone and Mark Philip Boone. At a young age, Jameson moved to Raleigh, North Carolina, which is where he would complete is primary and secondary education. Jameson enrolled at North Carolina State University in the Department of Natural Resources, which is where he would develop his interest in studying trees for management. His junior year he worked for a research lab in forestry, which would spark an interest in research. After graduating undergraduate at NC State, he would marry his highschool sweetheart Haley Boone on May 16th, 2017. After undergraduate he accepted a graduate teaching assistantship that allowed him to purse his graduate work in forestry.

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CHAPTER 1: LITERATURE REVIEW ON THE BIOMASS INDUSTRY AND SRWC SYSTEMS

Changing Energy Production

As the global CO_2 concentration in the atmosphere continues to rise, the world needs sustainable solutions to meet rising energy needs (Hanson et al. 2013). With climate change as a central topic in how the world produces energy, sustainable and carbon-neutral or carbon-negative solutions will become critical. According to the Environmental Protection Agency (EPA) the world has produced 374 billion metric tons of carbon since 1751 (Boden et al. 2015). This has increased the amount of CO_2 in the atmosphere to over 400 ppm from roughly 280 ppm before industrialization (Boden et al. 2015). This will lead to lasting damage to our planet. The production and utilization of renewable and sustainable biomass from planted trees and forest residuals provides a potential solution to the problem (Pimentel 2003).

Due to recent policy by the EU that mandates that member states create a renewable energy plan, energy produced from solid biomass is projected to nearly double to 155 terra watt hours (TWH) in 2020 from approximately 77 TWH in 2010 (Little et al. 2013). Wood pellets from North Carolina and the southern United States have increased dramatically since 2006 to fill this need in the UK, Netherlands, Belgium, and Denmark. The South will need a sustainable source for wood as this industry grows (Little et al. 2013). Realistically to provide sustainable fuel biomass plantations need to provide 8-10 Mg ha^{-1} yr^{-1} of wood (English et al., 2005).

Unlike corn grown as a biofuel, trees grown on marginal agriculture land do not compete with the food supply. Marginal agriculture land is defined as land where growing high value crops is not profitable to the farmer (Gopalakrishnan 2011). Many question the sustainability of growing corn for ethanol (Granda et al. 2007, Pimentel 2003, Mohr and Raman 2013). Corn grown for ethanol production typically requires large fertilizer and water inputs to sustain high yields. This can increase costs greatly, add carbon to the atmosphere in the fertilizer production, and can potentially reduce the water table (King et al. 2013). Unfertilized native trees are generally able to grow deep roots to access more water, thus irrigation only marginally affects growth in areas of high precipitation (Brinke et al. 2011, Davis, Trettin 2006, King et al. 2013). Corn generally has a shallow root system, whereas, trees' more productive roots allow for higher carbon input into soil through root turnover (Pimmentel 2003). One study found that sycamore grown as a SRWC had 45 percent of the total biomass as roots (Davis and Trettin 2006). Though ethanol produced from first generation crops, such as corn, are where most US ethanol fuel comes from, there is a large potential for second-generation fuels from trees in the United States and worldwide (Lee and Lavoie 2013).

First generation fuels primarily come from food crop sources that are fermented and converted to ethanol as a substitute for gasoline (Lee and Lavoie 2013). Due to high gasoline prices in the early 2000s, this became the focus of research for alternative fuels (Naik et al 2010). Due to environmental and land use concerns, however, researchers are now investigating environmentally friendly second generation fuels or so-call "lignocellulosic" fuels. This form of fuel can come from a variety of sources such as C_3 and C_4 grasses and woody crops. Woody crops typically come from either short rotation woody crops (SRWC) or most commonly in the Southeast from woody residuals (Lee and Lavoie 2013, Little et al. 2013). The ligncellulosic feedstock source is converted into bioethanol through hydrolysis and fermentation or through gasification. While in their infancy, the development of these technologies will make woody bioenergy crops more economical and sustainable.

Since much of the biomass energy in the South currently comes from forest residuals, there is some concern that as the biomass industry increases, demand will overcome the supply. This may lead to unsustainable harvesting or other unintended ecological consequences. SRWCs can provide a sustainable solution to the rising demand in the woody biomass industry. Much of the current research for bioenergy investigates trees grown in high-input systems to maximize production. SRWCs do not necessarily require heavy inputs of fertilizer and insecticide to grow productively in the Southeastern US (Fischer et al. 2017). A study of sycamore and sweetgum grown on marginal agriculture land in South Carolina showed sycamore marginally affected by irrigation in a SRWC system (Davis and Trettin 2005). Another study in the southern Appalachians showed little difference in irrigation of sycamore though significant differences occurred with fertilizer (Brinks et al. 2011).

Low input SRWC systems have shown to produce over 200 percent more energy than required to grow and transport the crop to the mill (Djomo et al. 2013). As ligncellulosic technology increases, the energy production from wood will continue to increase (Liptow 2012). Along with sequestering carbon, SRWCs provide both carbon to the soil and enhance biodiversity (Granda et al 2007, Lemus, Lal 2005). Clearly, growing trees in SRWC systems not only provide sustainable solutions to the energy crisis, but also provide biodiversity, enhancement of soil properties, and other environmental benefits of low input systems.

Biomass industry

Due to global energy initiatives, the bioenergy market has expanded in the United States and around the world (Granda et al 2007). Some of these initiatives include requirements for energy companies to have a certain percentage of their energy come from renewable resources. The United Kingdom plans to have 30 percent of their energy from renewable sources by 2030. The latter initiative has led to the development of a wood pellet industry in the US Southeast primarily in North Carolina (Little et al. 2013). Several wood mills that focus on creating wood pellets from micro-chips have been built throughout North Carolina (Little et al. 2013). To prevent land conversion driven by the biomass industry, land managers can plant dedicated bioenergy plantations on marginal lands (Berndes et al. 2003). Broadly defined, marginal lands are places where growing a commercially viable food crop is not profitable, so growing trees not only provides an income to the farmer, but also provides a needed carbon-neutral energy resource (Gopalakrishnan et al 2011). Though trees may not reach the productivity of trees grown on nutrient rich sites, marginal lands prevent competition for land usage especially for food. Growing trees on marginal lands helps prevent the environmental impact of land use change, for example, from converting mature forests in sensitive areas to tree plantations. Trees grown for bioenergy in the Southeast have shown to be productive in marginal lands, though more research is needed to find optimum management strategies, especially with minimal inputs (Davis, Trettin 2005, Wear 2010, Fisher et al. 2017).

Wood is converted to bioenergy in may ways, including burning wood directly, extracting ethanol from the wood to make so-called ligncellulosic fuel, and by gasification, making wood highly efficient to burn (Naik et al. 2010). Wood burns with relatively low emissions of sulfur dioxide and methane, making woody fuel favorable to traditional fossil fuels, such coal and natural gas (Naik et al. 2010). Burning wood directly is currently the most common use of wood for bioenergy. Wood has been used for thousands of years for heat and cooking, but more recently, wood is burned for industrial-scale energy production (Dickmann 2006). Wood can be used in combination with coal to reduce fossil CO2 emissions, thus producing positive environmental impacts in the existing power structure.

Sycamore

Sycamore (*Platanus occidentalis)* is primarily a bottomland species with a wide native range across the mid-west and eastern US (Wells and Schmidtling 2004). Sycamore is considered a pioneer species grown for a wide range of uses including furniture, pulpwood, fiberboard, and fuel uses. Sycamore can produce 19.2 KJ kg^{-1} of energy, similar to other bioenergy species including *Populus* and cellulosic-ethanol from corn and soybeans (Ashley 2015, Domec et al. 2017). The species is known as a successful plantation species and establishes easily on poor sites (Dickmann 2005). Throughout the 1970's and '80s, most research on sycamore focused on growing sycamore in high-intensity systems for quality pulp. Rotations of this previous work were longer, up to 13 years, which allowed time for an

Anthracnose disease to develop, leading to insect infestation that killed the trees (Filer 1975). Much of this worry lead to a decline in the amount of research focused on sycamore until recently. Young sycamore typically does not develop Anthracnose so much of the research today focuses on the specie grown in short rotations, under 7 years or so. Coppicing the stems could be a way to keep shoots in the juvenile stage, preventing disease as Anthracnose forms on mature trunks (Filer 1975).

Experiments have shown sycamore to have high productivity as a short-rotation crop species (SRWC) in systems that optimize biomass with fertilizer, insecticide and water inputs (Henderson et al. 2010). Sycamore grows well in marginal farmland and has a low mortality rate in the first four years in intensively grown plantations (Davis and Trettin 2006, Brinks et al. 2011, Fisher et al. 2017). The species has been shown to outgrow black locust, sweetgum, cottonwood, willow and oak in comparative studies throughout the Southeast (Brinks et al. 2011, Cobb et al. 2008, Davis and Trettin 2006, Henderson et al. 2010). Sycamore has shown a wide range of productivities depending on the site and management.

A review of a wide range of bioenergy studies throughout the Southeast show sycamore biomass production ranging from 2.4 Mg ha^{-1} yr^{-1} to 14.5 Mg ha^{-1} yr^{-1} depending site, inputs and planting density (Henderson et al. 2010). No studies in the Southeast, except the previous rotation of this study, investigate how sycamore biomass allocation and productivity, and growth efficiency is affected by drought, similar to many studies in Europe on *Populus* and *Salix* (Ashley 2015, Domec et al. 2017). Studies that investigate *Populus* response to planting density have shown either conflicting results or no correlation, depending on the site and length of the rotation. Little research has focused on growing sycamore at varying densities (Dickmann 2006, Ghezehei et al. 2016, Strong and Hansen 1993). Tighter densities are typically favored for shorter rotations while wider densities are better for plantations with longer rotations for a mix of final products. More research needs to be done to compare the effects of drought and density on production, allocation of resources and growth efficiency.

Coppice Biology

Sycamore is known to coppice well from stumps or stools after a winter harvest (Wells and Schmidtling 2004). The stored sugars in the roots of sycamore allow shoots to sprout from the stool, quickly producing a large amount of biomass (Sullivan 1994). From general field observations, the larger the stool the more shoots are produced. After the first year, the trees start to self-thin down to a few large or dominant stems with small, often dead shoots attached underneath (Dillen et al. 2013). We expect higher productivity during the second rotation, as studies of sycamore and *Populus* have shown higher biomass in trees with multiple stems (Francis 1984, Ghezehei et al. 2016). In this study, I investigated the productivity of sycamore three growing seasons after the first coppice (2014).

Though the current study only investigates *Platanous occidentalis*, it is useful to compare with other coppicing studies of *Populus* grown on marginal lands. Though many other hardwood species, such as sweetgum and oak, have the ability to coppice, there is little/no research on coppiced rotations of these species to compare to the present study. A study comparing the production from seedlings to the biomass production from the coppice stand found the coppiced stands more productive in river birch, and green ash (Stringer

1985). A study by Wittwer and Stringer (1985) showed hybrid poplar with initially higher biomass then sycamore but an inability to coppice due to high competition from weeds. Biomass yields for the current study will be compared to the previous rotation sycamore grown from seedling on the same site. On a degraded site in Belgium, *Populus* clones averaged 4.3 Mg ha^{-1} yr^{-1} with the highest clones producing 10.5 ton ha^{-1} yr^{-1} across 4 coppice rotations (Dillen et al. 2013). Average productivity of *Populus* coppice relied heavily on stool survival. This study will investigate the productivity of coppiced sycamore and compare the results to the mentioned *Populus* study.

CHAPTER 2. IMACTS OF SPACING AND DROUGT ON ABOVEGROUND BIOMASS PRODUCTIVITY OF COPPICED AMERICAN SYCAMORE

INTODUCTION

High production of fossil fuels due to rising energy needs will lead to increasing the concentration of CO_2 in the atmosphere, thus accelerating climate change (Hansen et al. 2013). One of solutions to this problem is through sustainable fuel sources such as energy produced from dedicated energy crops (English et al. 2006). Corn is currently the most produced crop for ethanol production though there are some ethical issues in growing bioenergy crops in ways that compete for food production (Naik et al 2010). As more advanced technology from so-called lignocellulosic fuel production develops, dedicated woody bioenergy plantations will become essential in providing a sustainable fuel source (English et al. 2006, Liptow 2012, Lee and Lavoie 2013). The US South and North Carolina in particular is projected to supply a significant amount of woody fuel in the future (Little et al. 2013).

For woody plantation to be sustainable, the trees will need to be grown on low productive or marginal agriculture land (Gopalakrishnan et al. 2011). Many studies show Sycamore with high productivities compared to other species on marginal agriculture land in the South (Henderson et al. 2010). Sycamore has shown higher productivities than block locust (Brinks et al. 2011), sweetgum (Cobb et al. 2008, Davis and Trettin 2006), cottonwood, and oak (Henderson et al. 2010). Much of the research focuses on Sycamore grown in high input systems but no research focuses in on the effects of planting density and drought on a low input rotation of coppiced sycamore.

Hypotheses and objectives

In this study I investigated the American sycamore coppiced four years after planting with no herbicide, fertilization or irrigation (e.g. low inputs). I investigated the effects of tree planting density and a 20 % throughfall reduction on productivity and allocation of biomass. For bioenergy crops to be sustainable, they need to produce high quality biomass with low inputs on marginal land (English et al. 2006). Minimal inputs will allow growers to decrease costs, allowing the trees to provide a revenue stream that may have not been available in the past while maximizing environmental benefits. Coppicing hardwoods further decrease costs by removing the planting at the establishment of every rotation such as with conifers. This study quantifies the productivity of coppiced sycamore in the second rotation with an imposed 20 % drought.

The null hypothesis for this study is that coppicing does not have an effect on productivity after three years. Within the coppiced rotation, the null hypothesis is that planting density and drought treatment do not affect above ground net primary production, leaf area index, growth efficiency, wood density, or weed production. The alternative hypotheses are that 1) planting density would be directly proportional to the amount of biomass produced, consistent with the previous study 2) leaf area would increase with higher planting densities though maintaining similar growth efficiencies 3) ANPP and growth efficiencies would be higher than the previous rotation due to the established root system.

METHODS AND MATERIALS

Study site

This research study site was located on North Carolina Agricultural Research Service land outside Butner, North Carolina (36° 7'58.20"N 78°48'26.49"W). The site is located in the Piedmont of North Carolina with soils consisting of an Altavista silt loam and a Creedmoor sandy loam with 2 to 6 percent slopes (websoilsurvey.usda.gov).

Thirty year averages for a nearby weather station showed the average high of 21.2^{o}C and average low of 8.8^{o}C with an average rainfall total of 122.1 cm for the year (US Climate data, http://www.usclimatedata.com/climate/durham/north-carolina/united-states/usnc0192).

The rainfall in the growing seasons of 2014-2016 (May-September) totaled 57.2 cm in 2014, 42.1 cm in 2015, and 90.6 cm in 2016. July 2016 had the highest monthly rain total of 33.8 cm (DURH weather station, http://climate.ncsu.edu/cronos?station=DURH&temporal=hourly).

Experimental design and treatments

The study was established in January, 2010, to quantify the effects of drought and spacing on the aboveground productivity and growth efficiency of *Platanus occidentalis* grown as a short rotation woody crop species. The trees were coppiced in March, 2014, to complete the first rotation. The study was set up as a 4 x 2 randomized complete block design with a through fall reduction treatment (control and 20 % throughfall reduction) and 4 levels of planting densities.

The *Platanous. occidentalis* was planted as bareroot seedlings of Piedmont half-sib families purchased from the North Carolina Forest Service Claridge Nursery, Goldsboro, NC. Upon establishment, the plots had an application of glyphosate with mowing to control weeds 3-4 times during the first and second growing seasons. The trees were planted the first time in 2009. Initially, the study was designed to compare four species as candidates to grow as SRWCs (*Liquidambar styraciflua* L., *Platanus occidentalis*, *Liriodendron tulipifera* L. and *Populus nigra L.* × *P. maximowiczii* A. Henry). Due to weather conditions, the sycamore, yellowpoplar and poplar trees experienced 75-100% mortality and the sycamore experienced almost no mortality (Ashley 2015, Domec et al. 2017). The sycamore was coppiced at 10 cm in March of 2014, beginning the second rotation, with no addition of weed control or other inputs.

The four tree planting spacings (planting densities) for the study were: 0.5 x 2.0m (10,000 ha^{-1}), 1.0 x 2.0m (5,000 ha^{-1}), 2.0 x 2.0m (2,500 ha^{-1}), and 4.0 x 2.0m (1,250 ha^{-1}). The throughfall reduction treatment was installed in 2012, consisting of natural precipitation (control) and throughfall reduction (dry). The throughfall reduction treatment composed of rain gutters that covered approximately 20% of the ground area, intercepting rainfall and moving the water off of the plots. Gutters were installed below the tree canopy, between 30 and 60 cm above the soil, placed between the rows 50 cm from the tree trunks (figure 1). The gutters drained to large corrugated pipe on the edge of the plots that carried the rainwater outside the plots. Each drought treatment plot was surrounded by a lined trench 1 meter deep to constrain lateral soil water flow and root growth.

The 4x2 completely randomized block design study consisted of:
3 blocks
4 planting densities (10,000 ha^{-1}, 5000 ha^{-1}, 2500 ha^{-1}, and 1250 ha^{-1}) within each block
2 throughfall reduction treatments per planting density (20% reduction and control)
24 plots total

Soil Water Content

Volumetric soil water content was measured 3-5 times within each plot using a Field Scout TDR 300 (Spectrum Technologies, Aurora, IL, USA) with 12 cm long soil probes in four months throughout the growing season (May, July, August, and October) (Figure 3 a-d).

Inventory Measurements

After the coppice (2014), diameter at breast height (DBH), basal diameter and height measurements were taken on 4-6 measurement trees in the center of each plot during the dormant season after the first growing season. Following the second and third growing seasons (2015 and 2016), DBH was measured on each primary shoot of each stump excluding the edge row. The edge row was removed from measurements as it could overestimate the productivity of the trees due to receiving more sun and space to grow than interior trees. On the same 4-6 measurement trees used in the previous year, the DBH and basal diameter of all the stems were measured for development of allometric biomass regressions. This allowed me to scale the biomass for the main shoots to the whole tree. Following the third growing season (2016), DBH measurements were taken of all dominant shoots, excluding the edge trees.

Allometric Measurements

For the second growing season, two individual shoots from each of the planting densities were harvested, measured and weighed (24 shoots total). Diameter at breast height (DBH), basal diameter, and height of each stem were measured. Branches were partitioned into live and dead, and weighed. This gave us an individual diameter to weight ratio. These numbers were applied to the first growing season. Equations used to calculate the dry biomass of individual stems in 2015 were:

$\text{stembio}=0.5757(\text{dbh})^{2.2942}$ $R^2=0.92$

$\text{stembio}=0.2317(\text{bd})^{2.2808}$ $R^2=0.93$

To calculate the total dry biomass for each tree in the second growing season, I used the following formula:

$y=\big(\Sigma(stembio)\big)*percentdominant^{-1}$ (Table 1)

For the third growing season, two entire trees from each plot were harvested (48 trees total), measured and weighed. The diameters of the primary stems were measured and weighed. The branches and small shoots that did not reach DBH were separated into live and dead and weighted. The diameters were converted into basal area (BA) and summed to give total BA to weight ratio. Several samples of stems and branches were dried to 70 ^{0}C and reweighed to measure the water content. The equation used to calculate total dry biomass of individual trees in 2016 were:

$y= 0.0013(\text{BA})^{1.0922}$ $R^2=0.9594$

The individual tree components were calculated from the summed basal areas (BA) of the shoots measured at DBH:

Total stem weight: $y=0.0015(\text{BA})^{1.0922}$ $R^2=0.9751$

Total live Branches: $y=0.00002(\text{BA})^{1.3088}$ $R^2=0.6649$

Total dead Branches: $y=0.00002(\text{BA})^{1.0426}$ $R^2=0.7466$.

Weed collection

Weeds from each plot were harvested inside a 0.25 m^2 square at the center of each plot. The weed biomass was then dried and weighed two times during the season. Results were scaled up the ha^{-1} basis for comparison to tree biomass.

Litterfall collection/leaf mass calculation

Litter fall was collected during the third growing season. Using baskets of 2500 cm^2, litter fall was collected, dried to 70° C and weighed. Two baskets were placed in the 1250 trees ha^{-1} spacing to account for the large variability in the plots while in the other planting densities, one basket was placed. These weights were then scaled to the ha^{-1} scale to compare with the other biomass data.

Leaf Area Index

LAI was calculated using two independent methods, litterfall and photosynthetically active radiation (PAR) with a ceptometer. To convert the litter basket weights to LAI, 50 green leaves were collected, scanned for surface area, dried to 70° C, and weighed to measure the specific leaf area (SLA). The green leaves were collected at different heights to ensure that any changes in position in the canopy (i.e. sun or shade leaves) would be accounted for. The green leaves were then scanned using the imaging software imageJ (Schneider 2012) to calculate the SA. Specific leaf area averaged 134.8 cm^2 g^{-1} with SE 2.85. The specific leaf area (cm^2 g^{-1}) was multiplied by total litterfall (g cm^{-2}) to estimate LAI (m^2 m^{-2}) (Albaugh et al. 1998).

I used a ceptometer to compare the LAI measured from absorbed radiation to the littler basket collection. The ceptometer ACCUPAR LP-80 (Decagon Devices, WA, USA) is a standard tool to estimate leaf area. The ceptometer works by comparing the full sun photosynthetically active radiation (PAR) to PAR inside the plots. The ceptometer automatically converts these measurements into LAI. The LAI from the ceptometer was estimated at maximum LAI, which happened in the middle of July. Measurements were taken between 11AM to 2PM on cloudless days. PAR outside the plots in July ranged from 1,300 to 1,700 μmols m^{-2} s^{-1}.

Growth Efficiency

Growth efficiency is defined broadly by the yield of a process per unit of resource (Binkley et al. 2004). In this case Aboveground Net Primary Production (ANPP) was divided by LAI to calculate GE.

Wood Density

Samples for wood density were taken from stems of each planting density randomly throughout the site. Wood density was calculated by dividing the sample mass by the sample volume. Sample weights ranged from 13.51 to 75.77 g. Wood volume was calculated from water displacement with the assumption that 1 g of water displaced is the same as 1 cm^3 of volume. Results were scaled to kg m^{-3} to compare with other studies.

Statistical Model and Analysis

The overall statistical model used to analyze all variables was:

$$Y_{ijkl} = \mu + \alpha_i + \beta_j + \alpha_i\beta_j + \gamma_k + \alpha_i\gamma_k + \beta_j\gamma_k + \varepsilon_{ijkl}$$

$$\varepsilon \sim N(0, \sigma_\alpha^2)$$

where Y_{ijkl} is the total primary aboveground biomass plot total (Mg ha^{-1}), α_i is effect due to planting density (i=1,250, 2,500, 5,000, and 10,000), β_j is effect due to the throughfall reduction treatment (j=control [C] or drought [D]), γ_k is the effect due to the block (k=1…3), $\alpha_i\beta_j$, $\alpha_i\gamma_k$, and $\beta_j\gamma_k$ are the effects due to the interaction between main effects, and ε_{ijkl} is the random error associated with the model.

The experiment was divided into blocks based on slope position (upper, mid, lower), so block term in the model was treated as a fixed effect. All statistics were performed with SAS statistical software (SAS Institute, Cary, NC). In instances where there was significant differences between treatments (α < 0.05) in the fixed effects, a Tukey adjustment for LSMeans was performed, with significant values indicated in bold (Tables 14-17).

RESULTS

Drought treatment

The 20 percent throughfall reduction treatment showed no discernable effects in many variables (Tables 1-8), except soil water content in some plots and leaf mass. There were differences in volumetric soil water content (VWC) between throughfall reduction treatments, but they seemed to be randomly distributed across the site (Figure 1). The VWC in the throughfall reduction plots was lower at the 1,250 ha^{-1} planting density but the opposite trend occurred at the planting density (10,000 ha^{-1}). The leaf mass showed significant differences due to the 20 percent throughfall reduction (Table 16). Differences could have been due to basket placement within the plot and natural variability, as there were no statistically significant differences in LAI measured with the ceptometer between treatments (Table 11). For further analysis, leaf mass was averaged across drought treatment levels (Tables 2 and 3).

Height

After the first growing season, the trees grew tall and above the weeds during the first year, with average height between 3.0 and 4.0 m tall (Figure 2). After the third growing season, the trees reached heights of 5.5 to 8.0 m tall.

Weed biomass

Similar LAI across planting density levels resulted in a large change in the amount of weedy biomass (alpha<.05). The significant difference occurred between the highest and lowest planting densities, with the 10,000 ha^{-1} having an average of 0.03 Mg ha^{-1} (SE 0.27) while the 1,250 ha^{-1} had 1.36 Mg ha^{-1} (SE 0.46) weed biomass.

Wood Density

Wood density for the sycamore ranged from an average of 596 kg m^3 to 623 kg m^3 (Table 3). Wood density did not vary significantly by planting density (Table 14).

Biomass partitioning

Leaf mass measured from the litter baskets did not change due to planting density, but there was a significantly difference due to throughfall reduction treatment. Similar to GE, leaf mass was a larger percentage of the total biomass in the 1,250 ha^{-1} than the other planting densities.

Dead and live branches and stems were significantly affected by planting density, with the 10,000 ha^{-1} having the greatest amount and the 1,250 ha^{-1} the least (Table 2). All of the planting density levels followed the same trend line for total biomass, dead and live branches and stem wood (Figures 4 and 5). Leaves made up 23 % of the total biomass in the 1,250 ha^{-1} planting density while in the other planting densities, leaves composed 14-18 % of the total biomass. The percentages of dead and live branches remained the same at 6 to 9 % of the total biomass regardless of plating density, while the stem wood made up 61 % in the lowest density and 66 to 70 % in the 2,500, 5,000, and 10,000 ha^{-1} planting density levels.

Stems produced and stool survival rate

The amount of shoots produced per ha depended on the planting density (Figure 9). The lowest planting density produced fewer stems per ha with 25,000 stems while the highest planting density (10,000 ha^{-1}) had the most stems ha^{-1} at over 110,000 in the first growing season. The trees quickly self thinned, by the third growing season, the each of the planting densities had fewer than 23,000 stems ha^{-1}. On the $tree^{-1}$ level, the lower the planting density, the more stems $tree^{-1}$. Figure 8 shows the basal area of the dominant stems for each of the planting densities across all three growing seasons. The figure shows the growth in size of the dominant stems.

To calculate the amount of stems ha^{-1}, the stems $tree^{-1}$ was averaged and scaled to the ha^{-1} basis based on the planting density and the mortality of that plot (table 4). Survival percentages ranged from 0.72 to 1.00 depending the plot.

Biomass totals

The 10,000 and 5,000 ha^{-1} had the highest total biomass at 27.11 (SE 0.75) and 25.31 (SE 0.76) Mg ha^{-1}, respectively (Table 2). The 5,000 ha^{-1} planting density had the highest ANPP in the third growing season, at 11.11 (SE 0.47) Mg ha^{-1} yr^{-1} (table 3). High stool survival occurred in most plots, with survival rates between 72 and 100 %. There was no stool death in the 5,000 ha^{-1} spacing, allowing productivity to almost reach that of the higher planting density levels (10,000 and 5,000 ha^{-1}).

Leaf Area Index (LAI)

There were no statistically significant differences in LAI across the different planting densities ($\alpha<0.05$) (Table 11). An average 5.62 m^2m^{-2} LAI was displayed across the experiment, with no statistically significant treatment differences. The LAI calculated from leaf mass and measured from the LP-80 ceptometer showed good agreement (Figure 2).

While the LAI was the same across planting density levels, the distribution of the leaves on individual trees appeared to differ. From field observations, each tree in the 10,000 ha^{-1} planting density had fewer leaves per tree, but the leaves were more or less evenly distributed within the stands with some light reaching the soil between tree rows. The trees in the 1,250 ha^{-1} planting density, appeared to have more leaf area per individual tree, clustered around the tree leaving more sunlight between trees. These differences in leaf area distribution were expressed in the larger variance in LAI with planting density (Table 2).

Significantly less biomass was produced at the 1,250 ha^{-1} planting density with the same LAI as the 10,000 ha^{-1} (Tables 2 and 3), resulting in significantly lower growth efficiency (GE). The other planting density levels had similar GE, with the 5,000 ha^{-1} having the greatest efficiency, though it was not significantly greater than the 10,000 and 2,500 ha^{-1} plots.

Growth Efficiency

The highest total biomass was produced at the 10,000 and 5,000 ha^{-}-^{1} planting density levels with no statistically significant difference between the two (Table 14). After three growing seasons, the 10,000 ha^{-1} reached a total of woody biomass of 27.11 (SE 0.75 Mg ha^{-1}) or an average of 9.04 Mg ha^{-1} yr^{-1}. The ANPP for the third growing season was only lower in the 1,250 ha^{-1} planting density level, with a productivity of 5.14 Mg ha^{-1} yr^{-1}. The highest ANPP in third growing season was the 5,000 ha^{-1} with an ANPP of 11.11 Mg ha^{-1} yr^{-1} SE 0.47 though this is not significantly higher than the 10,000 and 2,500 ha^{-1} planting densities (Tables 3, 14).

The lower ANPP for the 1,250 ha^{-1} planting density with similar LAI to the other levels resulted in the only statistically significantly difference in GE (0.96 Mg ha^{-1} yr^{-1} LAI^{-1} SE 0.18). The other three planting density levels had GE that ranged from 1.73 to 1.95.

DISCUSSION

The growing need for sustainable solutions to combat climate change and develop renewable energy technologies require that marginal agriculture lands be evaluated for the potential to grow SRWCs (Ghezehei et al., 2015). Results show that coppiced American sycamore grown on marginal lands has a high potential for bioenergy use. With an average productivity of over 9 Mg ha^{-1} yr^{-1} of woody biomass, this crop showed similar or greater productivity to *Populus* grown on marginal land (Dillen et al. 2013, Djomo et al. 2015, Fischer et al. 2017). This productivity matched the average ANPP in natural hardwood stands in the southern Appalachian with an ANPP of 9.2 Mg ha^{-1} yr^{-1} (Bolstad 2001). The productivity of the coppiced sycamore showed higher productivity in three years than in four years of the first rotation (Ashley 2015, Domec et al. 2017). Though there was similar (low) mortality in all of the treatments, the impact of each tree dying in the 1,250 ha^{-1} plots was higher than the denser stands. The similar amounts of biomass in the 10,000 and 5,000 ha^{-1} plots suggests that much of the death was related to intraspecific competition; when one tree dies, another will take up the growing space of that tree. When trees died in the 1,250 ha^{-1} spacing, the other trees were not able to take up this growing room. In longer rotations, the impact of mortality may even out as the trees may eventually occupy open growing space. In the three years of the current study the missing trees made a big difference. Survival rates were similar or greater than reported for another coppiced sycamore study (Wittwer and Stringer 1985).

There is an economic advantage of the coppiced second rotation as well. The trees produced all of the biomass with no additional inputs leading to greater return on investment relative to planting a new stand. This allows landowners to receive more end value as they will not have to pay for seedlings, labor, herbicide, and other costs associated with plantation establishment. In addition to economic benefits, environmental benefits are realized from coppicing due to avoided energy consumption associated with plantation establishment, and perhaps greater C storage from decreased site disturbance (Djomo, 2015). Similar to *Populus* and *Salix*, sycamore has potential to coppice repeatedly and maintain productivity (Sullivan 1994).

The 20% throughfall reduction treatment had no effect on either the soil water content or biomass production (Figure 3, Tables 5-13). The plots SWC varied by the location on the site instead of by planting density and throughfall reduction treatment. The amount rain the site received during the study period eliminated any effects we expected to see in the biomass production. The rain total of 147.2 cm in 2016, with 90.6 cm coming between May and

September was highly unusual. In the nearby city of Durham, NC, precipitation averages 122.1 cm per year, with about 54.1 cm coming between May and September (US Climate data, http://www.usclimatedata.com/climate/durham/north-carolina/united-states/usnc0192). Part of the high productivity reported in this study could be due to the unusually high rainfall, since the lack of differences soil water content due to planting density, time, and throughfall reduction suggest there was no water limitation (Figure 3), as was reported in the previous study (Ashley 2015, Domec et al. 2017).

The leaf area index and associated growth efficiency of trees in the 1,250 ha^{-1} planting density showed that each tree in the least dense plots allocated more energy into growing leaves than producing woody biomass compared to the higher density levels. At the 1,250 ha^{-1} planting density, each tree had access to full sunlight so the crowns had branches and leaves on all sides and up the full height of the tree. At the higher planting densities, each tree had access only to light from above, and therefore leaf area was restricted vertically and horizontally to a much smaller volume per tree. High planting density trees produced more biomass per unit leaf area than the widest spacing. The average LAI of 5.6 was similar to another study of sycamore in Florida that reported a control LAI of 5.48 after 7 years (Henderson et al. 2010). The first rotation study showed the highest LAI of 11.56 in the densest stand and an average of 5.81 in the least dense stand (Domec et al. 2017).

The second rotation GE value of 1.7 to 2.0 Mg ha^{-1} yr^{-1} LAI^{-1} in the 2,500, 5,000 and 10,000 ha^{-1} planting density levels and 0.85 Mg ha^{-1} yr^{-1} LAI^{-1} in the 1,250 ha^{-1} planting density

(Table 3) were higher than for the first rotation (Ashley 2015), and compared to a study in Florida that found GE of traditionally managed sycamore to be 0.55 to 0.62 Mg ha^{-1} yr^{-1} LAI^{-1}. The growth efficiencies reported in this study were closer to natural stands in the southern Appalachian, with GEs between 1.25 and 2.15 Mg ha^{-1} yr^{-1} LAI^{-1} (Bolstad et al. 2001). Similar to the current study, Binkley et al. (2004) found a sharp increase in growth efficiency with small differences in LAI. Though the differences in LAI were not statistically significant in this study, there was a slight trend in the LAI data using the ceptometer (Figure 11). The standard error was highest in the lowest planting density (1,250 ha^{-1}) thus showing the largest variability among treatments.

Contrary to abundant published literature (Albaugh et al. 1998, Bolstad et al. 2001, Brinkley et al. 2004, Waring 1983), LAI was not directly related to the amount of biomass produced. These results suggest that the coppiced stands perform differently than traditionally managed stands, requiring a reevaluation of LAI as a driver of productivity. This is due to the way the low planting density coppiced trees displayed leaf area compared to the higher planting density levels (and indicated by the higher within plot variance in LAI). In the 1,250 ha^{-1} spacing, weed biomass was very high (Table 3) indicating that adequate light reached the soil to sustain significant weed NPP. At the higher planting densities, weed NPP was almost completely shaded out, even though LAI was the same as in the 1250 ha^{-1} treatment, because the leaf area was more evenly distributed across the surface area of the plot. Thus in coppiced systems at low planting density, the traditional concepts of LAI and LAI:NPP appear not to hold.

A possible better way to characterize the amount of leaves per stand is either to directly measure the leaf area of select trees inside the plot or to measure the crown width and height, which relates to the amount of leaves per tree.

Planting density did not affect wood density unlike the previous study (Ashley 2015, Domec et al. 2017). The large number of stems prevented much denser tension wood from developing due to the stems buffering the wind in the 1,250 and 2,500 ha^{-1} planting densities. Overall the wood densities remained close to the previous study with an average density of 614 Kg m^{-3} SE 44.92.

Biomass production was high in the first year, and increased substantially in the second and third years due to the developed rootstock from the previous rotation. This allowed stored carbohydrates in the roots to re-sprout many initial shoots per stool (Dillon et al. 2013). This study found initially the trees produced 12 to 23 stems per stool translating to 25,000 to 110,000 stems ha^{-1} (Figure 7). The trees quickly self-thinned the next two growing seasons down to 2-4 dominant shoots per stool or over 5,000 to over 20,000 shoots ha^{-1} depending on the planting density. The high planting density treatments (i.e. 10,000 and 5,000 ha^{-1}) had fewer shoots stool^{-1} but overall more shoots ha^{-1} than the low density plots. Many of the dead branches stayed on the trees, as there were almost equal amounts of dead and live branches on individual trees. As expected, the size of individual trees was smaller in the denser stands (10,000 and 5,000 ha^{-1}), but the total amount of biomass was greater compared to the lower density treatments (Figures 6 and 7).

The total biomass produced after the third growing season was 27.11 Mg ha^{-1} thus greater than the first rotation after 4 growing seasons of 23.26 Mg ha^{-1}. The ANPP of 11.11 Mg ha^{-1} yr^{-1} in the third growing season rivals that of many *Populus* species grown for bioenergy in Europe (Dillen et al 2012). This net primary production per year is not expected to increase for the fourth growing season as the trees are expected to lose much of the dead biomass and further self-thin, as occurred in the first rotation (Ashley 2015).

The 5,000 ha^{-1} seems to be the best planting density as it produced statistically the same amount of biomass as the 10,000 ha^{-1} treatment with half the number of trees planted. This would result in a larger return on investment for the landowner as there is less cost for seedlings and labor when establishing the plantation. The 2,500 ha^{-1} planting density had no mortality, making the productivity almost competitive with the other planting densities with a total biomass of just over 20 Mg ha^{-1}. If the rotation length was longer, this planting density could be an attractive option as individual trees are bigger with fewer branches, leading to a higher wood-to-bark ratio, which may affect end product value.

Ultimately, sycamore produced a competitive amount of biomass after three growing seasons on marginal agriculture land under low-input management, making it a good potential candidate for bioenergy SRWC. The productivity results are consistent with Fischer et al.

(2017), who found that low-input sycamore had higher yields than a hybrid *Populus* clone (NM6) and yellow poplar (*Liriodendron tulipifera*), even when grown with high-inputs. Similar to *Populus* and *Salix* grown for bioenergy, sycamore produced more biomass, more efficiently after the coppice (Dillen et al. 2012). As the future needs for sustainable energy increase, marginal agricultural land in the Southeast can play a key role in providing an environmentally sustainable source of clean, renewable energy. For a wood energy industry to be environmentally sustainable and economically competitive, an abundant supply of high quality wood is needed, produced in short rotations on marginal land with as few inputs as possible. This study, and others, are beginning to show that Coppiced sycamore grown on marginal land in the piedmont of North Carolina demonstrates that, as lignocellulosic ethanol technology increases, short rotation woody crops may have great potential to help meet this demand, providing locally-sourced energy with economic and environmental benefits into the future.

CONCLUSION

The impact of climate makes studies that investigate alternative fuels for bioenergy especially with a drought aspect pressing. Recent climate change has produced rising variation in the climate, leading the risk of severe drought more likely (King et al. 2013). Much research has been done on high input bioenergy crops across Europe and the US though these systems are not always sustainable. First generation crops such as corn compete with the food supply leading to ethical concerns, while second generation fuels are still not widely used (Granda et al. 2007, Johnson et al. 2007, Mohr and Raman 2013, Naik et al. 2010). *Populus* is well studied (Fischer et al. 2015), but some of the best candidates for bioenergy grow best in northern latitudes and is not as productive in low input systems (Dillon 2013). Clearly, there is need for research of a crop that produces high quality bioenergy on marginal land with few inputs. Coppiced sycamore, with growth rates of over 9 Mg ha^{-1} yr^{-1} is one potential candidate for sustainable SRWC in the Southeast. The trees' productivity is on the upper range of what researchers have come to expect (8-10 Mg ha^{-1} yr^{-1}) of SRWCs with low inputs (English et al. 2006).

Coppiced sycamore showed higher productivity than in the first rotation on the same site, and in a shorter time. The previous rotation had productivity of 23 Mg ha^{-1} after the forth growing season, while in this study I documented the most productive stands with an average of over 27 Mg ha^{-1} after three growing seasons with no additional inputs. This shows the advantage of early productivity gains from the established root systems, allowing higher return on investment, especially when compared to systems that have to be planted anew after each rotation, such as plantation pine.

For both economic and environmental reasons, SRWC sycamore has high potential for production in the South. With the growing biomass market, sycamore can play a large role in providing fuel for current and future energy needs. More research needs to be done in the belowground aspect of the bioenergy cropping systems, along with managing larger plots across different kinds of sites (soils, climate, hydrology).

We have shown that sycamore can survive and thrive in North Carolina weather condition when managed in high density stands as a bioenergy crop. These positive results should encourage landowners to consider growing sycamore as a bioenergy species in short rotations. The coppicing ability of sycamore should encourage researchers to push the extent to how many productive rotations the tree will give.

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APPENDICES

APPENDIX A: TABLES

Table 1. Percentage increase of measured stems in the inventory to the suppressed or other stems not measured biomass for 2015.

Density	Dominant Stems	Suppressed Stems
10,000	87.37%	12.63%
5,000	84.56%	15.44%
2,500	83.00%	17.00%
1,250	81.39%	18.61%

Table 2. Least Square Mean (Standard Error) of biomass of dead branches, live branches, stems, foliage, and total biomass averaged by tree density ha^{-1} in the third growing season (2016)

Tree Planting Density	Dead Branches (Mg ha^{-1})	Live Branches (Mg ha^{-1})	Stem (Mg ha^{-1})	Biomass (Mg ha^{-1})	Leaf Mass (Mg ha^{-1})
1,250 ha^{-1}	1.47 (0.20)	1.50 (0.22)	11.24 (1.50)	13.81 (1.90)	4.22 (0.48)
2,500 ha^{-1}	2.07 (0.23)	1.83 (0.23)	15.79 (1.74)	20.17 (2.29)	4.41 (0.32)
5,000 ha^{-1}	2.65 (0.08)	2.09 (0.08)	20.23 (0.58)	25.31 (0.76)	4.57 (0.38)
10,000 ha^{-1}	2.91 (0.79)	2.04 (0.07)	22.14 (0.59)	27.11 (0.75)	4.55 (0.37)

Table 3. Least square means (standard error) for weed biomass. Annual net primary production (ANPP), leaf area index (LAI), and growth efficiency (GE) in the third growing season (2016)

Tree Planting Density	Weeds	ANPP (Mg ha-1 yr-1)	LAI (m2 m-2)	GE (Mg ha-1 yr-1 LAI -1)	Wood Density (Kg m^{-3})
1250	1.36 (0.46)	5.14 (1.09)	5.22 (0.44)	0.96 (0.18)	623 (8.18)
2500	0.76 (0.41)	9.05 (0.66)	5.31 (0.43)	1.73 (0.12)	623 (7.93)
5000	0.29 (0.18)	11.11 (0.47)	5.74 (0.24)	1.95 (0.09)	610 (15.25)
10000	0.03 (0.27)	10.78 (0.75)	6.20 (0.39)	1.76 (0.12)	596 (11.60)

Table 4. Least square means (standard error) for the number of stems per ha by plot in the third growing season (2016)

Planting Density	Drought Treatment	Block	Stems tree^{-1}	Percent Survival	Stems ha^{-1}
1,250 ha^{-1}	C	1	4.66 (0.31)	1	5833.33 (387.22)
1,250 ha^{-1}	C	2	2.15 (0.22)	0.76	2046.15 (210.95)
1,250 ha^{-1}	C	3	5.00 (0.47)	0.92	5750.00 (536.88)
1,250 ha^{-1}	D	1	3.82 (0.64)	0.72	3436.36 (579.70)
1,250 ha^{-1}	D	2	4.27 (0.54)	0.84	4480.00 (565.60)
1,250 ha^{-1}	D	3	5.08 (0.42)	0.84	5330.77 (436.20)
2,500 ha^{-1}	C	1	2.21 (0.24)	1	5520.83 (601.54)
2,500 ha^{-1}	C	2	3.33 (0.26)	1	8333.33 (650.16)
2,500 ha^{-1}	C	3	3.80 (0.24)	1	9500.00 (577.35)
2,500 ha^{-1}	D	1	3.12 (0.30)	1	7800.00 (740.50)
2,500 ha^{-1}	D	2	3.12 (0.19)	1	7800.00 (485.63)
2,500 ha^{-1}	D	3	3.88 (0.25)	1	9700.00 (617.79)
5,000 ha^{-1}	C	1	3.02 (0.14)	0.95	14331.90 (632.23)
5,000 ha^{-1}	C	2	2.37 (0.09)	1	11833.33 (427.95)
5,000 ha^{-1}	C	3	2.83 (0.16)	0.967	13671.38 (753.42)
5,000 ha^{-1}	D	1	2.91 (0.13)	0.95	13840.52 (632.23)
5,000 ha^{-1}	D	2	3.29 (0.19)	0.967	15898.14 (942.75)
5,000 ha^{-1}	D	3	2.88 (0.12)	0.983	14171.58 (573.42)
10,000 ha^{-1}	C	1	1.81 (0.08)	0.831	15021.92 (655.48)
10,000 ha^{-1}	C	2	1.82 (0.07)	0.931	16972.85 (605.48)
10,000 ha^{-1}	C	3	2.06 (0.07)	0.908	18731.97 (679.05)
10,000 ha^{-1}	D	1	2.13 (0.08)	0.946	20102.50 (763.90)
10,000 ha^{-1}	D	2	2.16 (0.07)	0.985	21291.15 (695.49)
10,000 ha^{-1}	D	3	2.29 (0.08)	0.938	21501.85 (712.99)

Table 5. F-tests of fixed effect of Dead branch biomass in the third growing season (2016)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
density	3	7.38444608	2.46148203	41.96	**0.0002**
trt	1	0.12376398	0.12376398	2.11	0.1966
density*trt	3	0.20562571	0.0685419	1.17	0.3968
block*density	6	1.4069075	0.23448458	4	0.058
block*trt	2	0.5741321	0.28706605	4.89	0.0549
Error	6	0.35201423	0.05866904		

Table 6. F-tests of fixed effect of live branch biomass in the third growing season (2016)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
density	3	1.27984074	0.42661358	6.47	**0.0261**
trt	1	0.14852698	0.14852698	2.25	0.184
density*trt	3	0.34630972	0.11543657	1.75	0.2558
block*density	6	1.61627188	0.26937865	4.09	0.0553
block*trt	2	0.62969558	0.31484779	4.78	0.0574
Error	6	0.39538	0.06589667		

Table 7. F-tests of fixed effect of stem biomass in the third growing season (2016)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
density	3	425.8990015	141.9663338	41.46	**0.0002**
trt	1	7.2274709	7.2274709	2.11	0.1965
density*trt	3	12.0534477	4.0178159	1.17	0.3952
block*density	6	82.1904689	13.6984115	4	0.0579
block*trt	2	33.5250172	16.7625086	4.89	0.0549
Error	6	20.5469307	3.4244885		

Table 8. F-tests of fixed effect of total woody biomass in the third growing season (2016)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
density	3	641.7502984	213.9167661	34.98	**0.0003**
trt	1	9.5472973	9.5472973	1.56	0.258
density*trt	3	16.3026764	5.4342255	0.89	0.4988
block*density	6	146.3943371	24.3990562	3.99	0.0582
block*trt	2	57.6124692	28.8062346	4.71	0.0589
Error	6	36.6934676	6.1155779		

Table 9. F-tests of fixed effect of weed biomass in the third growing season (2016)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
density	3	6.14104136	2.04701379	5.43	**0.0381**
Trt	1	0.06929451	0.06929451	0.18	0.6831
density*trt	3	0.2800736	0.09335787	0.25	0.8603
block*density	6	3.69664528	0.61610755	1.63	0.2828
block*trt	2	0.36599397	0.18299699	0.49	0.6376
Error	6	2.26153232	0.37692205		

Table 10. F-tests of fixed effect of Aboveground net primary production (ANPP) in the third growing season (2016)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
density	3	199.7965092	66.5988364	14.1	**0.004**
trt	1	0.4847334	0.4847334	0.1	0.7595
density*trt	3	2.4178396	0.8059465	0.17	0.9124
block*density	6	12.0998276	2.0166379	0.43	0.8379
block*trt	2	18.1906395	9.0953198	1.93	0.2259
Error	6	28.332781	4.7221302		

Table 11. F-tests of fixed effect of Leaf Area Index (LAI) in the third growing season (2016)

Source	DF	Type I SS	Mean Square	F Value	Pr > F
density	3	3.61815	1.20605	2.23	0.185
trt	1	0.28166667	0.28166667	0.52	0.4974
density*trt	3	1.7901	0.5967	1.1	0.4176
block*density	8	9.63993333	1.20499167	2.23	0.172
block*trt	2	2.59145833	1.29572917	2.4	0.1716
Error	6	3.241275	0.5402125		

Table 12. F-tests of fixed effect of Growth Efficiency (GE) in the third growing season (2016)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
density	3	5.16369198	1.72123066	12.01	**0.006**
trt	1	0.06566398	0.06566398	0.46	0.5237
density*trt	3	0.23473235	0.07824412	0.55	0.6688
block*density	6	0.58483991	0.09747332	0.68	0.6742
block*trt	2	0.27361832	0.13680916	0.95	0.4366
Error	6	0.85989662	0.1433161		

Table 13. F-tests of fixed effect of the number of shoots in the third growing season (2016)

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
density	3	27276417386	9092139129	208.08	**<.0001**
trt	1	388062373	388062373	8.88	**0.0029**
density*trt	3	803733365	267911122	6.13	**0.0004**
block	2	291181532	145590766	3.33	**0.036**
block*density	6	413846027	68974338	1.58	0.1497
block*trt	2	210820206	105410103	2.41	0.09
Error	1335	58334748404	43696441		

Table 14. F-tests of fixed effect of wood density due to planting density in the third growing season (2016)

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Planting density	3	0.00731492	0.00243831	1.22	0.3098

Table 15. P-values for effects at varying densities in the third growing season (2016) testing the null hypothesis of the LS Means being the same using Tukey adjustment. Significant p-values (alpha <.05) are bolded.

Least Squares Means for effects
Pr > |t| for H0: LSMean(i)=LSMean(j)

Weeds

i/j	1250	2500	5000	10000
1250		0.4024	0.0841	**0.036**
2500			0.5807	0.2662
5000				0.8811

Dead Branches

i/j	1250	2500	5000	10000
1250		**0.0203**	**0.0006**	**0.0002**
2500			**0.0225**	**0.0039**
5000				0.3539

Live Branches

i/j	1250	2500	5000	10000
1250		0.2191	**0.0283**	**0.0419**
2500			0.3811	0.5466
5000				0.9838

Stem

i/j	1250	2500	5000	10000
1250		**0.0207**	**0.0006**	**0.0002**
2500			**0.023**	**0.0041**
5000				0.3635

Total Biomass

i/j	1250	2500	5000	10000
1250		**0.0168**	**0.0008**	**0.0004**
2500			**0.0427**	**0.0112**
5000				0.6163

Aboveground Net Primary Production (ANPP)

i/j	1250	2500	5000	10000
1250		0.0603	**0.0093**	**0.0123**
2500			0.3796	0.5095
5000				0.9914

Growth Efficiency (GE)

i/j	1250	2500	5000	10000
1250		**0.0279**	**0.0086**	**0.0232**
2500			0.6799	0.998
5000				0.7698

Table 16. Least Squares Mean (Standard Error) in the third growing season (2016) and test of null hypothesis that the LSMeans of the water reduction treatments are the same using Tukey adjustment.

Water Treatment	Leaf mass LSMEAN (Mg ha^{-1})	H0:LSMean1=LSMean2 Pr > |t|
Control	3.82 (0.24)	**0.0012**
Drought	5.07 (0.13)	

Table 17. P-values for number of stems ha^{-1} at varying densities and drought treatments (Dry or Control) in the third growing season (2016) testing the null hypothesis of whether the LS Means are the same using Tukey adjustment. Significant values (alpha <.05) are bolded.

Least Squares Means for effect density*trt

Pr > |t| for H0: LSMean(i)=LSMean(j)

i/j	1250 C	1250 D	2500 C	2500 D	5000 C	5000 D	10000 C	10000 D
1250 C		1	0.2086	0.0589	**<.0001**	**<.0001**	**<.0001**	**<.0001**
1250 D			0.2053	0.0572	**<.0001**	**<.0001**	**<.0001**	**<.0001**
2500 C				0.9989	**<.0001**	**<.0001**	**<.0001**	**<.0001**
2500 D					**<.0001**	**<.0001**	**<.0001**	**<.0001**
5000 C						0.5144	**<.0001**	**<.0001**
5000 D							**0.0041**	**<.0001**
10000 C								**<.0001**

Table 18. P-values for number of stems ha^{-1} at each of the block treatments in the third growing season (2016) testing the null hypothesis of whether the LS Means are the same. Significant values (alpha <.05) are bolded.

Least Squares Means for effect block

Pr > |t| for H0: LSMean(i)=LSMean(j)

i/j	1	2	3
1		0.8548	**0.0402**
2			0.1238

APPENDIX B: FIGUES

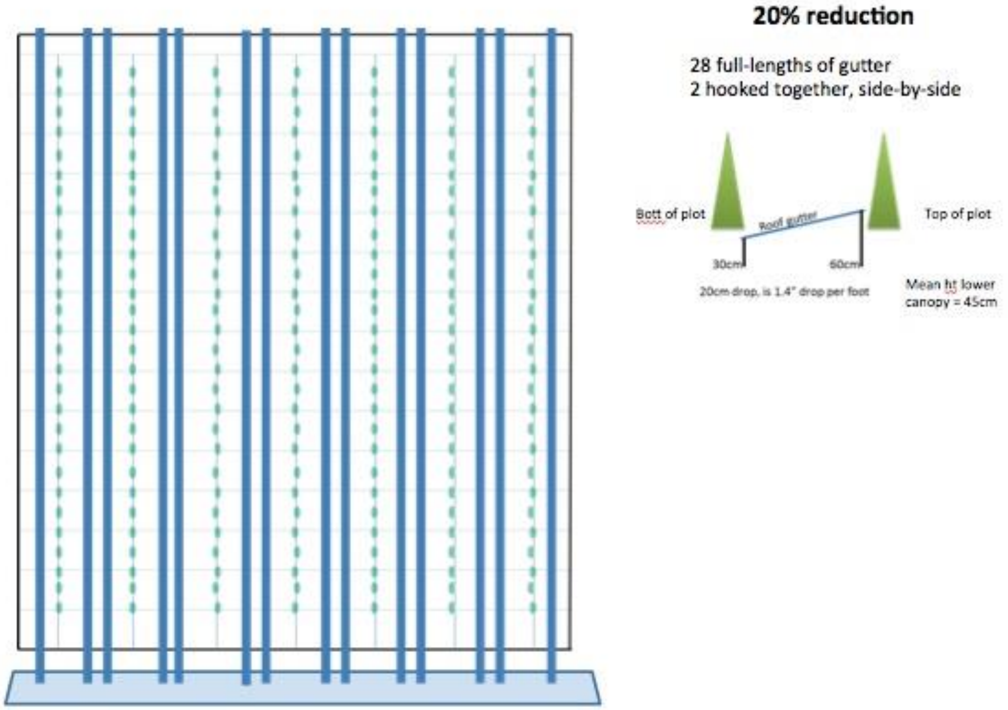


Figure 1. Diagram of gutter system put in place to impose a 20 percent through fall reduction at the study site.

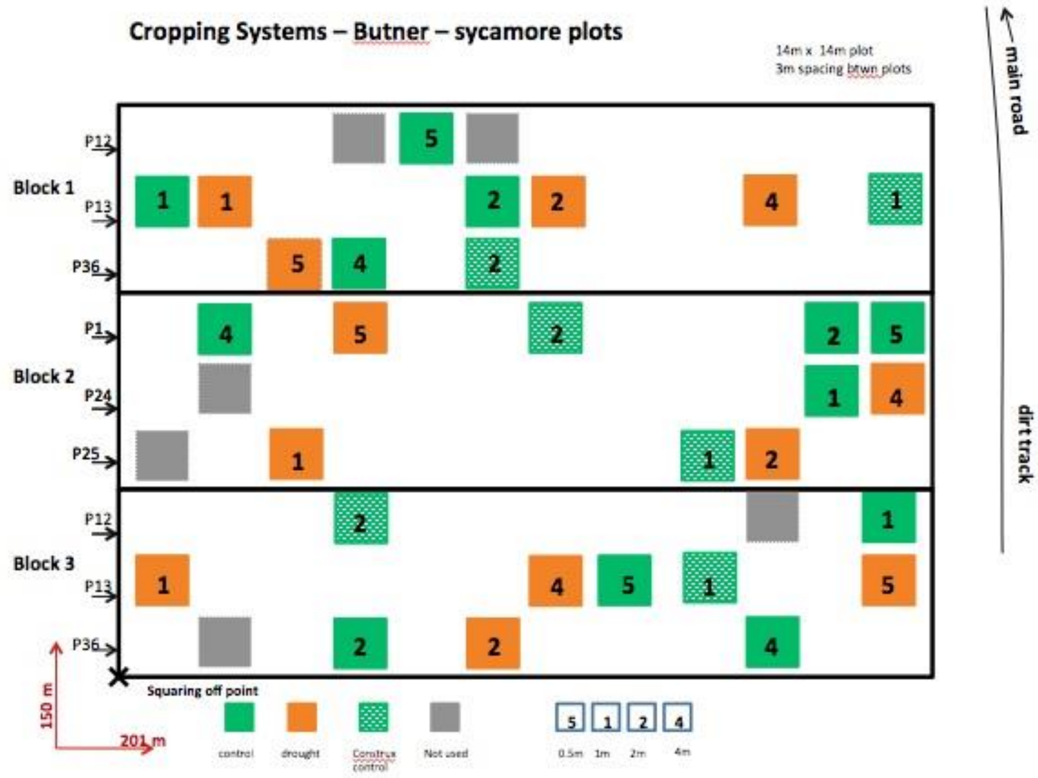
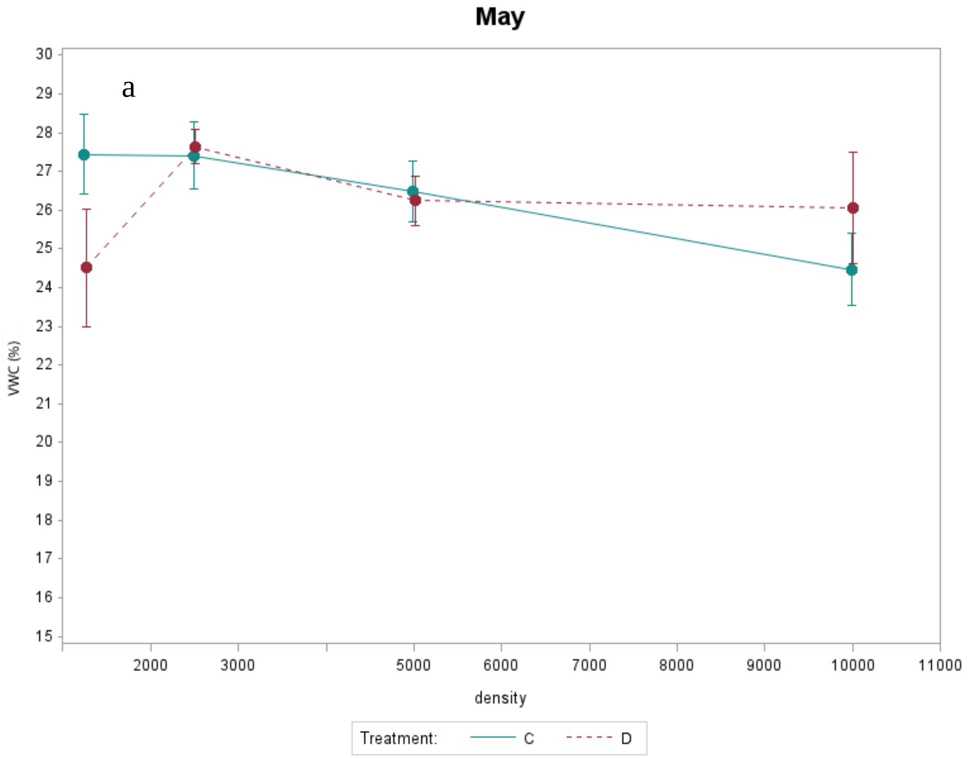
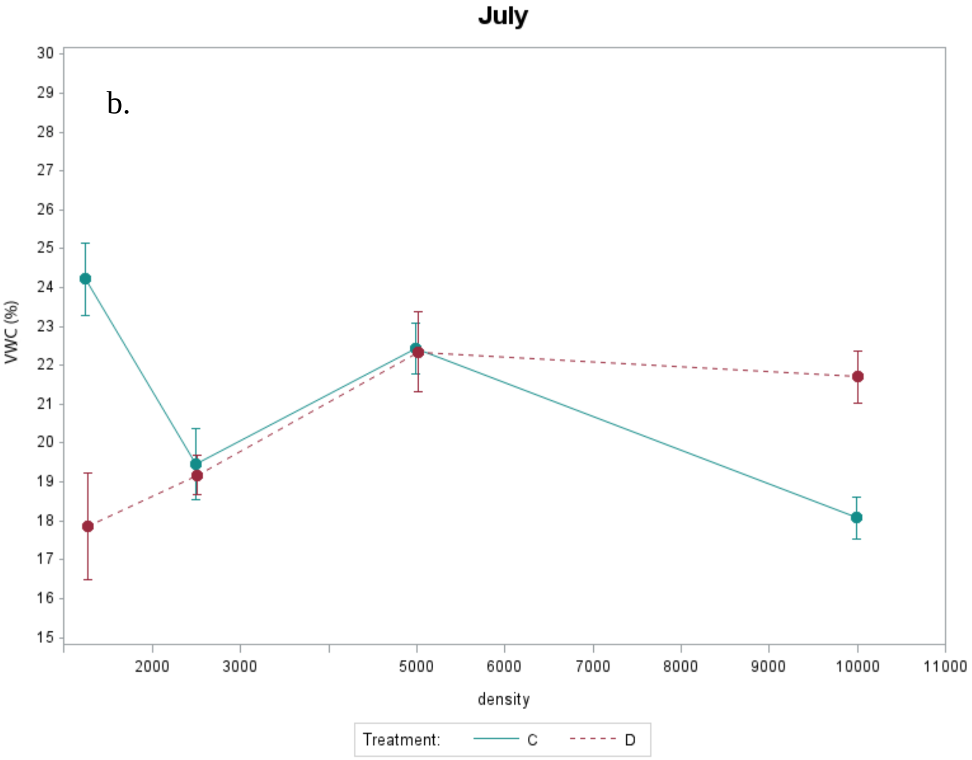


Figure 2. Layout of plots on the site in a Randomized Complete Block Design. The numbers 5, 1, 2, and 4 correspond with the planting densities of 10,000 ha^{-1}, 5,000 ha^{-1}, 2,500 ha^{-1}, and 1,250 ha^{-1} respectively. The control (green) does not have gutters while the 20% throughfall reduction treatment (orange) has gutters. The blocks are sloped with block 1 the highest elevation to block 3 the lowest.


May
a
VWC (%)
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
2000
3000
5000
6000
7000
8000
9000
10000
11000
density
Treatment: C D


July
b.
VWC (%)
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
2000
3000
5000
6000
7000
8000
9000
10000
11000
density
Treatment: C D

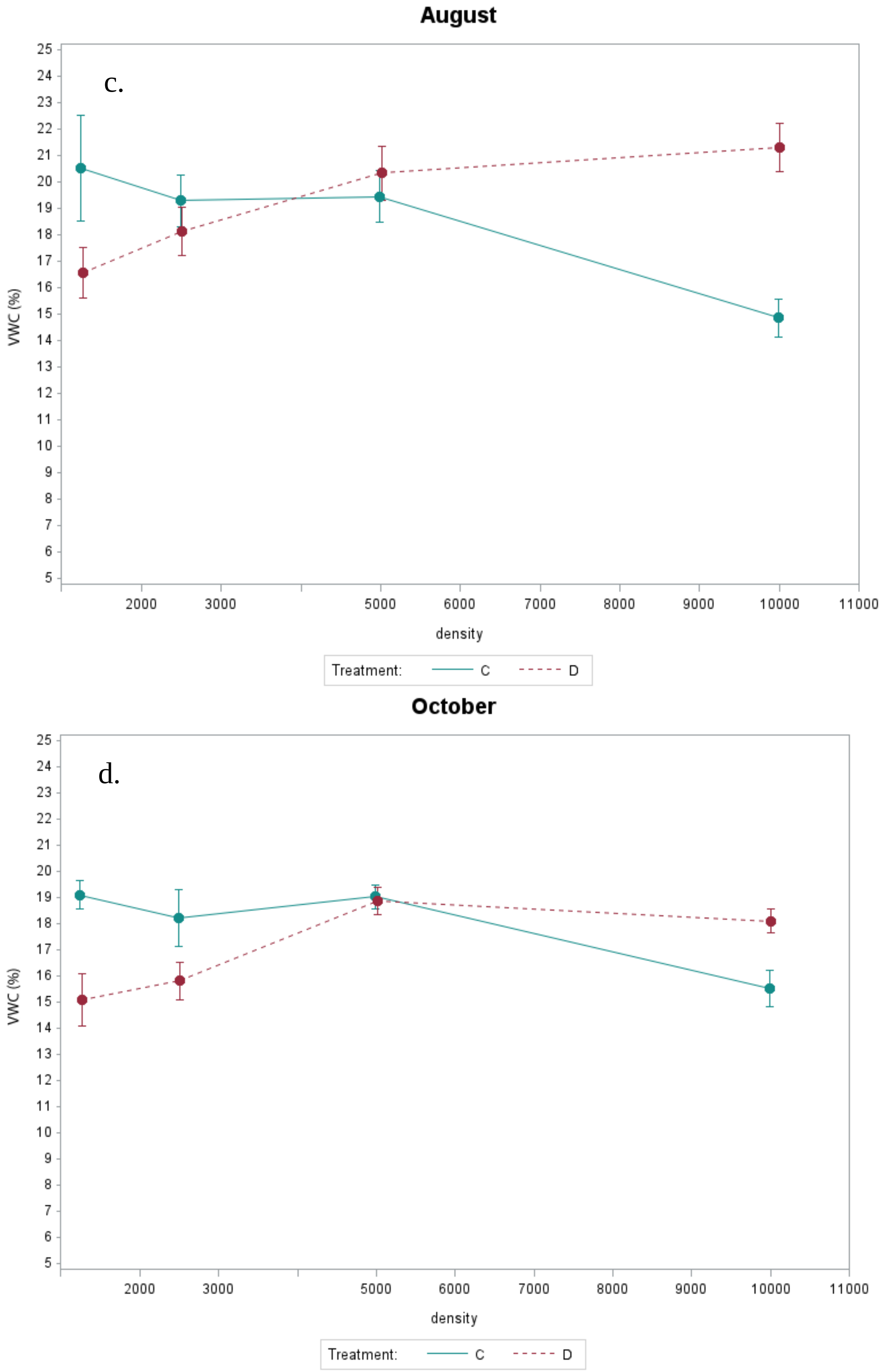


Figure 3 a-d. Volumetric soil water content by spacing and throughfall reduction treatment for different months throughout the growing season. C (blue)-Control, D (red)-20% Simulated throughfall reduction.

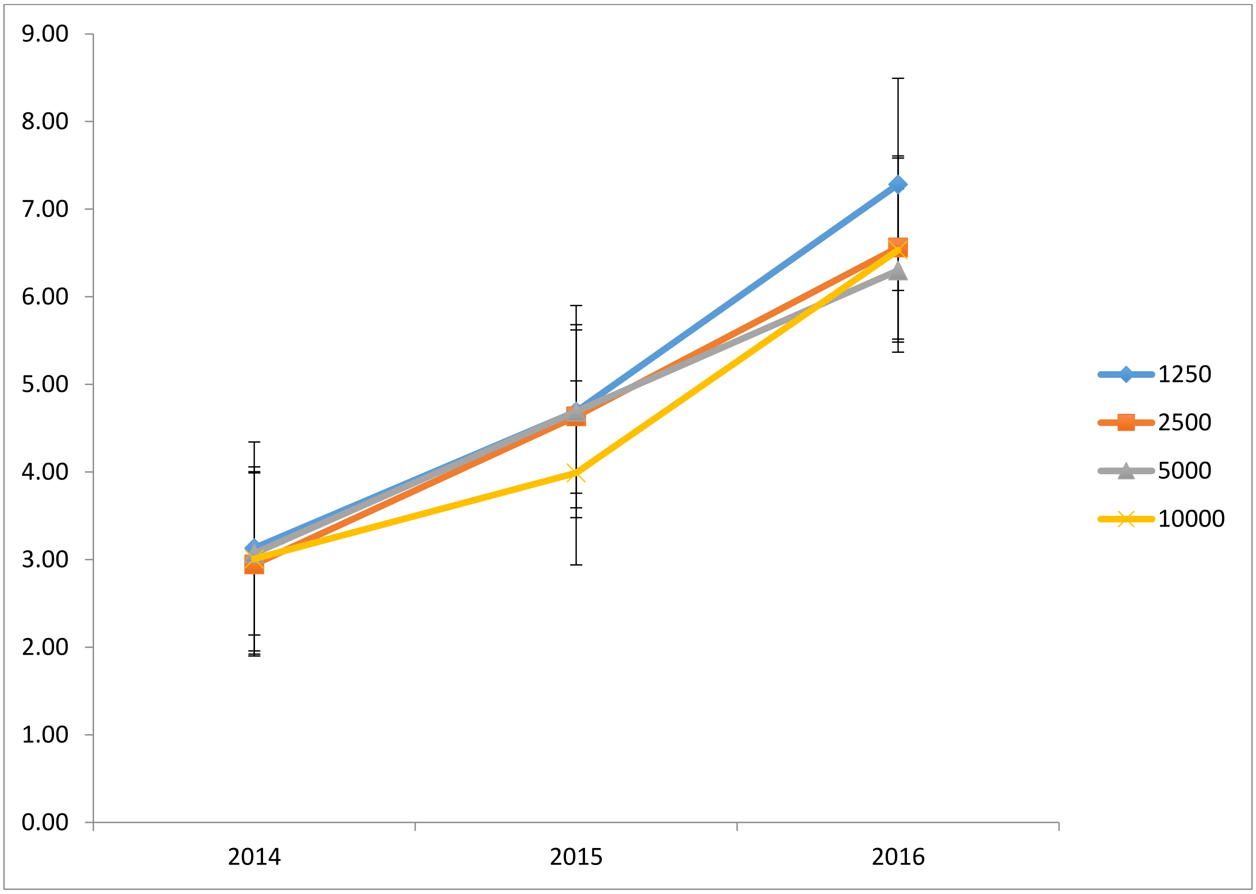


Figure 4: Mean (SE) height (m) of sycamore trees by planting density and year.

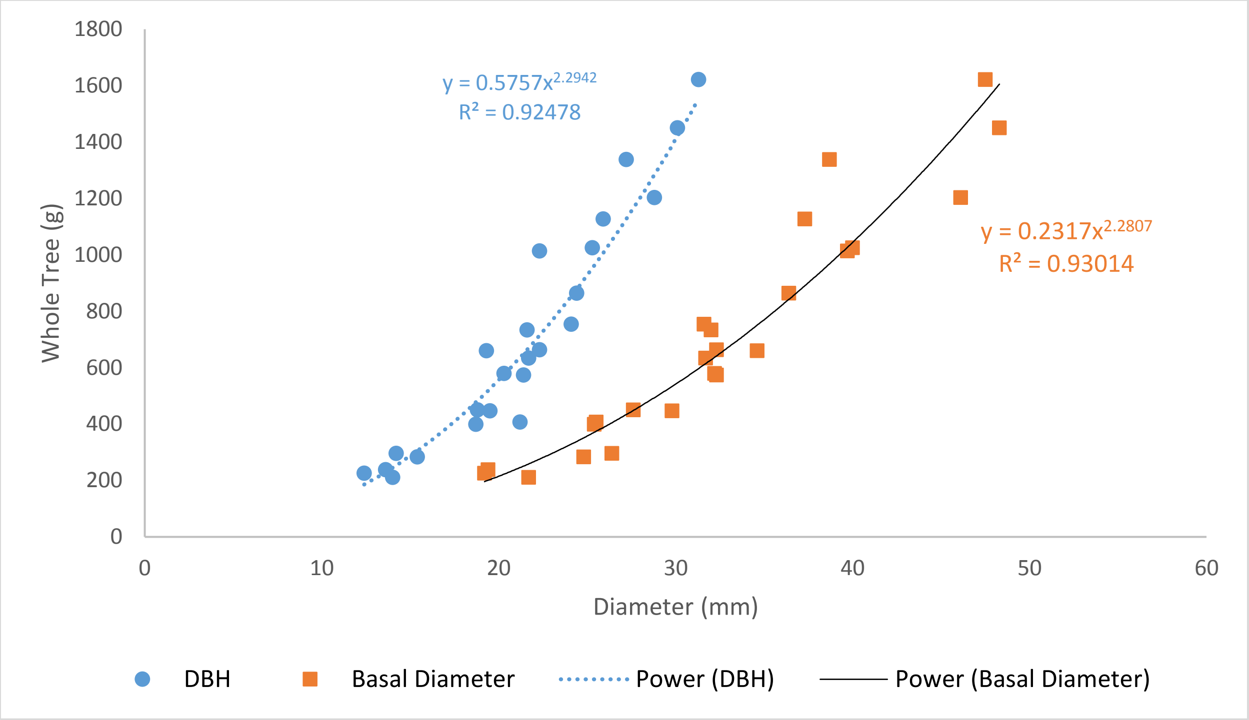


Figure 5: Allometric equations for 2014 and 2015 for calculating dry weight of individual shoots.

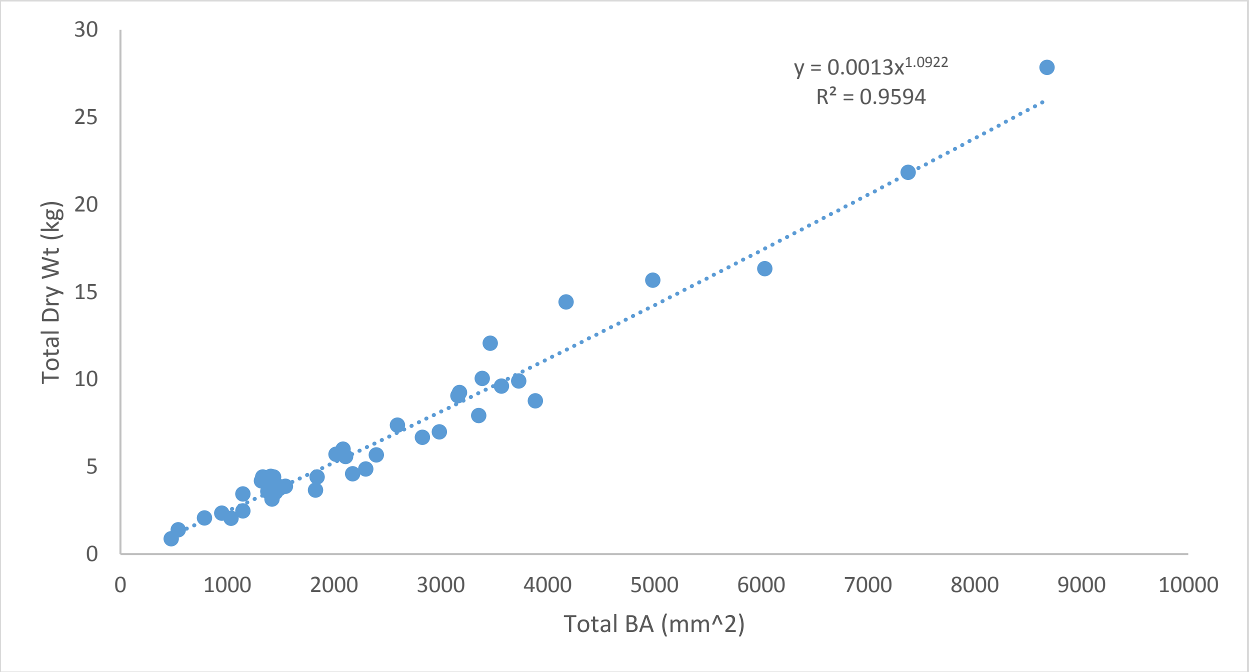


Figure 6. Allometric equation for 2016 inventory converting total basal area (BA) at breast height for dominant trees to the total tree biomass.

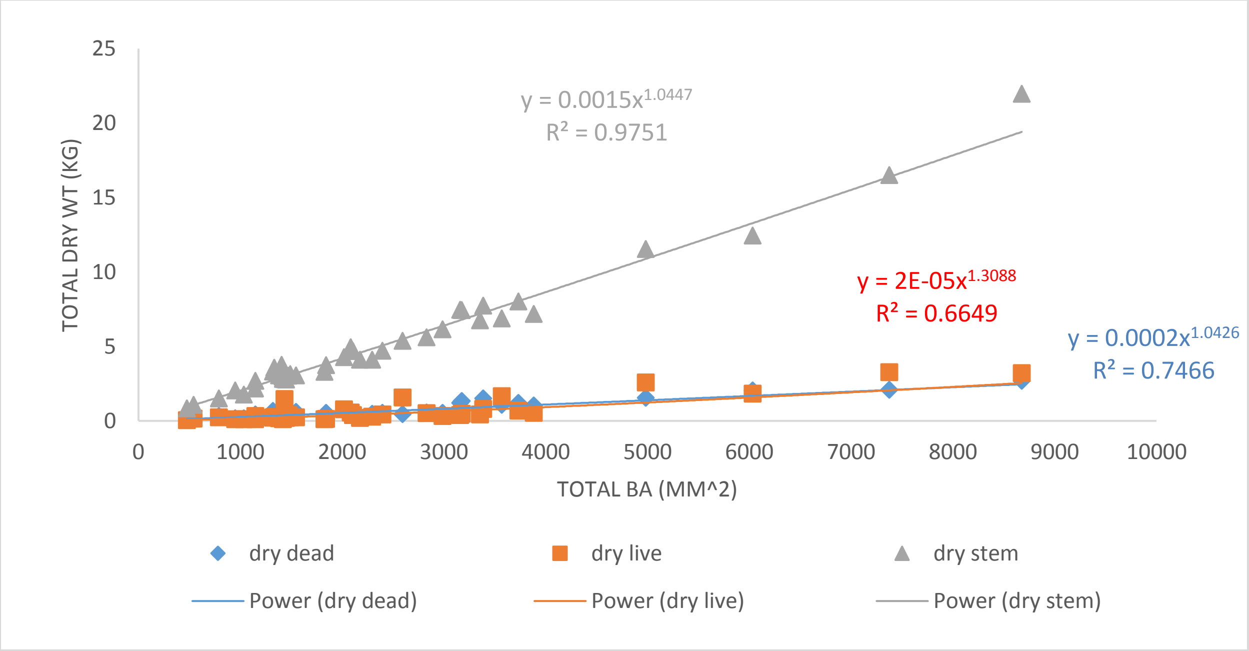


Figure 7. Relationship of total basal area (BA) to the biomass partitioned to the stem, dead branches, and live branches.

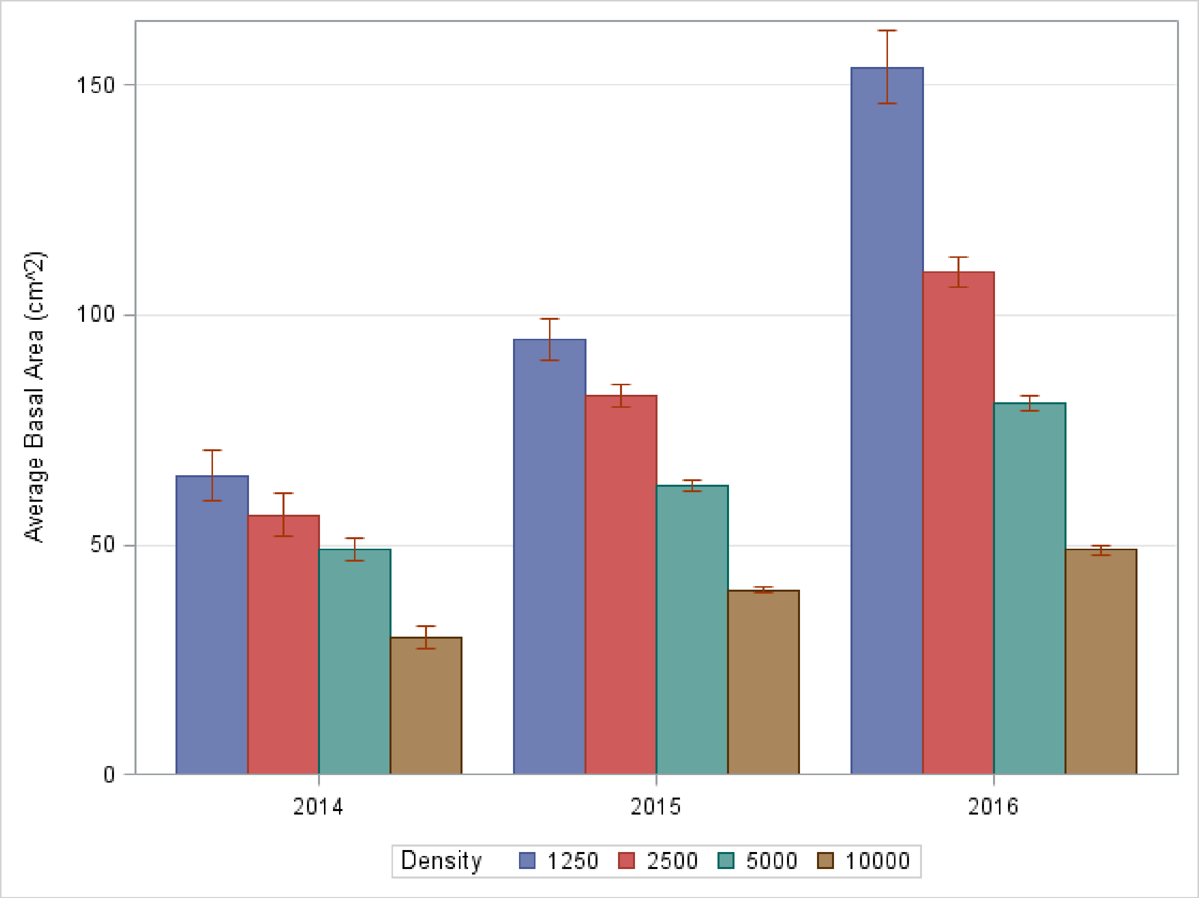


Figure 8. Average basal area (BA) of dominant stems for the different planting densities by year.

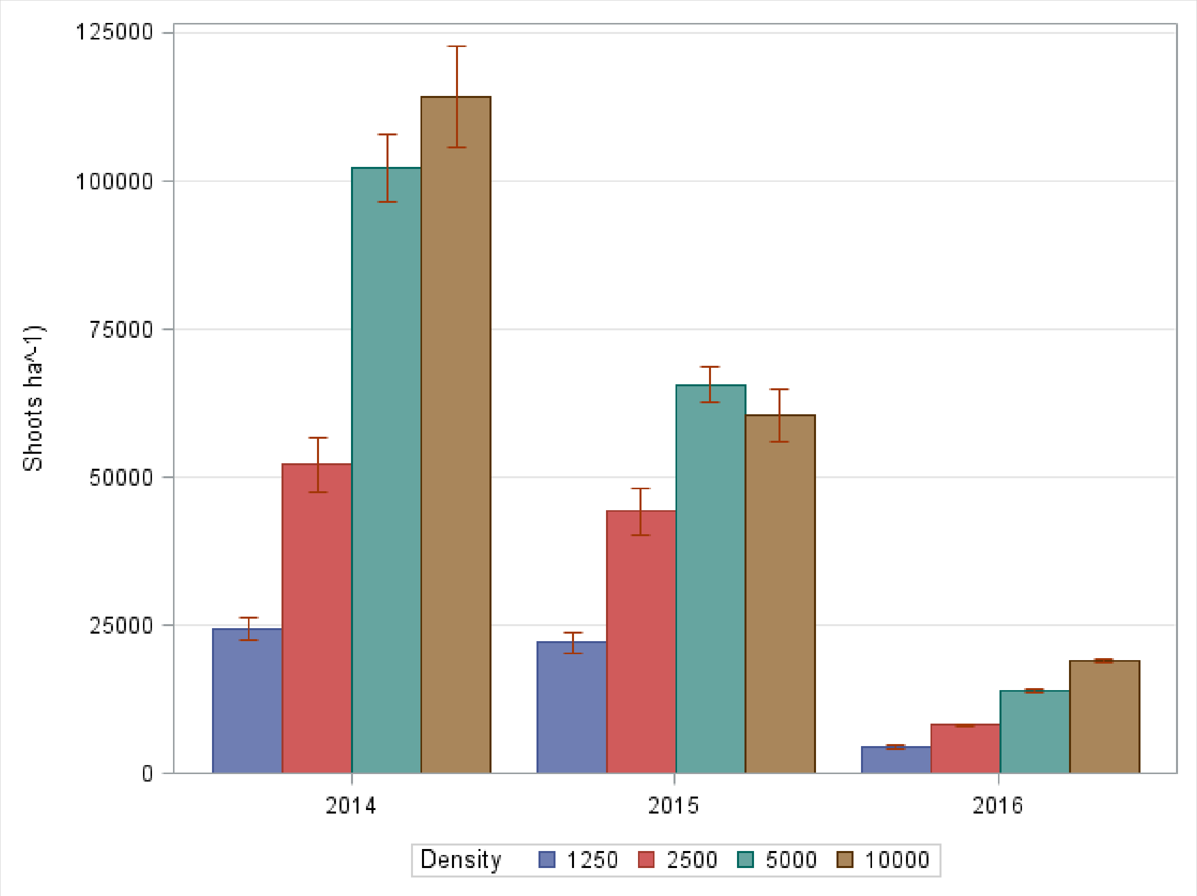


Figure 9. Average number of total shoot ha^{-1} at each of the original planting densities with standard error by spacing after the three growing seasons

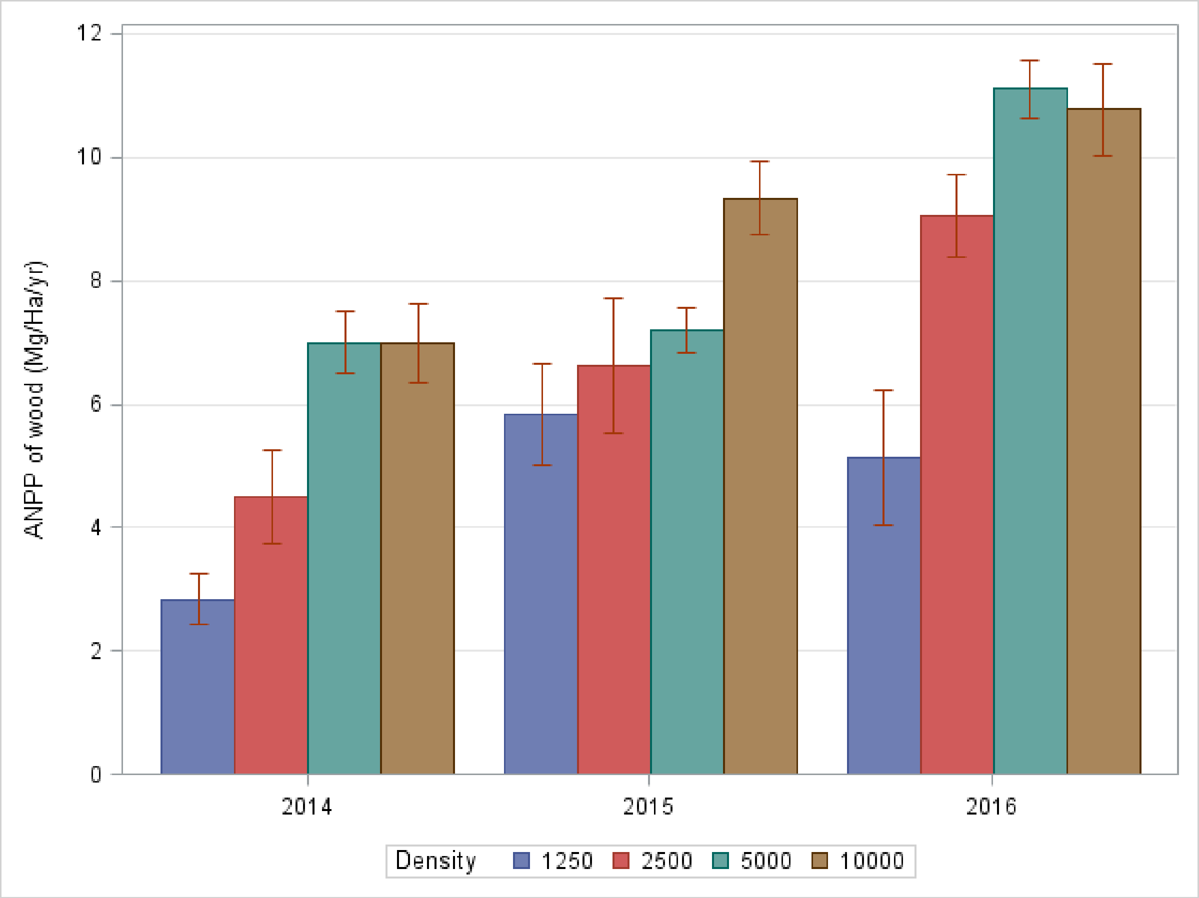


Figure 10. Above ground net primary production (ANPP) of wood with standard error for the three growing seasons

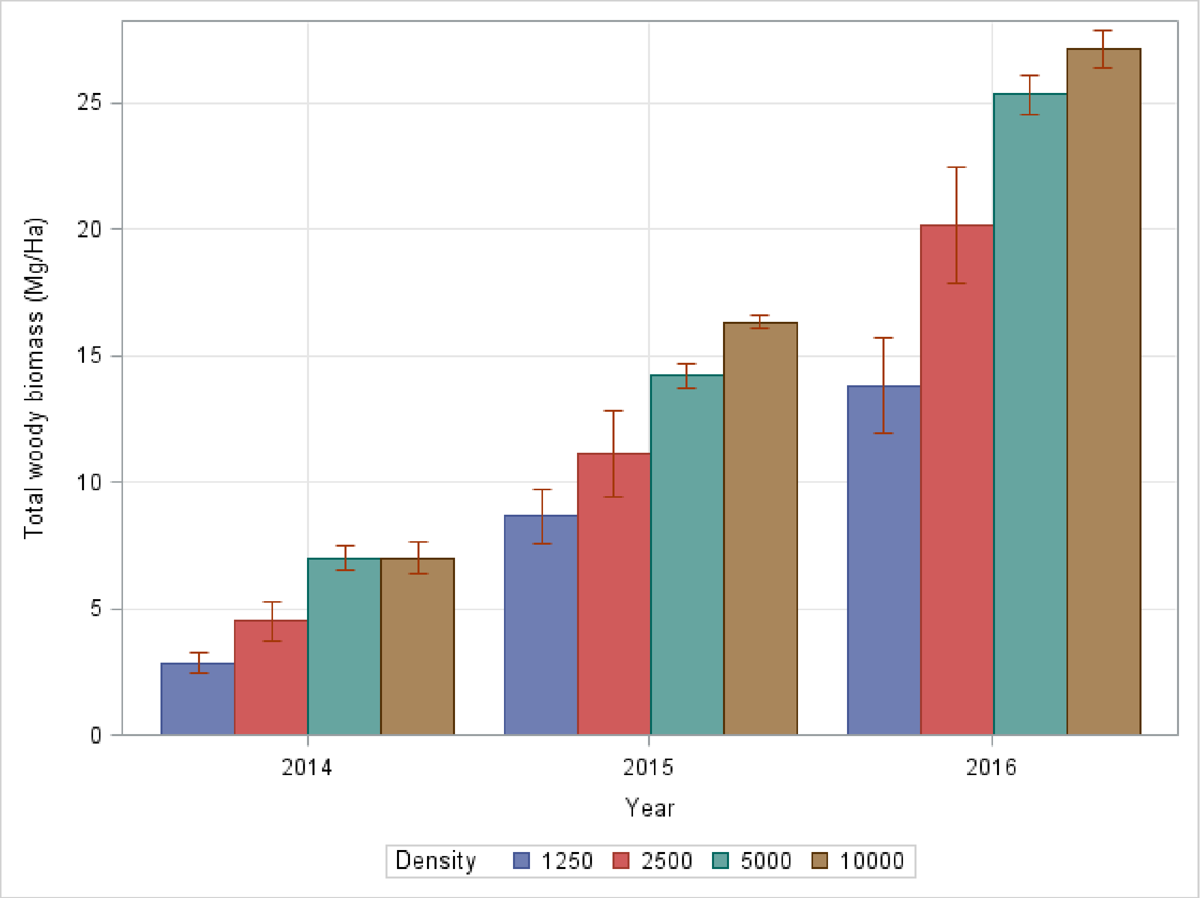


Figure 11. Cumulative sycamore total aboveground woody biomass by planting density with standard error for the three growing seasons.

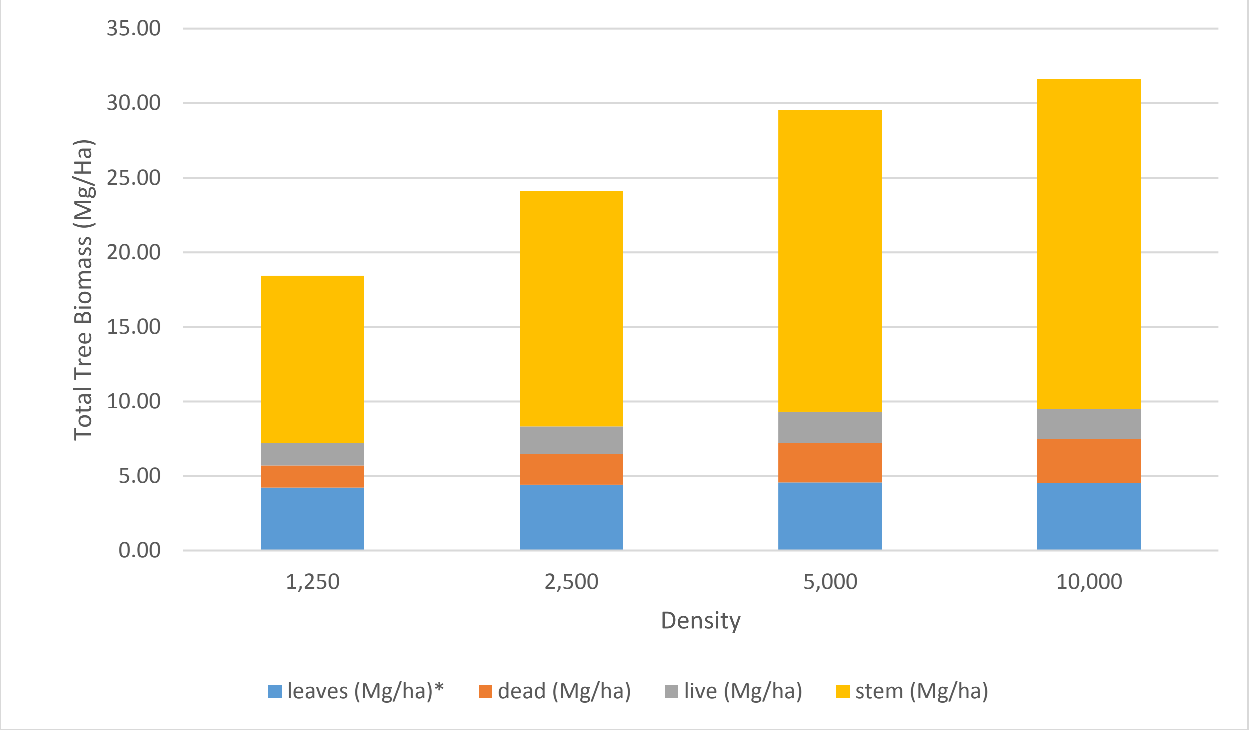


Figure 12. Mean (SE) total aboveground biomass of the trees (2016) partitioned into foliage, live and dead branches and stems by planting density.
*leaf biomass calculated from litter baskets

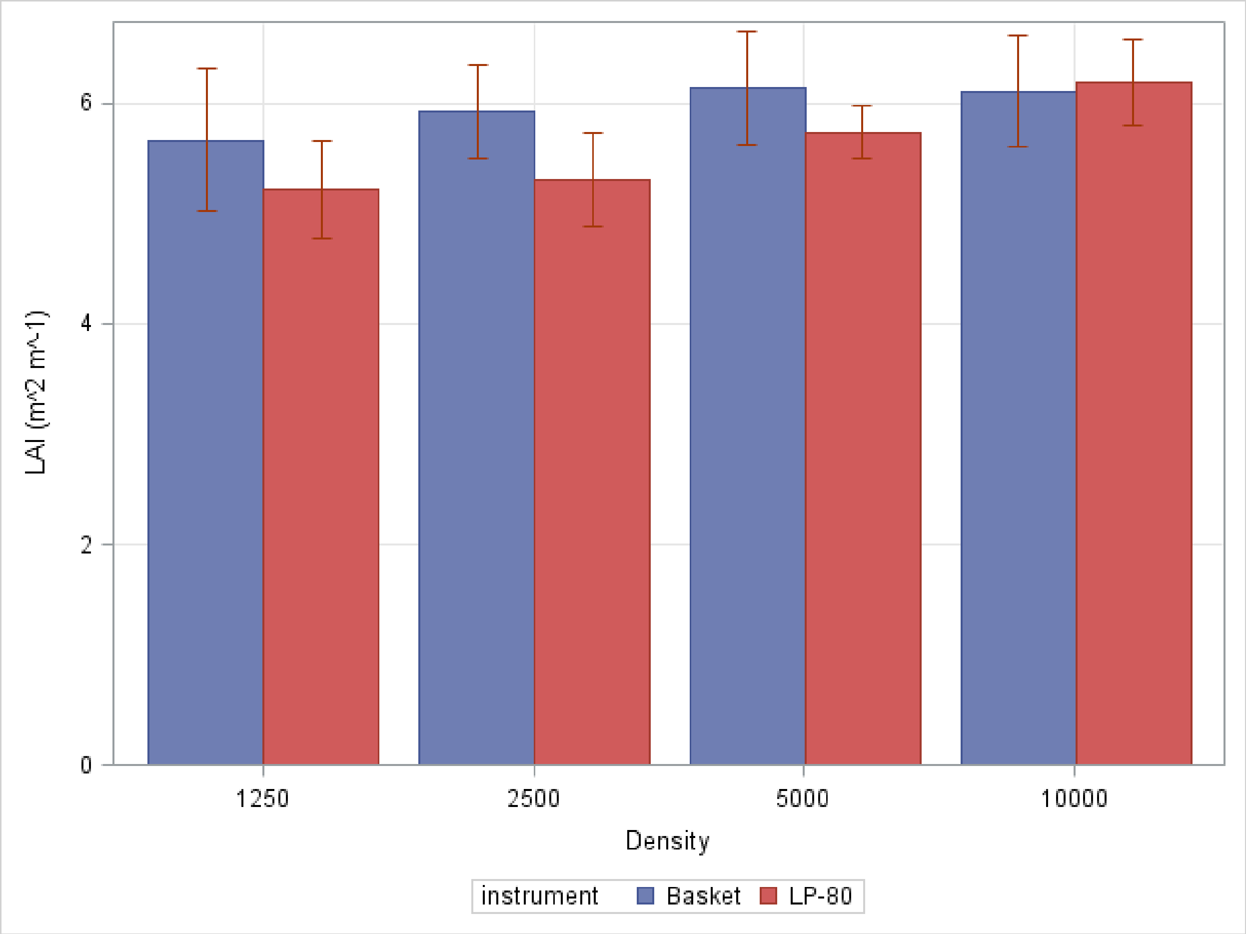


Figure 13. Comparison of leaf area index (LAI) measured with two different instruments: 2500 cm^2 litter baskets and a ceptometer LP-80 for the third growing season (2016).

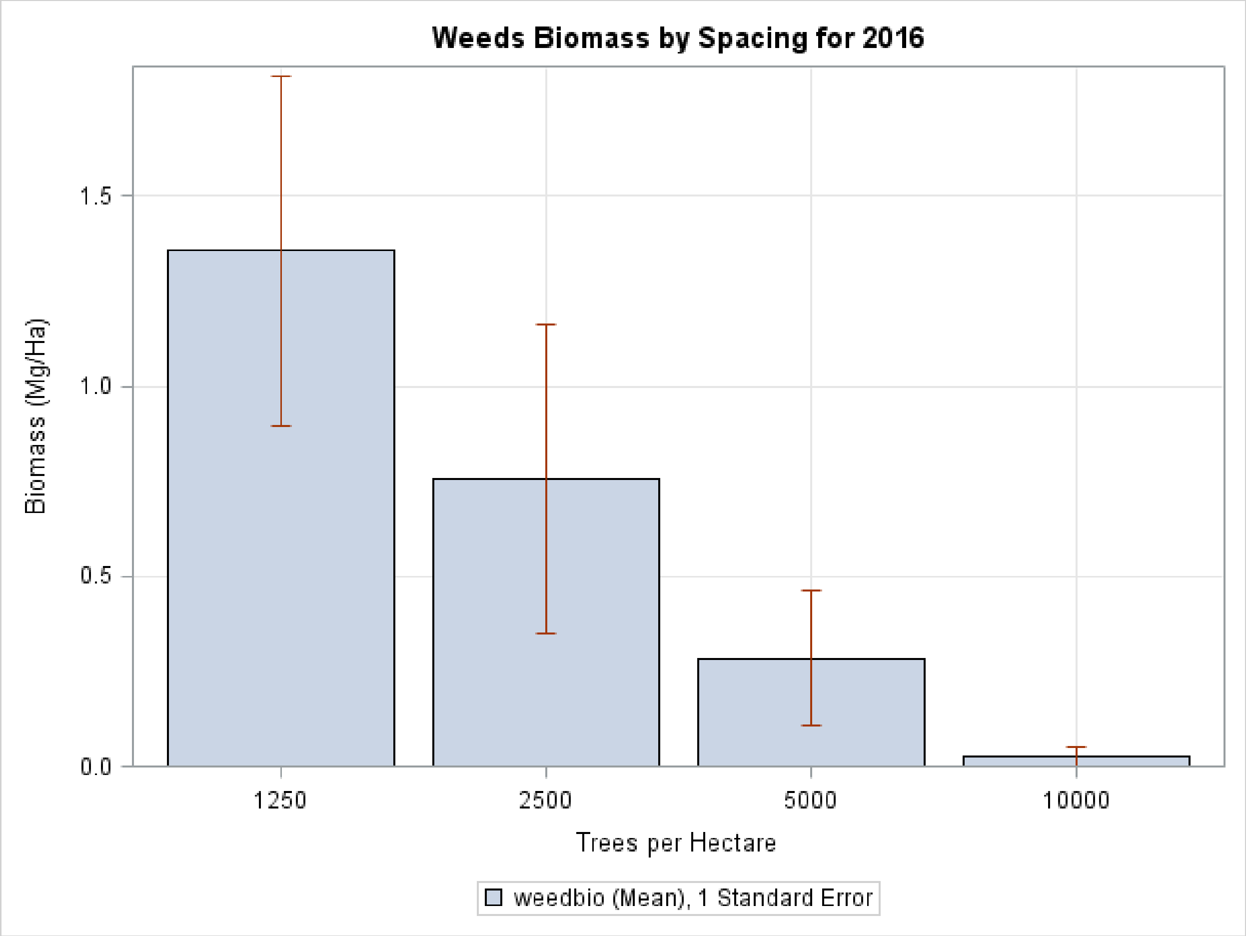


Figure 14. Mean (SE) total aboveground biomass of weeds by planting density (2016).