ABSTRACT

ILE, OMOYEMEH JENNIFER. Short-Rotation Coppice Culture of American Sycamore as a Purpose-Grown Feedstock for Bioenergy: Productivity and Effects on Soil Properties. (Under the direction of Dr. John S. King).

Short rotation woody crops (SRWCs) may be a sustainable form of biomass energy that can be integrated into combined energy-food production systems. This may help offset fossil fuel CO_2 emissions, reduce the use of environmentally harmful chemicals, and improve agricultural soil health. American sycamore has shown high SRWC productivity with low silvicultural inputs (fertilization, weed control, pesticides, or irrigation) when compared with other woody bioenergy feedstocks (Fischer et al., 2017). In this study, I quantified the biomass productivity of American sycamore after 5 growing seasons during the second SRWC rotation, quantifying the effects of four planting density treatments (10,000 trees ha^{-1}, 5,000 trees ha^{-1}, 2500 trees ha^{-1} and 1250 trees ha^{-1}) on productivity and soil properties. The mean cumulative aboveground biomass produced in the second rotation (39.12 ± 2.36 Mg ha^{-1}) was more than the 4-year first rotation (23.2 ± 0.9 Mg ha^{-1}) in the 10,000 tph treatment. Soil in the 10,000 trees ha^{-1} treatment had significantly higher saturated hydraulic conductivity and higher pore volume than the other planting densities. However, it also had the lowest amount of plant available water and soil field capacity ($p < 0.05$) of all planting density treatments. There was a significant amount of the large size class (>2mm) of water stable aggregates in all planting densities compared to the smaller sizes (1-2 mm, 0.50-1 mm, 0.25-0.50 mm, 53 µm-0.25 mm). Multivariate analysis showed that soil field capacity, saturated hydraulic conductivity, bulk density and mesopore space are the most important soil properties driving aboveground net primary productivity and mortality rate.

This study has shown that American sycamore SRWC managed with low silvicultural inputs has productivity comparable to other SRWC species and perennial grasses with higher inputs, while having the potential to improve agricultural soil properties.

Short-Rotation Coppice Culture of American Sycamore as a Purpose-Grown Feedstock for Bioenergy: Productivity and Effects on Soil Properties

by
Omoyemeh Jennifer Ile

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the degree of
Master of Science

Forestry and Environmental Resources

Raleigh, North Carolina

2020

APPROVED BY:

Dr. John S. King
Committee Chair

Dr. Joshua Heitman

Dr. Jodi Forrester

BIOGRAPHY

Omoyemeh Jennifer Ile was born on April 2nd, 1990 in Lagos, Nigeria to Helen Ile and Smart Ile. After getting her bachelor's degree in Forest Resources Management at University of Ibadan, she got married to Alvan Ukachukwu. Omoyemeh looked for opportunities to explore her passion for forestry and environmental resources, hence actively searched for opportunities to further her education in the United States. She was offered a graduate teaching assistantship position that allowed her to pursue a master's degree at North Carolina State University in the Department of Forestry and Environmental Resources in 2018. There she had an opportunity to work with successful colleagues in the Tree Physiology and Ecosystem Science Lab Group. In her master's thesis, she focused on Short-rotation coppice culture of American sycamore as a purpose-grown feedstock for bioenergy: productivity and effects on soil properties.

ACKNOWLEDGEMENTS

I would first like to express my gratitude to my advisor Dr. King for giving me the opportunity to pursue this degree by offering me the graduate teaching position. He further supported and guided me through the completion of my research project and writing of this thesis. I deeply appreciate his motivation, encouragement, and immense knowledge.

I would like to acknowledge my committee members, Dr. Heitman and Dr Forrester. Dr. Heitman guided me through the soil's aspects of this project with encouragement and insightful comments. Dr. Forrester provided her ecological expertise and knowledgeable comments as well.

I thank the post-doctoral fellows in the Tree Physiology and Ecosystem Science Lab at NCSU: Kevan Minick and Maricar Aguilos, Kevan for helping me with some soil analysis in the lab and Maricar for helping me with some of my data analysis. I acknowledge my other lab group members Suna Morkoc, Chandler Cowell, An Le, Deanna Hardesty and Maccoy Kerrigan for supporting with field work.

I am extremely grateful to my husband, Alvan Kelechi Ukachukwu for his endless support and helping with editing this thesis. I am grateful for my parents, for the sacrifices they made in providing me with good education up until college. Lastly, and with all my heart I appreciate my two beautiful daughters, Nnenna and Kosi, the thought of you two is all the strength I need to push forward.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: WOODY BIOMASS ENERGY, SHORT ROTATION COPPICE CULTURE OF TREES AND AMERICAN SYCAMORE: A LITERATURE REVIEW

Need for alternative sources of energy

Due to the world's growing population, millions of barrels of crude oil are used daily to meet energy needs. By 2030, it is projected that over 110 million barrels per day will be used, compared to the 91 million barrels we use presently (IEA 2007). With this increase in the use of crude oil, there is a projected depletion of oil reserves, which calls for concern on energy security and volatile oil prices (Hill et al., 2008). Furthermore, the variability and hostile politics of the oil market in many oil-rich countries of the world have proven the need for renewable energy technologies which are sustainable and financially viable (Debbage and Kidd., 2011). In addition, the effects of greenhouse gas (GHG) emissions as well as local air pollution on human welfare are of great concern (Hill et al., 2008), indicating the need for development of alternative sources of energy. Alternative, renewable energy systems include but are not limited to solar energy, wind energy and biofuels. In this work, we focused on biomass, a renewable energy source that can be produced domestically from a wide variety of plant materials like herbaceous perennial crops, crop residues and woody bio-energy species. Biomass-based fuels can offset the effects of GHG emissions, as well as enhance domestic economic development by supporting rural economies and industries which make bio-based products (Malmsheimer et al., 2008).

Bioenergy research has been mainly on herbaceous perennial crops, and less on woody energy species (Domec et al., 2017). Presently, crop residues such as corn stover are the prime lignocellulosic feedstock for producing ethanol in the U.S (Blanco-Canqui, 2010). However, corn grown for ethanol production is carbon intensive and dependent on large fertilizer and water inputs to sustain high yields. This can increase production costs greatly, add carbon to the atmosphere during fertilizer production and tillage, and can potentially reduce the water table (King et al., 2013). A more sustainable feedstock for bioenergy production would be second-generation biofuels, which are renewable fuels from cellulosic woody biomass of trees. Trees have a relatively unlimited biomass potential unlike other biomass species, such as perennial grasses. Another advantage of woody biomass-based energy over corn ethanol is the reduction of competition with agricultural crops for global food supply. Furthermore, trees grow deep roots to access water, and their root systems provide higher carbon inputs to soil through root turnover, in contrast to shallow root systems of annual crops (Pimentel, 2003 and King et al., 2013). Woody bioenergy systems may provide ecosystem services such as soil restoration, build-up soil organic matter, recycle nutrients, and maintain vegetative cover (Brinks et al., 2011).

Woody biomass for bioenergy production

The US Department of Energy considered wood to be the major potential source of renewable biomass energy when forest plantations are managed intensively (Geyer and Melichar, 1985).Wood burns highly efficiently, with relatively low emissions of sulfur dioxide and methane, making woody fuel preferable to coal and natural gas (Naik et al. 2010). Woody biomass used for energy is often comprised of residues from the production of lumber, pulp and paper, and other wood products. The processes of converting woody biomass into energy include direct burning, conversion to ethanol as lignocellulosic biofuels, hydrolysis and fermentation, pyrolysis, by gasification, charcoal, making pellets, and briquettes (Naik et al., 2010, Malmsheimer et al., 2008). The United States National Defense Authorization Act of 2010 has mandated federal agencies to produce or consume 25 % of their total energy from renewable energy sources beginning in 2025

(Ghezehei et al., 2015). Therefore, wood pellets from forest biomass have potential to play a major role in the future of global renewable energy and are already in high demand for power generation in Europe. This initiative has led to a thriving wood pellet industry in the Southeastern US, where several wood mills produce pellets from micro-chips in North Carolina (Little et al., 2013). Wood pellets are shipped to Europe at a large scale to meet increasing demand there. Therefore, wood pellet production provides an opportunity for North Carolina if sustainable production rates of 8-10 Mg ha^{-1} yr^{-1} of woody biomass can be demonstrated (English et al., 2006; Little et al., 2013), providing a diverse source of income for landowners and rural communities in North Carolina (Susaeta et al., 2009; Nesbit et al., 2011). It has been shown that consumers in the state are willing to pay more for cleaner sources of energy, such as wood- based biofuels (Susaeta et al. 2010).

Short Rotation Woody Crops (SRWCs) may offer high productivity in varying environmental conditions and reliable economic returns on investment when grown on marginal lands (Fischer et al., 2017; Domec et al., 2017). With a fast growth rate and good productivity at age 3-5 years, they can provide a continuous supply of biomass as they re-sprout into multiple stems after coppicing. Growing SRWCs on marginal lands minimizes concerns about using cropland for bioenergy production (Ghehezei et al., 2015). It may also help to alleviate the decline of timber and wood pellet markets, as urbanization continues to reduce forest acreage in the Southeastern US (Wear and Greis, 2013). Growing SRWC trees may thus provide an income to the farmer, as well as a needed carbon-neutral energy resource. It has been estimated that the US needs 16 to 21 million ha of marginal land to meet the 2022 mandate for cellulosic ethanol (Lewis and Kelly, 2014). Europe requires 17 to 30 million ha of land to achieve their 10 % bioenergy target by 2020 (Scarlat et al., 2013). The genera *Populus* L. and *Salix* L. are the most widely investigated SRWC candidate trees (King et al., 2013; Fischer et al., 2015). However, many fast-growing species of these genera are not native to the southeastern US region and cannot tolerate summer droughts as well as high temperatures (Fischer et al., 2015). When cultivating a species for maximum productivity needed for a bioenergy feedstock, tolerance to environmental stresses, such as drought, should be an important consideration (King, et al., 2013).

Integrating short rotation woody crops into conventional agricultural practices

Agroforestry systems are farming systems that integrate trees into agricultural practices, providing positive effects to farmers and landowners. Jose et al., (2012) stated that agroforestry systems are well suited for diversifying farmer income while providing environmental services and ecosystem benefits, thus increasing receptivity on the part of some landowners, with the potential to produce more food from the diminishing land resource and maintain crop productivity sustainably (Ferdush et al., 2018). Globally, tree products may create opportunities for small-scale forest-based enterprises and increase the number and diversity of jobs, especially for young people (FAO, 2017). This diversification helps stabilize revenues in the face of fluctuations in the prices obtained for commodity crops (FAO, 2017). Intensive agriculture has resulted in the removal of trees, and attendant ecosystem services, from agricultural landscapes. Short rotation woody cropping systems provide an opportunity to combine annual food production with woody plants for biomass production by integrating fast-growing trees into conventional agricultural sites.

The farming of fast-growing trees has been demonstrated as SRWC, where trees are planted in high densities and harvested after 3-6 years (Bohm et al., 2014). American sycamore has the potential to produce high yields in a 3-year rotation length when planted at a density of 10,000 trees ha^{-1} in the first rotation cycle (Fischer et al., 2017). Hence, they have the potential to be used in agroforestry systems such as fallowing, where tree crops are planted on agricultural land that have been left uncultivated. In addition, woody crops provide more ecological benefits such as higher nutrient use efficiency, low input requirements (herbicide, pesticide and fertilizer), while reducing soil erosion, compared to annual plants or leguminous crops (Tsonkoya et al., 2012).

With the increased understanding of the strengths and weaknesses of agroforestry practices has come an increased receptivity of landowners to explore its use to address farm-related environmental issues (Udewatta et al., 2002). However, progress on acceptance by practitioners, farmers and policymakers has been hindered by paucity of evidence to support the practice (Jose et al., 2012). For a wide adoption of bioenergy production from trees by industry and farmers, farmers should be able to achieve the same success as they would with conventional food crops (Fischer et al., 2017). Further, consideration should include maintaining high productivity in variable environmental conditions using low silvicultural inputs. Low inputs, as well as the coppicing system of bioenergy trees, will reduce plantation establishment costs for growers, diversify farm income, and increase pest resistance while maximizing environmental benefits

SRWC American sycamore as a potential bioenergy tree crop

American sycamore (*Platanus occidentalis* L.) is a tree species native to the Southeastern US. In contrast to other native hardwood species considered difficult to establish, sycamore has shown superiority in survival, biomass increment, and resilience to adverse conditions (Fischer et al., 2017; Steinbeck et al., 1972). It has fast growth with medium wood density, excellent coppice ability, and very thin bark (low ash content), and can thrive on highly degraded agricultural areas

(Isenburg, 1981; Brinks et al., 2011). It was once considered one of the most promising hardwood plantation species in the Southeastern US, grown for a wide range of uses, including furniture, pulpwood, fiberboard, and fuel uses. However, there has been a decline in the study of American sycamore, partly due to the development of an anthracnose disease that caused high mortality of American sycamore trees in plantations of up to 13 years or more (Filer, 1975). Coppicing the stems for SRWC could be a way to keep shoots in the juvenile stage, preventing disease such as anthracnose from forming on mature trunks (Filer, 1975). As such, current research focuses on growing the species in SRWC for bioenergy in short rotations of under 5 years (Domec et al., 2017; Fischer et al., 2017).

A review of bioenergy studies throughout the Southeast show American sycamore biomass production ranges from 2.4 Mg ha^{-1} yr^{-1} to 14.5 Mg ha^{-1} yr^{-1}, depending on site, silvicultural inputs and planting density (Henderson et al., 2010). Studies have shown increased productivity of sycamore after coppicing because of stored sugars in the roots (Steinbeck et al., 1972). This allows shoots to sprout quickly from stool, producing a large amount of biomass quickly (Sullivan 1994). Coppiced five-year-old American sycamore had higher mean annual increment ranging from 7-17 Mg ha^{-1} yr^{-1} than non-coppiced sycamore, with mean annual increment of 9.6 Mg ha^{-1} yr^{-1} and 9.4 Mg ha^{-1} yr^{-1} at five and ten years, respectively (Ghezehei et al., 2015). This suggests sycamore is a good candidate for bioenergy SRWC, with increasing productivity through multiple rotations (Davis and Trettin, 2006). Therefore, we expect higher productivity of American sycamore during its second rotation. Research on sycamore has been limited to the pulp and paper industry with little investigation of productivity, stress-tolerance, energy value and potential ethanol yield (Domec et al., 2017). Studies have reported changes in wood quality depending on planting density, such as specific gravity of the stem wood increasing with wider spaced trees and decreased wood density with tightly spaced trees (Olson and Wittwer, 1980). Furthermore, there are no known studies that investigate the effect of tree spacing on the productivity and growth response of sycamore grown as a bioenergy feedstock other than Domec et al. (2017). The current study adds to that analysis by quantifying productivity potential of SRWC American sycamore over multiple rotations on a marginal site in the Piedmont of North Carolina.

CHAPTER 2. EFFECT OF SPACING ON ABOVEGROUND BIOMASS PRODUCTIVITY OF COPPICED AMERICAN SYCAMORE

Introduction

The evolving need for alternative fuel (woody biomass) has caused a decline in forests in many parts of the world, the source of woody biomass, making it difficult for resource managers to meet these needs sustainably (FAO, 2017). Thus, it is essential to find possible long-term solutions that will preserve our natural forests (Hauk et al., 2017). One possible solution being investigated to meet the increasing demand for woody biomass is short-rotation coppice of fast-growing tree species, also known as Short Rotation Woody Crops (SRWCs), on agricultural land (Foley et al., 2011). This planting system has the potential for higher productivity than conventional tree systems grown on forestland. Although growing SRWCs on agricultural land may result in competition for land with food crops, there are environmental and economic benefits to the land use change where these lignocellulosic crops can store above and belowground carbon, thereby mitigating greenhouse gas emissions (Dimitriou et al., 2012; Rowe et al., 2009; Paquette et al., 2010). Furthermore, the production of woody biomass is energy efficient, requiring minimal to no inputs such as pesticides and fertilizers (Fischer et al., 2017; Domec et al., 2017). It further has the capacity to provide energy security, labor options and a source of diversified income, particularly in rural communities (Dale et al., 2011). The adoption of SRWCs into conventional American agricultural systems offers economic diversifications, increasing agriculture profits while providing effective risk-management strategies. Despite the benefits of SRWCs planting system, it has not been widely adopted in North America, mainly due to economic and socio-economic reasons (Hauk et al., 2014; Hauk et al., 2017).

There is long-term data on the biomass productivity of corn and perennial grasses as a result extensive bioenergy research on these species compared to woody bioenergy species (Domec et al., 2017). Short rotation woody cropping systems are resilient to climate variability, adaptable to existing managed and natural uses, and provide ecosystem services (King et al., 2013; Johnson et al., 2007). Studies on the effect of planting density on wood quality have involved high inputs such as fertilization, irrigation or both (Brinks et al., 2011; Davis and Trettin, 2006; Coyle and Coleman, 2005; Olson and Wittwer, 1980; Steinbeck et al., 1972). To optimize sustainability of bioenergy SRWC, plantings need to be established on marginal land using low silvicultural inputs. Research on sycamore established on marginal land in Southern US shows higher productivity than black locust (Brinks et al., 2011), sweetgum (Davis and Trettin, 2006), cottonwood, and oak (Henderson et al., 2010).

Planting at high density increases (short-term) productivity, although it requires more resources and larger economic investment. However, this can be compensated for as closely spaced American sycamore trees were shown to shade out competing vegetation, decreasing the need for weed control in the first growing season compared to wider spaced trees (Steinbeck et al., 1972). Furthermore, planting trees at wider spacings reduce intra-specific competition, less efficient nutrient-use, and inability to shade out competing vegetation which could increase stool mortality (Domec et al., 2007; Ashley, 2015). Higher planting densities produce smaller individual trees, higher total aboveground biomass, more partitioning to stem wood than tree branches, and are favored for SRWC. This suggests that short rotation coppicing of American sycamore could be ideal for supplying future energy demands. A study of the effects of planting density on American sycamore in a low input system, and its effects on woody biomass over multiple rotations is required. This study quantifies the effects of planting density on the productivity of coppiced sycamore at the end of the second five-year rotation.

Hypotheses and objectives

In this study, I investigated the productivity of a low-input American sycamore SRWC (no fertilization/irrigation/herbicides) after the fifth growing season of the second rotation in the piedmont of North Carolina. An allometric approach that scales to the stand level (King et al., 1999) was used to quantify aboveground biomass production. I examined the effects of planting density treatments on biomass productivity.

The null hypothesis for this study was that planting density would not affect aboveground biomass production. The alternative hypotheses were:

1) Planting density is directly proportional to the amount and partitioning of biomass produced. That is, biomass partitioning will be more towards stems relative to branching at higher planting densities.
2) Aboveground net primary production will be higher than the previous rotation due to the established root system.
3) Lowest planting density will have more stool mortality relative to higher planting densities.

Materials and Method

Study site

The study site is located on North Carolina Department of Agriculture and Consumer Services land near Butner, North Carolina (36° 7'58.20"N 78°48'26.49"W). It is in the Piedmont physiographic region 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 from a nearby weather station showed the average high temperature of 21.2 ^{o}C and average low of 8.8 ^{o}C with an average rainfall of 122 cm for the year. The rainfall in the growing seasons of 2017 & 2018 (May-September) totaled 51.3 cm in 2017 and 51.0 cm in 2018 (North Carolina Climate Office, US Climate data, http://www.usclimatedata.com/climate/durham/north-carolina/united-states/usnc0192). Bare-root seedlings were purchased from the North Carolina Forest Service Tree Seedling store and hand planted to establish the site. At initial establishment, there was a single application of glyphosate herbicide between rows at planting and mowing for weed control.

Experimental design and treatments

The study site was established in January of 2010 to quantify the effects of planting density and drought on the aboveground biomass productivity of sweetgum (*Liquidambar styraciflua*), American sycamore (*Platanus occidentalis*), tuliptree (*Liriodendron tulipifera*) and the hybrid poplar 'NM6' (*Populus nigra* × *P. maximowiczii*) grown as a short rotation coppice culture in the Piedmont of North Carolina. However, after two growing seasons sweetgum, tuliptree, and poplar all suffered exceedingly high mortality, despite replanting and competition control efforts. American sycamore experienced very minimal mortality (<3%) after the second year (Domec et al., 2017). Therefore, the study continued to quantify aboveground biomass productivity of sycamore alone. The trees were coppiced in March of 2014 to complete the first rotation and begin the second rotation, with no additional weed control or other inputs. The study was set up as a 4 x 2 randomized complete block design with throughfall reduction and planting density treatments, replicated three times. In 2012, the drought treatment was created by installation of PVC gutters that covered 20 % of the plot surface area, 50 cm above the soil surface to avoid artifacts to the soil and divert water off the plots. This treatment was to investigate effects of changes in precipitation with climate change/drought on tree biomass productivity. The 4x2 completely randomized block design study used to quantify biomass productivity consisted of:

- 3 blocks as replicates, to control for slope topography on the site
- 4 planting density treatments (0.5 x 2.0 m (10,000 trees ha^{-1}), 1.0 x 2.0 m (5,000 trees ha^{-1}), 2.0 x 2.0 m (2,500 trees ha^{-1}), and 4.0 x 2.0 m (1,250 trees ha^{-1}) randomized within each block,
- 2 drought treatments per planting density (20 % reduction and control) randomized within each block,
- 24 plots in total. Each plot size (14 m x 14 m).

Inventory and biomass allometry measurements

For the fourth and fifth growing seasons (2017 and 2018), diameter at breast height (DBH) was measured on the three dominant shoots of each tree for allometric biomass regressions. For the fifth growing season, one individual shoot from each of the planting densities (control or 20% reduction) on each block was harvested, measured, and weighed (12 shoots total). Branches were partitioned into live and dead, and weighed to derive individual diameter to weight ratio. Some samples of stems and branches were dried to 70 °C and reweighed to measure the water content. Tree diameters were converted into basal area (BA) and summed to give total BA to weight ratio excluding trees growing on the edge of plots to avoid overestimating productivity, since these trees receive more sunlight and have more space to grow. Biomass regression equations from a previous study conducted at the same site (Boone, 2017) were used to quantify biomass/productivity of all individual trees and components (stem wood, live branches, dead branches) in a plot for 2017 and

2018, which were then summed to arrive at plot-level estimates (per unit ground area), then scaled to the stand level (e.g. Mg ha^{-1}). The diameter ranges for the previous and current study are between 10 mm – 58 mm. The site-specific equations (Boone, 2017) were:

Table 1.1. Biomass regression equation used to estimate productivity of American sycamore

Estimated variable	Biomass regression equation	R^2
Total tree	$0.0013(BA)^{1.0922}$	0.9594
Total stem weight	$0.0015(BA)^{1.0447}$	0.9751
Total live Branches	$0.00002(BA)^{1.3088}$	0.6649
Total dead Branches	$0.00002(BA)^{1.0426}$	0.7466

Total foliage biomass was calculated by subtracting the sum of the other predicted components (stem weight, live and dead branches) from Total tree. Aboveground Net Primary Productivity (ANPP) was derived by subtracting the total tree biomass of the previous year (2017) from the current year (2018).

Statistical analysis

Statistical analysis (PROC GLM) was performed with SAS statistical software (SAS Institute, Cary, NC) using a significance level of 0.05. Further analysis was conducted in case of significant differences between treatments (α < 0.05) using Tukey adjustment for LSMeans with significant values indicated in bold.

The statistical linear model used to analyze tree 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 aboveground biomass plot totals (Mg ha^{-1}) for total tree, stem wood, dead branches, live branches, leaves; 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. Block was treated as a fixed effect.

RESULTS

Aboveground biomass

Consistent with previous studies, the effect of the throughfall reduction treatment (drought) was not significant for all tree variables tested (*P-0.5*). Therefore, data were averaged over drought treatment for all analyses of the current study. At the end of the fifth growing season, there were significant effects of the planting density treatments on aboveground biomass. Mean cumulative aboveground biomass was significantly greater in the 10,000 tph (39.12 ± 2.36 Mg ha^{-1}), and the 5,000 tph (36.52 ± 0.96 Mg ha^{-1}), planting density than the two lower densities *($P < 0.05$)* (Tables 1 and 2, Figure 3). The 2500 tph treatment had biomass of 22.05 ± 1.48 Mg ha^{-1} , which was significantly greater than the 1250 tph treatment which had the lowest biomass of 14.48 ± 1.56 Mg ha^{-1} *($P < 0.001$)* (Tables 1 and 2, Figure 3).

During this second rotation of the SRWC plots, total tree biomass increased between the third-to-fourth and fourth-to-fifth growing seasons (Figure 4). The 10,000 tph treatment increased total biomass 11 % between the third and fourth growing seasons (27.11 to 30.09 Mg ha^{-1}), and had the highest percentage of growth at 30 % (30.09 to 39.12 Mg ha^{-1}) between the fourth and the fifth growing seasons, compared to the other planting densities. The 5,000 tph treatment had a 19.6 % increase in total biomass (25.31 to 30.27 Mg ha^{-1}) between the third and fourth growing seasons, and a 20.6 % increase (30.27 to 36.52 Mg ha^{-1}) between the fourth and fifth growing seasons. The 2,500 and 1,250 tph had the lowest growth percentage increases. Between the third and fourth growing season, the 2500 tph had 2.3 % increase in total biomass (20.17 to 20.63 Mg ha^{-1}), and a 6.9 % increase between the fourth and fifth growing seasons (20.63 to 22.05 Mg ha^{-1}). The 1,250 tph treatment had the least increase of only 0.43 % (13.81 to 13.87 Mg ha^{-1}) in aboveground total tree biomass between the third and fourth growing seasons, and 4.4 % increase (13.87 to 14.48 Mg ha^{-1}) between the fourth and fifth growing seasons (Figure 4).

Aboveground Net Primary Productivity

After five growing seasons, the highest wood aboveground net primary production ($ANPP_{wood}$) was recorded in the 10,000 tph planting density treatment, with an average of 9.03 Mg ha^{-1} yr^{-1} (SE 1.67). $ANPP_{wood}$ in the 1,250 tph planting density level was significantly *($P < 0.05$)* lower than all other densities, at 0.61 Mg ha^{-1} yr^{-1} (SE 0.13). $ANPP_{wood}$ for the 5,000 tph treatment was 6.25 Mg ha^{-1} yr^{-1} (SE 1.81), and 4.22 Mg ha^{-1} yr^{-1} (SE 1.90) for the 2,500 tph planting density (Tables 1 and 7, Figure 5).

Biomass Partitioning

In all planting densities, stem wood made up majority of the biomass proportion ranging from 74 % to 79 %, from the lowest to the highest planting density treatments, with statistically significant differences (($P < 0.001$), Table 3, Figure 7). Planting density treatments affected other biomass components (live branches, dead branches and leaves), with the highest planting density treatments producing significantly more biomass in these parts (Tables 4,5,6, Figure 7). Dead branch biomass was the lowest component regardless of planting density, at about 1 % of the total biomass.

Stool mortality rate

The 1,250 tph treatment had a significantly higher mortality rate of 15 % compared to the other planting densities *($p = 0.00$)*. The other three planting density treatments had minimal mortality, ranging between 1-5% with no significant differences (Table 1 and 8, Figure 8).

DISCUSSION

Aboveground Net Primary Production

American sycamore SRWC has great potential to help meet the growing demand for alternative fuel production/energy, and the United States Public Law 110-140 mandates of an increase in biofuel production from 34 hm^3 in 2008 to 136 hm^3 by 2022 (Kline and Coleman, 2010). Results from the current study are consistent with previous studies that show high productivity of coppiced American sycamore on eroded Piedmont soils of North Carolina with low silvicultural inputs (Fischer et al., 2017; Domec et al., 2017; Boone, 2017). This reduces concerns of the loss of agricultural land being used for bioenergy production (Ghezehei et al., 2015), and provides economic and environmental advantages due to the use of minimal inputs.

In the current study, I observed an average ANPP of 5.0 Mg $ha^{-1}yr^{-1}$ woody biomass across planting densities at the end of the second 5-year rotation, with the highest planting density treatment producing as much as 9.0 Mg biomass $ha^{-1}yr^{-1}$. In another study in North Carolina, the mean productivity of non-irrigated *Populus* and American sycamore tree crops ranged from 2.4 – 5.3 Mg $ha^{-1}yr^{-1}$ and 2.5-7.6 Mg $ha^{-1}yr^{-1}$, respectively (Ghezehei et al., 2015). Contrary to my hypothesis, this was a decrease from the first 4-year rotation, where American sycamore produced over 7.0 Mg $ha^{-1}yr^{-1}$ without additional inputs at this site (Domec et al., 2017). It was also a decrease from the average productivity of 9.0 Mg $ha^{-1}yr^{-1}$ recorded in an earlier study at this site (Boone, 2017). The study of Boone (2017) showed similar biomass productivity as southern Appalachian hardwoods, within a productivity range of 8.0-10.0 Mg $ha^{-1}yr^{-1}$, and other low-input SRWC that have been considered profitable (Bolstad et al., 2001; Fischer et al., 2015). A decrease in ANPP was noted in the first rotation of this study, due to the loss of dead branch biomass (Ashley, 2015). Furthermore, shorter rotation lengths of the right species established at suitable sites are more favorable for SRWCs to achieve high productivity, reduce pest infestation and improve economic performance (Ghezehei et al., 2015; Fischer et al., 2017).

Total tree biomass and biomass partitioning

Cumulative total biomass productivity continuously increased from 2014, the beginning of the second rotation, to 2018 at the end of the rotation, although, the rate of increase declined after the third year (Figure 2). The total woody biomass productivity at the end of the second rotation of 39 Mg ha^{-1} was higher than the end of the first 4-year rotation of 23.16 Mg ha^{-1} due to the pre-existing root systems/stool from the previous rotation. Establishing bioenergy trees at high planting densities increases intraspecific competition and efficient nutrient-use, leading to higher biomass productivity in shorter rotation lengths to meet feedstock demands (Burkes et al., 2003). Therefore, my results support the hypothesis that planting density does affect biomass productivity, with the high density planting treatments (10,000 tph and 5,000 tph) having the smallest size of individual trees, but the highest amount of biomass yield compared to the lower density planting treatments (Table 1 and 2, Figures 3 and 4). Furthermore, intraspecific competition results in changes in biomass partitioning with more allocation to stem wood and lower allocation to branches at high densities (Burke et al., 2003; Domec et al., 2017). In all four planting densities of the current study, stem wood had much more biomass, up to 79% of the total biomass, compared to the other biomass components, followed by foliage and then branches (Table 1, Figure 7). This result supports the hypothesized allocation of more biomass towards the stem. The foliage biomass ranged from 1.95 to 4.32 Mg ha^{-1} across planting densities, where the 10,000 tph and 5,000 tph had similar values of 4.32 Mg ha^{-1} (Table 1). In studies by Burkes et al. (2003) and Wood et al. (1977), investigating the relationship between stand density and leaf biomass, they reported little change in the leaf mass allocation at different planting densities. Coppicing of American sycamore may extend the lifespan of the plantation by keeping the trees in the juvenile stage, thereby reducing the possibility of disease infestation such as anthracnose (Filer, 1975). Multiple rotations of hardwood SRWC improves the environmental footprint of bioenergy by avoiding the energy-use involved with plantation establishment, and higher ecosystem C storage from decreased site disturbance (Djomo et al., 2015).

Stool mortality rate

As hypothesized, the 1,250 tph treatment had the highest stool mortality rate, at 15 %, consistent with an earlier study (Domec et al., 2017). It is uncertain why this occurred, but perhaps intense competition with competing weeds due to the high light environment after coppicing played a role, and as such, it contributed to the low biomass productivity at low planting density. Due to the larger spaces in between trees in each row, it is difficult for a tree to take up the space of a dead tree (Table 1 and Figure 8). The impact of mortality on biomass productivity may eventually become insignificant with longer rotation lengths and as trees occupy more growing space (Boone, 2017). The low mortality in the 5,000 tph treatment, along with its high total woody biomass of 36.0 Mg ha^{-1}, which was statistically not different from the 10,000 tph treatment (39.0 Mg ha^{-1}), suggests this planting density may be the most economically viable option. Establishment costs would be greatly reduced due to purchasing and planting half the number of trees as the 10,000 tph planting density, in turn increasing profit for the landowner or farmer.

CONCLUSION

American sycamore SRWC produced total wood up to 39 Mg ha^{-1} biomass and ANPP up to 9 Mg $ha^{-1}yr^{-1}$ by the end of its second 4-5-year rotation with minimal silvicultural inputs. An advantage of the second (and subsequent) rotation(s), is that it produced more biomass than the first rotation, without the cost of a new plantation establishment, that is, no planting labor cost, no seedlings cost, nor herbicides or fertilizer application costs. The only investment in the second rotation is the coppicing cost, which is cheaper than other associated costs of new establishment. This illustrates the advantage of coppiced SRWCs over pines, which would have to be re-planted with each rotation. Planting density affected biomass productivity, biomass partitioning, and mortality rates, with the higher planting densities producing more biomass, and proportionally more of it was allocated towards the stem. The 5,000 tph treatment seemed to be an economically viable option, it produced total woody biomass of 36.0 Mg ha^{-1}, similar to the 10,000 tph treatment of 39.0 Mg ha^{-1} and would cost less to establish compared to the latter. The established root systems/stools from the previous rotation greatly increase the speed of establishment of the new stand, and early productivity, and likely provide additional ecosystem services such as preventing soil erosion and fostering biodiversity. The current study shows that American sycamore grown as SRWC for bioenergy in the Piedmont of North Carolina has the potential to produce environmentally sustainable and economically competitive woody biomass feedstocks.

CHAPTER 3. EFFECTS OF PLANTING DENSITY OF COPPICED AMERICAN SYCAMORE ON SOIL HEALTH

Introduction

Soil is an ecosystem of itself, a fundamental natural resource that supports various ecosystem functions including goods and services for social well-being (Laishram et al., 2012). Soil has many ecological functions, including but not limited to the cycling of nutrients, carbon and water, supporting microbial populations, and filtering/buffering potential pollutants to protect water quality. Soil health is defined as the continued capacity of soil to function as a vital living system, by recognizing that it contains biological elements that are key to ecosystem function within land-use boundaries (Doran and Zeiss, 2000; Karlen et al., 2001). Soil can act as a buffer for hydrologic and biogeochemical processes to reduce the impacts of ever-changing weather variability and unavailable water resources due to global climate change (Larson and Pierce 1994). This requires in-depth understanding of the effects of land-use management systems on soil health to meet the needs for food production and ecosystem services in the face of the threats of global climate change (Doran and Safley 1997). There are challenges in preserving and protecting soil health under intensive land use and rapid economic development, particularly in the developing world where adverse effects of soil health arise from excessive fertilization, soil pollution, nutrient imbalance and soil loss processes (Doran et al.,1996b; Zhang et al., 1996; Hedlund et al., 2003).

The common physical and chemical properties used in assessing soil health are aggregate stability, bulk density, soil water properties, total nitrogen and total carbon (Valle and Carrasco, 2018). These properties can be improved through additions of organic matter from trees to soils, thereby increasing the suitability of soil to sustain plant growth and other biological activities. Soil health assessment can be beneficial in estimating land degradation for landowners and farmers following various land use and identifying appropriate management interventions (Lal and Stewart, 1995). Furthermore, other stakeholders benefit from soil health and soil quality assessments, such as when forming management decisions by extension personnel (Barrios et al., 2006). For researchers, there is still a need to develop reproducible soil quality and soil health assessments (Kang et al., 2005). Presently, the concept of soil health is evolving from just crop productivity into environmental quality, food safety and possibly human health aspects, and SRWCs have the potential to contribute much to improvement of soil health (Karlen et al., 1997).

SRWCs are becoming a fundamental component of regional and national energy systems, as well as providing essential ecosystem services, such as biomass supplies, carbon sinks, and healthy soils (Zalesny et al., 2016). SRWCs can increase soil organic carbon from tree litter inputs as well as improve other soil properties (Blanco-Canqui, 2010). They can improve soil water retention due to the high concentration of soil organic matter (Bharati et al., 2002). Organic matter added as tree biomass and from root activity can increase stable aggregate proportions and improve other physical soil properties at a much greater rate than might be achieved with conventional cropping practices alone (Udawatta et al., 2014). In addition, stable aggregates are significant factors for high productivity and sustainability, providing good soil structure for crop growth (Tisdall and Oades, 1982). The stability of aggregates is important for water infiltration and internal drainage, aeration for roots and soil microorganisms, root growth and nutrient uptake, as well as stability against rainfall and water movement.

In a conversion of cropland to SRWCs, Kahle et al. (2005) reported a decrease in soil bulk density, and increased soil porosity and microbial activity after six years of conversion. In another study comparing soil physical properties under SRWCs of poplar/willow to cropland, bulk density was significantly lower within 10 cm of the soil surface and had higher plant-available water (Kahle and Janssen, 2019). There was significant improvement in the soil C after two years of converting a no-till corn system to sycamore biomass plantation (Devine et al., 2004). Longer rotation lengths of American sycamore could potentially increase aggregate stability and infiltration rates, as well increase soil C concentration, thereby benefiting subsequent annual crop production (Devine et al., 2004). Little is known about the long-term impacts of SRWCs, specifically of American sycamore, on soil health. Since soil is necessary for tree growth, root growth and in turn biomass productivity, there is need to investigate the long-term effects of this management system on soil properties.

Hypotheses and objectives

In the current study, I investigated the effects of planting density of a low-input American sycamore SRWC (no fertilization/irrigation/herbicides) on soil properties in the piedmont of North Carolina. The inclusion of the cropping sycamore systems into traditional American agricultural practices may provide an alternative source of income for farmers that leave their fields fallow. Sycamore SRWC establishes well (Fischer et al., 2017), and the cost of production is low due to the coppicing nature of the hardwood trees. Bioenergy SRWC also may have significant environmental benefits, including improvement of soil health (Zalesny et al., 2016). The null hypothesis for this study was that the planting density of woody bioenergy production would not affect soil health. The alternative hypotheses were:

1) Higher planting density will improve the formation water-stable aggregates structure.
2) Higher planting density would result in a higher proportion of soil macro-aggregate formation compared to micro-aggregates.

3) Higher planting densities will improve the hydraulic properties of soils under American sycamore SRWC.
4) Higher planting density will improve soil organic C and as such decrease bulk density relative to lower planting densities.

Materials and method

Study site

The study site is located on North Carolina Department of Agriculture and Consumer Services land near Butner, North Carolina (36° 7'58.20"N 78°48'26.49"W). It is in the Piedmont physiographic region 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 from a nearby weather station showed the average high temperature of 21.2 ^{o}C and average low of 8.8 ^{o}C, with an average rainfall of 122 cm for the year. The rainfall in the growing seasons of 2017 and 2018 (May-September) totaled 51.3 cm in 2017 and 51.0 cm in 2018 (North Carolina Climate Office, US Climate data, http://www.usclimatedata.com/climate/durham/north-carolina/united-states/usnc0192) Bare-root seedlings were purchased from the North Carolina Forest Service Tree Seedling store and hand planted to establish the site. At initial establishment, there was a single application of glyphosate herbicide between rows at planting and mowing for weed control.

Experimental design and treatments

The study site was established in January of 2010 to quantify the effects of planting density and drought on the aboveground biomass productivity of sweetgum (*Liquidambar styraciflua*), American sycamore (*Platanus occidentalis*), tuliptree (*Liriodendron tulipifera*) and the hybrid poplar 'NM6' (*Populus nigra* × *P. maximowiczii*) grown as a short rotation coppice culture in the Piedmont of North Carolina. However, after two growing seasons sweetgum, tuliptree, and poplar all suffered extremely high mortality, despite replanting and competition control efforts. American sycamore experienced very minimal mortality (<3%) after the second year (Domec et al., 2017). Therefore, the study continued to research on sycamore alone. To investigate the effects of SRWC of sycamore on soil health after 9 years in SRWC culture, soil samples were collected at 0-10 cm depth for soil aggregate and soil carbon analysis. Additional intact soil samples (7.6 cm diam. x 7.6 depth) were collected for analysis of bulk density, water retention, and hydraulic conductivity. Samples were taken from two positions between the second and sixth tree row in alleys of each planting density treatment. The overall experimental design was:

- 3 blocks as replicates, to control for slope topography of the site
- 4 planting density treatments (10,000, 5,000, 2,500, and 1,250 tph) per block,
- 2 soil samples from each planting density per block,
- for a total of 12 plots and 24 soil samples. Size of each plot (14 m x 14 m).

Soil texture

Soil samples were analyzed for particle size distributions (Gee and OR, 2002) at the Soil Physics laboratory at North Carolina State University (NCSU).

Soil aggregate stability

Water stable soil aggregates were quantified using the wet sieving method. Samples were weighed and air-dried. Five sieve sets were used to classify soil aggregates (2 mm, 1 mm, 0.50 mm, 0.25 mm and 53 µm sieve size). Sieve sets were arranged into a Yoder device with the 2 mm sieve at the top. Twenty-five grams from each air-dried soil sample was weighed out, placed on the top sieve, and immersed in water. Soil left on the sieve was oven dried at 70 °C and weighed. The process was repeated a second time for sand correction. Fractional soil aggregates were classified into (53 µm - 0.25 mm, 0.25 mm- 0.50 mm, 0.50 mm -1 mm, 1 mm - 2 mm, >2 mm) and mean weight by size class of each soil sample was derived. The sand correction subtracted from the original sample weight was used to determine the total water stable soil aggregates.

Saturated hydraulic conductivity

Intact soil core samples were taken from the tree plots and saturated from the bottom for 5 days. Saturated soil core samples were set up in the constant head system for hydraulic conductivity (Ksat) measurement. Constant head without flow was introduced into the system with a Marriotte bottle. Height of water ponded in the ring was recorded. Water outflow rate (volume per time) was measured with a graduated cylinder and stopwatch. Outflow measurements were repeated until a steady flow was established. Ksat was calculated as: (VL)/ (AtH), where:

Ksat = saturated hydraulic conductivity (cm/s)   H = hydraulic head = L + D (cm)

V = volume of outflow (cm^3)   A = soil cross-sectional area (cm^2)

L = length of soil core (cm)   D = ponded depth (cm)

t = time (s)

Low-pressure water retention and bulk density

Following hydraulic conductivity measurements, core samples were re-saturated. Soil cores were arranged into a low-pressure chamber system to determine water retention capacity. Water outflow from each core at 25, 100 and 333 cm water applied pressure was recorded as the sample lost water from its current state and reached equilibrium. At equilibrium at the final applied pressure (333 cm), the sample was removed, weighed, dried at 105 °C, and reweighed to determine the corresponding volumetric water content. Volume of water was back calculated to estimate volumetric water content at 100, 25, and 0 cm water applied pressure. Soil field capacity was estimated at 333 cm and soil porosity was estimated at 0 cm. Bulk density was calculated from the dry soil mass and total soil volume.

High-pressure water retention

Loose soil samples were placed onto a porous ceramic plate and re-saturated for water retention analysis. The soil samples and plate were placed in a pressure chamber where controlled pressure was applied. Pressure at 1.5 MPa was applied to the sample through the top side of the ceramic plate while the bottom side of the ceramic plate was left open to atmospheric pressure. The pressure gradient allows water outflow from the soil sample through the ceramic plate. At equilibrium, water stopped draining and the sample was removed from the chamber, weighed, dried at 105 °C and then reweighed to determine the corresponding volumetric water content. Water content at this pressure was estimated as the lower limit of plant available water since water retention corresponds mostly to water in small pores and adsorbed on surfaces.

Pore size distribution

Pore size class distribution was estimated from the water retention data by converting the pressure heads (333 cm, 100 cm, 25 cm) to pore diameter size classes. The resulting pore size classes were 0.003 mm (micropores), 0.009 mm (mesopores) and 0.04 mm (macropores), respectively

(Luxmoore, 1981). Water retention pressure head was related to pore size distribution using the equation: h= 0.3 cm^2 d^{-1}, where h is pressure head (cm), d is diameter (cm).

Total soil carbon

Soil samples were analyzed using a carbon analyzer combustion module (Picarro G2201-isotopic CO_2/CH_4) to determine percent soil carbon and evaluate the C concentration and $\delta^{13}C$ stable isotope composition at the Tree Physiology and Ecosystem Science Laboratory at NCSU. Percent soil carbon and bulk density were then used to estimate the total soil carbon of the treatments.

Isolating key soil properties

To reveal the major soil properties that can be used to relate biomass productivity, ANPP and mortality rate of American sycamore at my site, I ran a multivariate analysis using Principal Components Analysis (PCA). PCA is a multivariate technique that describes inter-related dependent variables by displaying similarities amongst them while reducing multicollinearity issues (Abdi and Williams, 2010; Aguilos et al., 2019). The correlation circle between a variable and a principal component is used as the coordinates of the variable on the principal component axes. The observations are represented by their projections, but the variables are represented by their correlations (Abdi and Williams, 2010).

Modelling the response of biomass, ANPP and mortality to key soil properties

In determining the most important soil property that can explain the changes in biomass, ANPP and mortality of American sycamore, a generalized additive modelling (GAM) was employed in R (R version 3.4.4 (Vienna, Austria)). To avoid model over-parameterization, a second order

Akaike information criterion (AIC) was used to determine the best smoothing dimension (Aguilos et al., 2018, Shao et al., 2015). The GAM function from the *mgcv* package in R was used to obtain the statistical models, while *MuMIn* package was used to obtain the best smoothing dimension.

Statistical analysis

Statistical analysis (PROC GLM) was performed with SAS statistical software (SAS Institute, Cary, NC) using a significance level of 0.05. Further analysis was conducted in case of significant differences between treatments (α < 0.05) using Tukey adjustment for LSMeans with significant values indicated in bold.

The statistical linear model used to analyze soil variables of the tree plot was:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + +\alpha_i\beta_j + \varepsilon_{ijk}$$

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

where Y_{ijk} is the soil variables of soil aggregate fractions, field capacity, porosity, permanent wilting point, macropores, mesopores and micropores, bulk density, hydraulic conductivity, total soil carbon, δ^{13}C; α_i is effect due to planting density (i=1,250, 2,500, 5,000, and 10,000 tph), β_j is effect due to block (k=1…3), $\alpha_i\beta_j$, is the effect due to the interaction between main effect and block, and ε_{ijk} is the random error associated with the model.

RESULTS

Soil Aggregate Stability

Contrary to my hypothesis, there was no significant effect of planting density on soil aggregate fractions (Table 10). However, there were significant differences amongst the fractional soil aggregate groups for each planting density (($p < 0.001$), Table 10f, Figure 9). The >2mm size class was the highest proportion of stable aggregates in all planting densities. The 10,000 tph and 5,000 tph had similar proportions at 0.58. The 2,500 tph was the highest at 0.60, while the 1,250 tph was the lowest at 0.50. The lowest proportion of soil aggregates was in 1-2 mm class size, ranging from 0.05 to 0.07 (Tables 21, Figure 9). No significant effect of planting density on mean weight diameter (MWD) of soil aggregate fractions was observed. The 5,000 tph planting density treatment had the highest value at 3.20 mm, with 96 % of aggregated silt and clay, followed by the 10,000 tph treatment at 3.13 mm, with 93 % of aggregated silt and clay. The 2,500 tph treatment had 3.07 mm MWD, and 95 % of aggregated silt and clay. The lowest treatment was 1,250 tph at 2.87 mm MWD, and 90 % of aggregated silt and clay with no significance (Tables 10g and 21).

Saturated hydraulic conductivity (Ksat)

Due to the high variation in estimated Ksat, the values were transformed to the natural logarithm to satisfy assumptions of ANOVA. The 10,000 tph treatment had significantly higher Ksat, at 2.2 mm d^{-1} *($p < 0.05$)* compared to 5,000 tph at 1.12 mm d^{-1}, and 1,250 tph at 1.32 mm d^{-1} (Tables 11 and 22, Figure 10).

Bulk density

There were no significant differences in soil bulk density between the planting density treatments ($P=0.7$). Mean bulk density ranged from 1.58 to 1.60 Mg m^{-3} (Tables 12 and 23).

Water retention

Soil porosity for the planting density treatments ranged from 0.37 to 0.40 m^3 m^{-3} with no significant differences (Tables 13 and 22, Figure 11). However, there was a significant difference in soil field capacity between planting density treatments, with the 10,000 tph being significantly lower at 0.21 m^3 m^{-3} ($p = 0.00$) compared to all other treatment levels at 0.28 to 0.30 m^3 m^{-3} (Tables 14 and 22, Figure 11). The same trend was observed for permanent wilting point, where the 10,000 tph treatment was significantly lower at 0.03 m^3 m^{-3} and compared to the other three planting densities at ~0.05 m^3 m^{-3} (($p = 0.00$), Tables 15 and 22, Figure 11). As a result, the 10,000 tph had the lowest amount of plant available water at 18 % ($p < 0.05$), which is the difference between field capacity and permanent wilting point. This corresponds to the higher rate of soil hydraulic conductivity recorded in the 10,000 tph planting density. The 2,500 tph treatment had the highest plant available water at 25 %, as it had the highest field capacity at 0.30 m^3 m^{-3} (Tables 11, 16 and 22, Figures 10 and 11).

Pore size distribution

There were significant differences between planting density treatments for the distribution of micropores (0.003 mm) and mesopores (0.009 mm) size classes ($p = 0.00$, $p=0.02$) relative to the overall mean. However, no significant difference was observed for the macropores (0.04 mm) size class across treatments. The 10,000 tph had a significantly higher amount of mesopores than the

5,000 tph treatment, as well as a significantly higher amount of micropores than the other three planting density treatments (Tables 17-19, Figure 12).

Total Soil Carbon and δ13C Concentration

There were no statistically significant differences in total soil organic C between planting density treatments (*P = 0.2*). Though not significant, the highest planting density (10,000 tph) had the lowest percent soil carbon at 1.01 % resulting in the lowest calculated total soil carbon content of 16.03 Mg ha^{-1}. The 5,000 tph treatment had the highest percent carbon at 1.50 % and total soil carbon content of 24.07 Mg ha^{-1}. The soil $\delta^{13}C$ between the four planting density treatments was also not significantly different, ranging from -25.16 to -25.58 ‰ (Tables 20 and 23).

Key soil properties

Planting densities were superimposed as categorical variables to highlight the proximity of these variables to soil property predictors (Figure 13). In the PCA, significant groupings were detected. The closer the proximity of soil properties in a group means the higher is the correlation. Closely correlated variables include field capacity, available soil water, wilting point, carbon content and mean weight diameter forming one major group. Mesopores, macropores, micropores and porosity formed another group, while K-sat and bulk density were not closely related with other variables. Obtaining the relative contribution of each soil property in each dimension helps determine which variables are key soil property predictors for biomass, ANPP and mortality, expressed as the PCA circle with soil properties alone, and the relative contribution of each variable in two-dimensional PCA circle (Figure 14). Only one variable in a group of closely related variables was chosen to avoid biases and collinearity problems in the analysis. Results showed that field capacity had the highest contribution in the first PCA dimension, while K-sat at its opposite end was another key variable to contrast field capacity (Figure 14). Closely related soil properties to field capacity (e.g. available water and carbon content) were discarded as they were highly correlated with field capacity In PCA dimension 2, mesopores contributed most and bulk density opposed mesopores, since porosity is very closely related to mesopores. Therefore, field capacity, mesopores, K-sat and bulk density appear to be important soil properties determining biomass productivity of sycamore SRWC in this study.

DISCUSSION

Soil aggregate stability

There was significantly greater macro-aggregate formation (>2mm) at a depth of 0-10 cm across the four planting density treatments compared to micro aggregates (53µm – 1mm) (Table 10f, Figure 9). In a study comparing the aggregate stability of a 4-year rotation of American sycamore converted to no-till corn (SY4C) and a continuous row crop of soybean and corn (SBC), the SY4C had a larger mean weight diameter and a higher fraction of macro aggregates (>2 mm) at 2.5-15 cm depth compared to the SBC with a greater fraction of micro aggregates (0.25 mm) (Devine et al., 2004). Another SRWC study of 17-year old willow and poplar reported significantly higher water-stable soil macro aggregates sized 2.00 - 3.15 mm than micro aggregates <2mm (Kahle et al., 2013). This could be expected from forested areas and tree plots due to presence of organic matter, root activity, soil fauna, tree litter inputs, etc. Absence of disturbance from agricultural activities has been shown to promote fungal hyphae growth that is instrumental in the formation of macro-aggregates (Beare et al., 1993). High amounts of macro-aggregates, especially in fine-textured soils, could be considered beneficial as it creates larger pore spaces around and between the structured aggregates allowing improved water infiltration rates, facilitating water and nutrient transport. In a conceptual model by Six et al. (2000), macro-aggregates are formed around fresh residues and the production of microbially-derived binding agents, whose lifecycle may be disrupted by external disturbances. In the current study, the macro-aggregates can be attributed to the sandy loam soil texture of the tree plots. Soil aggregate structure forms from the aggregation of fine texture particles into micro-aggregates and coarse textured particles into macro-aggregates with increasing dependence on prevalent organic matter (Tisdall and Oades, 1982), facilitated by above- and belowground organic inputs of sycamore SRWC.

Soil hydraulic properties and pore size distribution

Ksat is one of the most important soil physical properties determining soil health, and yet the most variable due to biological, chemical, and physical soil processes (Carlos et al., 2018; Jun Lu,2015). As hypothesized, planting density affected soil water properties in that the 10,000 tph planting density had significantly higher Ksat, and a significant decrease in soil water retention with applied pressure (Tables 11 and 14-16, Figure 11). Furthermore, this planting density had significantly higher pore volume than the other three planting densities in the micro-pore size class. It also had higher pore volume in the macro-pore size class, but this was not significant (Tables 17 and 19, Figure 12). Ksat is the rate at which water passes through pores under saturated conditions. High planting density has more tree litter, and possibly more tree root activity (Blanco-Canqui, 2010; Kahle et al., 2013; Udewatta et al., 2014), all of which help to create larger pore spaces in the soil, hence an increased rate of Ksat.

SRWCs have been shown to increase plant available water in the topsoil layer (0-10 cm) due to accumulation of soil organic matter, root channels, earthworm burrows and a high proportion of water-stable soil aggregates (Kahle et al., 2013). My results were not completely consistent with this, as planting density did not significantly affect soil porosity, and the lower tree planting densities had similar plant available water as the higher planting densities, except for the 10,000 tph treatment. Field capacity and plant available water of the 10,000 tph were significantly lower than the other three planting densities (Tables14-16, Figure 11). This can be attributed to the high Ksat rate observed in this planting density. Trees grown at high planting density were shown to have higher root water uptake, which markedly reduced soil water content as induced suction increased and approached field capacity at 25 kPa (Ng et al., 2016). Reduced tree spacing has been shown to result in root decay and increased tree competition for soil water, thereby reducing the water retention ability of the stands, in contrast to wider spacing that resulted in fresh roots and higher water retention ability (Ng et al., 2016). In addition, studies have reported root decay at high planting densities due to intra-specific competition, which may result in soil macropores, thus reducing soil water retention (Goldberg & Miller., 1990; Ghestem et al., 2011). The 10,000 tph treatment of the current study also had significantly lower permanent wilting point value of 0.03 m m^{-3} compared to the other treatments at 0.05 m m^{-3}, perhaps providing greater buffering of plant stress to low soil water content during times of drought.

Bulk density, soil organic carbon and soil texture

Contrary to my hypothesis, planting density did not significantly influence soil bulk density, which ranged from 1.58 to 1.60 Mg m^{-3}, nor total soil organic C of the mineral soil, ranging from 16 - 24 Mg ha^{-1}. The bulk density values are in the typical range for sandy soils of 1.2 – 1.8 Mg $m^{-3.}$, where sand or sandy loam soils have higher bulk density values than clay and clay loam soils (Chaudhari et al., 2013). There were no distinct differences in bulk density values between treatments since they had the same soil texture (sandy loam) and similar total soil organic C content (Tables 12, 20 and 23). Studies have reported high correlation between soil organic C and bulk density, as well as between sand content and bulk density (Morisada et al., 2004; Leifield et al., 2005; Chaudhari et al., 2013). It should be noted that bulk density was measured at a shallow depth of 0 - 7.6 cm, but it is possible bulk density was higher deeper in the soil profile. Makeschin (1994) reported that low bulk density facilitated root penetration of the topsoil due to SRWC, which increased over nine years due to natural compaction. Bulk density measured at shallow depths of longer rotation length of SRWCs have shown distinctly lower values compared to an agricultural field site due to longer coppicing age and higher planting density (Kahle et al., 2019). Furthermore, long term SRWC has been shown to loosen topsoil, which could improve biomass production (Kahle et al., 2019). The non-statistical difference observed for soil organic carbon and bulk density across the planting density treatments of the current study could be a result of the soil texture and relatively short time period in SRWC. There could also be a sampling effect because soils were taken in between rows, where all planting density treatments have a 2m spacing as opposed to within rows, where the trees at different spacings (0.5m, 1m, 2m and 4m) are located.

Soil properties driving biomass productivity, ANPP and mortality rate

In the PCA ordination, a soil property that is on the same side of a given planting density has a high value for this planting density and that of the opposite side has a low value for this planting density. Therefore, this study confirms the significance of high Ksat rate, as well as micropore and mesopore volume in the 10,000 tph planting density treatment (Figures 13 and 14). It also indicates the importance of the higher plant available water in the 2,500 tph and 5,000 tph treatments, particularly for the latter, which had similar biomass productivity as the 10,000 tph planting density at half the establishment cost (Figure 3). The combined effect of field capacity, mesopores and Ksat explained only 26 % of the variation in total biomass productivity. Field capacity, Ksat and bulk density explained 33 % of the variation in ANPP, while field capacity, bulk density and mesopores explained 55 % of the variation in tree mortality rate (Table 24). Soil properties such as water-holding capacity, porosity, texture, and organic matter content are intrinsic site factors impacted by natural and anthropogenic activities, and are well correlated with productivity (Carmean, 1975; Ralston, 1964; Grier, 1989). Becknell and Powers (2014) reported that stand age and soil properties explained 58 % of variation in the aboveground biomass of a secondary forest in French Guiana. This suggests that perhaps other factors such as climate variability, natural disturbances and stand dynamics are important for the unexplained variation in total biomass productivity, ANPP and mortality in the American sycamore SRWC of the current study.

Field capacity was the best predictor among the studied soil properties to explain variation in total biomass, ANPP and mortality rate. The GAM was used to rank the significance of each soil factor, noted with their individual F values (Table 24). It also explained their joint contributions to the variation observed in the dependent variables as a function of the PCA-selected soil properties (Aguilos et al., 2018; Shao et al., 2015). The combined effects of field capacity, Ksat, mesopores volume and bulk density only explained 26 % and 33 % of the variation in total biomass and ANPP, respectively. Thus, there are other major factors driving biomass productivity. This is also true for the stand mortality rate, as low mortality rates were recorded in the study and the combined effects of field capacity, bulk density and mesopores explained only 55 % of the variation. The 5,000 tph treatment had about 1 % mortality, while the 1,250 tph had the highest mortality rate at

15 %. The low productivity and high mortality indicate this planting density is not suitable for optimum SRWC biomass production.

CONCLUSION

Short rotation woody cropping of American sycamore improved the formation of water- stable soil macro-aggregates relative to micro-aggregates due to tree root activity, litter inputs, and soil organic matter. The soil texture (sandy loam) of the study site also played a role in the increased macro-aggregates formed. Planting density did not completely change soil hydraulic properties because there were no differences in the soil porosity of the treatments. The 10,000 tph planting density showed significant differences in soil water properties compared to the other treatments, such as the lowest plant available water, making the 5,000 tph a possibly better option for more return on investments to landowners, as well as favorable soil water retention. Soil organic C and bulk density did not differ significantly across treatments because of the same sandy loam soil texture across the study site. The results from this study show that the planting density of American sycamore SRWC is an important factor affecting multiple aspects of soil health, which feedback to provide some control over woody biomass productivity.

CHAPTER 4. CONCLUSIONS AND FUTURE DIRECTIONS

The findings of this research show that American sycamore SRWC produced more aboveground total wood biomass (39.0 Mg ha^{-1}) at the end of its second rotation than the first rotation (23.0 Mg ha^{-1}), without the cost of a new plantation establishment; the only investment being the coppicing cost. This is an advantage of coppiced SRWCs over pines, which require replanting with each rotation. Coppiced sycamore in the upper Piedmont of North Carolina produced an average ANPP of 5.0 Mg ha^{-1} yr^{-1} woody biomass across planting densities at the end of the second 5-year rotation, with the highest planting density treatment (10,000 tph) producing as much as 9.0 Mg biomass ha^{-1} yr^{-1}. Although, this was a decrease from the first 4-year rotation where sycamore produced over 7.0 Mg ha^{-1} yr^{-1} without additional inputs, the 5.0 Mg ha^{-1} yr^{-1} productivity is similar to another low-input sycamore study in North Carolina of 2.5-7.6 Mg ha^{-1} yr^{-1} (Ghezehei et al., 2015). It is likely that established root systems/stools from previous rotations enhanced the establishment of the new stand, early productivity, and provided additional ecosystem services, including preventing soil erosion and fostering biodiversity. The benefits of multiple rotation coppicing of American sycamore include producing environmentally sustainable and economically competitive woody biomass feedstocks, extending the lifespan of the SRWC plantations, and potential to improve the environmental footprint and ecosystem C storage of conventional agricultural systems.

Biomass productivity and partitioning, and mortality rates were all affected by planting density. My results showed higher biomass produced at higher planting densities, with more allocated towards the stems, and lower mortality compared to low planting density. Stool mortality was minimal in the 5,000 and 2,500 tph treatments, and highest in the widest spacing (1,250 tph). The high stool mortality in the latter planting density could be attributed to larger spaces in between trees in each row making it difficult for a tree to occupy the space of a dead tree. Furthermore, the results of this study suggest the 5,000 tph treatment would be a better option for woody biomass productivity, due extremely low stool mortality and competitive biomass production compared to the 10,000 tph planting density. It also maximizes profit for farmers or landowners because of the reduced purchasing (half number of trees) and associated planting labor costs.

Short rotation woody cropping of American sycamore improved the formation of water-stable soil macro-aggregates (>2mm) compared to micro-aggregates (53 μm – 2 mm). This is common with forested areas because of tree litter, root activities and organic matter recycled into the soil. However, soil hydraulic properties were not completely affected by the planting density, because it did not impact soil porosity. The 10,000 tph treatment showed the most significant difference for the other soil hydraulic properties tested. It showed a higher rate of saturated hydraulic conductivity and it had the lowest field capacity, and as such the smallest amount of plant available water. It also had significantly more pore volume in the mesopore and micropore sizes than other treatments, hence the higher Ksat rate observed in the treatment, and as such low water retention properties. Pore spaces are filled with water and air, and if the highest planting density (10,000tph) had more pore volume but lower water retention capacity, it suggests a higher air-filled pore space at field capacity compared to other treatments, which is favorable for aeration and oxygen uptake, especially important at wet sites. However, this effect on soil hydraulic properties could decrease ecosystem resilience during times of drought.

From the soil health indicators assessed, the 2,500 tph planting density showed more favorable results compared to other levels, particularly for water retention properties. However, from a wholistic point, that is in terms of biomass productivity as well as soil health improvement, the 5,000 tph planting density seems to have higher economic benefits. The choice of appropriate planting density would be determined based on landowner, farmer or stakeholder interests. Other soil health indicators assessed in the study were soil texture, soil organic C and bulk density. My results showed that having the same sandy loam soil texture in the study sites meant that there was no difference across treatments for the soil organic C and bulk density. Further analysis on the effects of soil properties on biomass productivity on mortality rate showed field capacity, mesopores, bulk density and Ksat to be the main drivers of biomass productivity and stool mortality at the sycamore site. Field capacity was, however, the best predictor among the studied soil properties to explain variation in total biomass, ANPP and mortality rate as it had the highest F value. Results also showed that the study site had a moderate field capacity for American sycamore because of the good biomass productivity and low stool mortality observed.

This research shows that future alternative carbon demands, reduced CO_2 emissions, and improved soil health can be achieved from sustainable bioenergy feedstock production from sycamore SRWC on marginal lands. However, it exposes the need to better understand the belowground processes controlling resource-use efficiencies, that is, soil ecosystem function and how it is affected by bioenergy SRWC in order to achieve future sustainable energy systems. It would be interesting to compare the biomass productivity of a non-coppiced sycamore and the coppiced sycamore in the current study, and there should be more research on how many productive rotations sycamore SRWC can give before it has to be regenerated with new plantings. In addition, exploring other biological and climatic drivers of total biomass, ANPP, mortality rate, and soil health is needed, especially given the limited knowledge of the effects of SRWC planting density on soil health deeper in the soil profile. Since the goal of this study is to incorporate SRWCs cropping system into traditional American agriculture and promote this planting system among farmers, it is necessary to investigate the response (acceptance/rejection) of farmers. Some of these directions will form the basis of my PhD research, in addition to studying the influence of improved soil properties on agricultural productivity.

REFERENCES

Abdi H, Williams L.J (2010). Overview: principal component analysis. Comp. Stat., 2 (2010), pp. 433-459.

Aguilos M, Stahl C, Burban B, Hérault B, Courtois E, Coste S, Wagner F, Ziegler C, Takagi K, Bonal D (2019). Interannual and seasonal variations in ecosystem transpiration and water use efficiency in a tropical rainforest. Forests, 10, 14; doi:10.3390/f10010014.

Aguilos M. Herault B, Burban B, Wagner F, Bonal D (2018). What drives long term variations in carbon flux and balance in a tropical and rainforest in French Guiana? Agric. For. Meteorol., 253–254.

Ashley E.M (2015). Assessing Aboveground Biomass Productivity of American Sycamore Grown as a Short Rotation Coppice for Bioenergy. Master's thesis. North Carolina State University. Raleigh, North Carolina. Pp. 1-35

Barrios E, Delve R.J, Bekunda M, Mowo J, Agunda J, Ramisch J, Trejo M.T, Thomas R.J (2006). Indicators of soil quality: A South-South development of a methodological guide for linking local and technical knowledge. Geoderma, 135, pp. 248-259.

Beare M.H, Pohland B.R, Wright D.H, Coleman D.C (1993). Residue placement and fungicide effects on fungal communities in conventional and no tillage soils. Soil Science Society of America j. 57: 392-299

Becknell J.M, Powers J.S (2014). Stand age and soils as drivers of plants functional traits and aboveground biomass in secondary tropical dry forest. Can. J. For. Res. 44: 604–613 dx.doi.org/10.1139/cjfr-2013-0331.

Bharati L, Lee K.H, Isenhart T.M, Schultz R.C (2002). Soil water infiltration under crops, pasture and established riparian buffer in mid-western USA. Agroforestry System. 56: pp 249-257.

Blanco-Canqui, H (2010). Energy crops and their implications on soil and environment. Agronomy Journal, Volume 102, Issue 2, pp 403-419. Doi: 10.2314/agronj2009.0333.

Bohm C, Kanzler M, Freese D (2014). Wind speed reductions as influence by woody hedgerows grown for biomass in short rotation alley cropping systems in Germany. Agroforestry Systems volume 88, pp 579-591.

Bolstad P, Vose J.M, McNulty S.G (2001). Forest productivity, leaf area, and terrain in southern Appalachian deciduous forests. For Sci 47(3):419–427.

Boone Jameson (2017). Productivity of Coppiced Sycamore as a Potential Short Rotation Woody-Energy Crop (SRWC). Master's thesis. North Carolina State University. Raleigh, North Carolina, pp 1-30

Brinks J, Lhotka J, Barton C, Warner R, Agouridis C (2011). Effects of fertilization and irrigation on American sycamore and block locust planted on reclaimed surface mine in Appalachia. Forest Ecology and Management 261: pp 640-648.

Burkes E, Will R, Barron-Gafforf G, Teskey R, Shive B (2003). Biomass partitioning and growth efficiency of intensively managed *Pinus taeda* and *Pinus elliottii* stands of different planting densities. Forest Science, 49 (2), 224-234.

Carlos G-G, Yakov P, Miguel A.M (2018). Technical note: Saturated hydraulic conductivity and textural heterogeneity of soils. Hydrol. Earth Syst. Sci., 22, 3923–3932, https://doi.org/10.5194/hess-22-3923-2018

Carmean W.H. 1975. Forest site quality evaluation in the United States. Advances in Agronomy. 27: 209-269.

Chaudhari P.R, Dodha V.A, Vidya D.A, Manab C, Saroj M (2013). Soil Bulk Density as related to Soil Texture, Organic Matter Content, and available total Nutrients of Coimbatore Soil. International Journal of Scientific and Research Publications, Volume 3, Issue 2, February 2013 1 ISSN 2250-3153 www.ijsrp.org.

Coyle, D., & Coleman, M. (2005). Forest production response to irrigation and fertilization are not explained by shifts in allocation. Forest Ecology and Management (208), 137-152.

Dale V.H, Kline K.L, Wright L.L, Perlack R.D, Downing M, Graham R.L (2011). Interactions among bioenergy feedstock choices, landscape dynamics, and land use, Ecol. Appl. 21 (4) 1039e1054.

Davis A, & Trettin C. (2006). Sycamore and sweetgum plantation productivity on former agricultural land in South Carolina. Biomass and Bioenergy (30), 769-777.

Debbage K.G, Jacob F.K (2011). Renewable Energy in North Carolina: The Potential Supply Chain and Connections to Existing Renewable and Energy Efficiency Firms. Southeastern geographer, 51(1): pp. 69–88.

Devine D.W, Mullen M.D, Donald T.D, Houston A.E, Joslin J.D, Hodges D.G, Tolbert V.R, Walsh M.E (2004). Conversion from a Sycamore Biomass Crop to a No-till Corn System: Effects on Soils. Soil Sci. Soc. Am. J. 68:225–233.

Dimitriou I, Mola-Yudego B, Aronsson P, Eriksson J (2012). Changes in organic carbon and trace elements in the soil of willow short-rotation coppice plantations, Bioenerg. Res. 5 (3) 563e572.

Djomo SN, Ac A, Zenone T, Groote De T, Bergante S, Facciotto G, Sixto H, Ciria Ciria, Weger J, Ceulemans R (2015). Energy performances of intensive and extensive short rotation cropping systems for woody biomass production in the EU. Renewable and Sustainable Energy Reviews. 41: 845-854.

Domec J.C, Ashley E, Fischer M, Noormet A, Boone J, Williamson J.C, King J.S (2017). Productivity, Biomass Partitioning, and Energy Yield of Low-Input Short-Rotation American Sycamore (Platanus occidentalis L.) Grown on Marginal Land: Effects of Planting Density and Simulated Drought. Bioenergy Resources 10; pp 903–914. DOI 10.1007/s12155-017-9852-5.

Doran J.W, Sarrantonio M., Liebig M (1996). Soil health and sustainability. In: Sparks, D.L. (Ed.), Advances in Agronomy, Vol. 56. Academic Press, San Diego, pp. 1–54.

Doran J.W, Safley M (1997). Defining and assessing soil health and sustainable productivity. In: Pankhurst, C. et al. (eds.). Biological indicators of soil health. Wallingford, UK: CAB International. p. 1–28.

Doran J.W, Zeiss M.R (2000). Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology, 15; pp 3-11.

DURH-North Durham Water Reclamation Facility. NC CRONOS Database version 2.7.2. 2003-2017, State Climate Office of North Carolina. http://climate.ncsu.edu/cronos?station=DURH&temporal=hourly.

English B. C, De La Torre, Ugarte D. G, Jensen K, Hellwinckel C, Menard J, Wilson B, Roberts R, Walsh M. (2006) 25% Renewable energy for the United States by 2025: *Agricultural and Economic Impacts*.

Knoxville: University of Tennessee Agricultural Policy Analysis Center. Available at www.agpolicy.org/ppap/REPORT%2025x25.pdf.

FAO (2017). Agroforestry for landscape restoration exploring the potential of agroforestry to enhance the sustainability and resilience of degraded landscapes. State of food and agriculture report. Food and Agricultural Organization of the United Nations. Rome 2017.

Ferdush J, Karim M, Himel R, Saha D.S, Ahamed T (2018). Impact of alley cropping on wheat productivity. IOSR Journal of Agriculture and Veterinary Science. Vol 11, Issue 2 Ver I, pp 17-25. Doi: 10.9790/2380-1102011725.

Filer Jr T.H, Cooper D.T, Collins R. J, Wolfe R (1975). Survey of sycamore plantations for canker, leaf scorch, and dieback. Plant Disease Reporter. 59 (2): 52-53.

Fischer M, Kelley A.M, Ward E.J, Boone J.D, Ashley E.M, Domec J-C, Williamson J.C, King J.S (2017) A critical analysis of species selection and high vs low-input silviculture on establishment success and early productivity of model short-rotation wood-energy cropping systems. Biomass and Bioenergy 98:214-227.

Fischer M, Fichot R, Albaugh J, Ceulemans R, Domec J.C, Trnka M, King J.S. (2015) Populus and Salix grown in a short-rotation coppice for bioenergy: ecophysiology, aboveground productivity, and stand-level water use efficiency, in: K. Bhardwaj Ajay, T. Zenone, J. Chen (Eds.), Sustainable Biofuels, an Ecological Assessment of the Future Energy, HEP deGruyter, Berlin-Beijing, 2015, pp.157-194.

Foley J.A, Ramankutty N, Brauman K.A, Cassidy E.S, Gerber J.S, Johnston M (2011) Solutions for a cultivated planet. Nature 478 (7369) 337e342.

Gee G.W, OR D (2002). Particle size analysis. In J.H. Dane and G.C. Topp (ed.) Methods of Soil Analysis, Part 4. Soil Sci. Soc. Am., Madison, WI. pp 255-294

Geyer W.A, Melichar M.W (1986). Short Rotation Forestry Research in the United States. Biomass 9; pp 125-133.

Ghestem M, Sidle R.C, Stokes A (2011). The influence of plant root systems on subsurface flow: implications for slope stability. Bioscience 61, No. 11, 869–879

Ghezehei S.B, Shifflett S.D, Hazel D.W, Nichols E.G (2015). SRWC bioenergy productivity and economic feasibility on marginal lands. J Environ Management 160: pp 57–66.

Grier, Charles (1989). Productivity of forests of the United States and its relation to soil and site factors and management practices: a review. Portland Or.: U.S. Dept. of Agriculture Forest Service Pacific Northwest Research Station

Goldberg D. E, Miller T. E (1990). Effects of different resource additions on species diversity in an annual plant community. Ecology 71, No. 1, 213–225.

Hauk S, Knoke T, Wittkopf S (2014). Economic evaluation of short rotation coppice systems for energy from biomass da review, Renew. Sustain. Energy Rev. 29 (0) 435e448.

Hauk S, Knoke T, Wittkopf S, Gandofer M, Müller U.K (2017). Ecological diversification is risk reducing and economically profitable - The case of biomass production with short rotation woody crops in south German land-use portfolios. Biomass and Bioenergy 98 142e152.
Hedlund A, Witter E, An B.X (2003). Assessment of N, P and K management by nutrient balances and flows on peri-urban smallholder farms in southern Vietnam. Eur. J. Agron. 20, 71–87.

Henderson D, Jose S (2010). Biomass production potential of three short rotation wood crop species under varying nitrogen and water availability. Agroforest System 80:259-273 DOI 10.1007/s10457-010-9283-1.

Hill J, Polasky S, Nelson E, Tilman D, Huo H, Ludwig L, Neumann J, Zheng H, Bonta D (2008). Climate Change and Health Costs of Air Emissions from Biofuels and Gasoline. Proceedings of the National Academy of Sciences of the United States of America, Vol. 106, No. 6; pp. 2077-2082.

International Energy Agency – IEA (2007) World energy outlook world energy outlook. International Energy Agency, Paris.

Isenburg I.H (1981). Pulpwoods of the United States and Canada. Revised by M.L. Harder and L. Louden. Volume II-Hardwoods. 3rd Edition. The Institute of Paper Chemistry, Appleton, WI. 168pp.

Johnson J, Coleman M, Gesch R, Jaradat A, Mitchell R, Reicosky D (2007). Biomass-bioenergy crops in the United States: a changing paradigm. The American Journal of Science and Biotechnology, 1 (1), 1-28.

Jose S, Gold M.A, Garrett H.E (2012). The future of temperate agroforestry in the United States. In: Nai P.K.R., Garrity D. (Eds.), Agroforestry- The future of Global Land Use, Springer Netherlands, Dordretch, 2012; pp 217-245. Doi:10.1007/978-94-007-4676-3-14.

Jun Lu (2015). Identification of Forensic Information from Existing Conventional Site-Investigation Data. Introduction to Environmental Forensics. http://dx.doi.org/10.1016/B978-0-12-404696-2.00006-0.

Kang G.S, Beri V, Sidhu B.S, Rupela O.P (2005). A new index to assess soil quality and sustainability of wheat-based cropping systems. Biology and Fertility of Soils 41, 389–398.

Kahle P, Baum C, Boelcke B (2005). Effects of afforestation on soil properties and mycorrhizal formations. Pedosphere 15: pp 754- 760.

Kahle P, Janssen M (2019). Impact of short-rotation coppice with poplar and willow on soil physical properties. Plant Nutrition. Soil Sci. 000, pp 1–10 DOI: 10.1002/jpln.201900443.

Kahle P, Möller J, Baum C, Gurgel A (2013). Tillage-induced changes in the distribution of soil organic matter and the soil aggregate stability under a former short rotation coppice. Soil and Tillage Research Journal 133:49-53. DOI: 10.1016/j.still.2013.05.010.

King J, Albaugh T, Allen H, & Kress L. (1999). Stand-level allometry in *Pinus taeda* as affected by irrigation and fertilization. *Tree Physiology* (19), 769-778.

King J.S, Ceulemans R, Albaugh J.M, Dillen SY, Domec J-C, Fichot R, Fischer M, Leggett Z, Sucre E, Trinka M, Zenone T (2013). The challenge of lignocellulosic bioenergy in a water-limited world. BioScience 63:102-117.

Kline K.L, Coleman M.D (2010). Woody energy crops in the southeastern United States: Two centuries of practitioner experience. Bioenergy 34: pp 1655 – 1666.

Laishram J, Saxena K.G, Maikhuri R.K, Rao K.S (2012). Soil quality and soil health: a review, (n.d.) 20. International Journal of Ecology and Environmental Sciences 38 (1): pp 19-37.

Lal R, Stewart B.A (1995). Soil Management: Experimental Basis for Sustainability and Environmental Quality. Advances in Soil Science CRC Press, Boca Raton, Florida, pp 181 - 222

Larson W.E, Pierce F.J (1994). The dynamics of soil quality as a measure of sustainable management. Pages 37 - 51 in J. W. Doran, D. C. Coleman, D. F. Bezdicek and B. A. Stewart, eds. Defining soil quality for a sustainable environment. SSSA- Special Publication 35. Soil Science Society of America, Madison, WI, USA.

Leifeld J, Bassin S, Fuhrer J (2005). Carbon stocks in Swiss agricultural soils predicted by land-use, soil characteristics, and altitude. Agr. Ecosyst. Environ., Vol. 105, 2005, pp. 255–266.

Lewis S.M, Kelly M (2014). Mapping the potential for biofuel production on marginal lands: differences in definitions, data, and models across scales. ISPRS Int. J. Geo-Inf 3, 430e459.

Little M.G, Appold S, Cagiran I, Primmer C, Gultekin M (2013). North Carolina's role in the global biomass energy market. Biofuels Center of North Carolina. North Carolina.

Luxmoore R.J (1981). Micro, Meso and Macroporosity of soils. Soil Science Society of America 45: pp 671-672.

Makeschin, F. (1994). Effects of energy forestry on soils. Biomass Bioenerg. 6, 63–79.

Malmsheimer R.W, Heffernan P, Brink S, Crandall D, Deneke F, Galik C (2008). Forest Management Solutions for Mitigating Climate Change in the United State. Journal of Forestry*;* Agricultural & Environmental Science Database, 2008; 106, 3; pg. 115.

Morisada K, Ono K and Kanomata H (2004). Organic carbon stock in forest soils in Japan. Geoderma, Vol.119, 2004, pp. 21-32.

Naik, S. N, Goud Vaibhav V, Rout Prasant K, Dalai Ajay K (2010). Production of first- and second-generation biofuels: a comprehensive review. Renewable and Sustainable Energy Review. 14 (2) pp 578-579.

Nesbit T, Alavalapati P, Dwivedi P, Marinescu M (2011). Economics of ethanol production using feedstock from slash pine (*Pinus elliottii*) plantations in the Southern United States. Southern Journal of Applied Forestry 35(2):61-66.

Ng C.W.W, Ni J, Leung A, Zhou C, Wang Z.J (2016). Effects of planting density on tree growth and induced soil suction. Géotechnique. 66. 1-14. 10.1680/jgeot.15. pp 196.

Olson J, Wittwer R (1980). Response of American sycamore specific gravity to intensive culture. Retrieved 12/12/2019 from Northern Research Station: http://www.nrs.fs.fed.us/pubs/ch/ch04/CHvolume04page039.

Paquette A, Messier C (2010). The role of plantations in managing the world's forests in the Anthropocene, Front. Ecol. Environ. 8 (1) 27e34.

Pimmentel D (2003). Ethanol Fuels: Energy Balance, Economics, and Environmental Impacts are Negative. Natural Resources Research 12: pp 127-133.

Ralston C. W 1964. Evaluation of forest site productivity. In: Romberger, John A.; Mikola, Peitsa, eds. International review of forestry research. Vol. 1. New York: Academic Press: 171-201.

Rowe R.L, Street N.R, Taylor G (2009). Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK, Renew. Sustain. Energy Rev. 13 (1) 271e290.

SAS Institute Inc., 2004. SAS OnlineDoc® 9.1.3. SAS Institute Inc., Cary, NC.

Scarlat N, Dallemand J.F, Monforti-Ferrario F, Banja M, Motola V (2015). Renewable energy policy framework and bioenergy contribution in the European Union – An overview from National Renewable Energy Action Plans and Progress Reports. Renewable and Sustainable Energy Reviews 51. pp 969–985. http://dx.doi.org/10.1016/j.rser.2015.06.062.

Shao J, Zhou X, Luo Y, Li B, Aurela M, Billesbach D, Blanken P.D, Bracho R, Chen J, Fischer M, Fu Y, Gu L, Han S, He Y, T. Kolb, Y. Li, Z. Nagy, S. Niu, W.C. Oechel, K. Pinter, P. Shi, A. Suyker, M. Torn, A. Varlagin, H. Wang, J. Yan, G. Yu, J. Zhang (2015). Biotic and climatic controls on interannual variability in carbon fluxes across terrestrial ecosystems**.** Agric. For. Meteorol., 205, pp. 11-22, 10.1016/j.agrformet.2015.02.007.

Six J, Eliott E.T, Paustian K (2000). Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biology & Biochemistry 32: 2099-2103.

Steinbeck, K., McApline, R., & May, J. (1972). Short Rotation of Sycamore: A Status Report. Journal of Forestry, 70 (3), 210-213.

Susaeta A., Alavalapati J, Lal P, Matta J.R (2010). Assessing public preferences for forest biomass-based energy in the Southern United States. Environmental Management 45(4): pp 697–710.

Susaeta A, Alavalapati P, Carter D (2009). Modeling impacts of bioenergy markets on nonindustrial private forest management in the southeastern United States. Natural Resource Modeling 22(3): pp 345–369.

Tisdall J.M, Oades J.M (1982). Organic matter and water stable aggregates soils. Journal of Soil Science. Vol 33, Issue 2. 141-163. ISSN: 00224588. Doi:10.111/j.1365-2389.1982.tb01755.x.

Tsonkoya P, Bohm C, Quinkenstein A, Freese D (2012). Ecological benefits provided by alley cropping systems for production of woody biomass in the temperate region: a review. Agroforestry System 85: 133 – 152.

Udewatta R.P. Krstansky J.J, Henderson G.S, Garrett H.E (2002). Agroforestry practices, runoff, and nutrient loss: A paired watershed comparison. J. Environmental Quality. 31: 1214-1225.

Udewatta R.P, Kremer R.J. Nelson K.A, Jose S, Bardhan S (2014). Soil quality of a mature alley cropping agroforestry system in temperate north America. Communications in Soil Science and Plant Analysis. 45: pp 2539 – 2551. Doi: 10.1080/00103624.2014.932376.

Valle S.R, Carrasco J (2018). Soil quality indicator selection in Chilean volcanic soils formed under temperate and humid conditions. Earth and Planetary Sciences. ISSN: 0341-8612, vol:162, pp 386-395. Doi: 10.106/j.catena.2017.10.024.

Wear D.N, Greis J.G (2013). Chapter 1. Design of the southern forest futures project. In: Wear, D.N., Greis, J.G. (Eds.), The Southern Forest Futures Project: Summer Report. SRS-GTR-168. USDA-Forest Service, Asheville, NC.

Wood B, Wittwer R, Carpenter S (1977). Nutrient element accumulation and distribution in an intensively cultured American sycamore plantation. Plant and Soil (48), pp 417 – 433.

Zalesny R.S, Stanturf J.A, Gardiner E.S, Perdue J.H, Young T.M, Coyle D.R, Headlee W.L, Banuelos G.S, Hass A (2016). Ecosystem services of woody crop production systems. Bioenergy Research. 9; pp 465-491. Doi: 10.1007/s12155-016-939.

Zhang W.L,Tian Z.X, Zhang N, Li X.Q (1996). Nitrate pollution of groundwater in northern China. Agricult, Ecosyst Environ 59, pp 223–231.

APPENDICES

APPENDIX A: TABLES

Table 2.1. Mean values of aboveground biomass and stool mortality of American sycamore.

Planting density (ha^{-1})	Total wood ($Mg\ ha^{-1}$)	Stem wood ($Mg\ ha^{-1}$)	Leaves ($Mg\ ha^{-1}$)	Live branches ($Mg\ ha^{-1}$)	Dead branches ($Mg\ ha^{-1}$)	Mortality Rate (%)	ANPP ($Mg\ ha^{-1} yr^{-1}$)
10000	39.12±2.36[a]	31.08±1.81	4.32±0.28	3.31±0.24	0.41±0.02	5.19± 2.12[b]	9.03±1.67[a]
5000	36.52±0.96[a]	28.43±0.71	4.32±0.13	3.4± 0.11	0.37±0.01	1.53±0.62[b]	6.25±0.53[ab]
2500	22.05±1.48[b]	16.71±1.08	2.96±0.32	2.16±0.18	0.22±0.01	2.38±0.97[b]	4.22±1.85[ab]
1250	14.48±1.56[c]	10.77±1.13	1.95±0.72	1.62±0.20	0.14±0.01	15.48±6.32[a]	0.61±1.90[ab]

Same lowercase letters within a column indicate no significant difference between treatments. Values are means and SEs of total wood biomass, biomass partitioning (stem, leaves, live and dead branches), aboveground net primary productivity (ANPP) and stool mortality of American sycamore following a 4-5-year growth in its second rotation. Four planting density treatments were used in the study: 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}), 4.0 x 2.0m (1,250 ha^{-1}). (Significance level: P<0.05).

F-tests of tree variables (significant *P* values <0.05 indicated in bold).

Table 3.1. F-tests of fixed effect of total woody biomass in the fifth growing season.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	4.75	2.38	0.13	0.88
Spacing	3	2487.27	829.09	46.80	**<.0001**
WaterTrt	1	7.63	7.63	0.40	0.54
Spacing*WaterTt	3	54.61	18.20	1.03	0.44
Block*Spacing	6	98.99	16.50	0.93	0.53
Block*WaterTrt	2	63.42	31.71	1.80	0.24
Error	6	106.30	17.72		

Table 4.1. F-tests of fixed effect of stem biomass in the fifth growing season.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	1.60	0.80	0.07	0.93
Spacing	3	1665.63	555.21	49.81	**<.0001**
WaterTrt	1	1.64	1.64	0.15	0.71
Spacing*WaterTrt	3	17.79	5.93	0.50	0.68
Block*Spacing	6	53.39	8.90	0.80	0.60
Block*WaterTrt	2	46.57	23.28	2.09	0.20
Error	6	66.88	11.15		

Table 5.1. F-tests of fixed effect of live branches biomass in the fifth growing season.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.06	0.03	0.14	0.87
Spacing	3	13.70	4.57	22.76	**<.0001**
WaterTrt	1	0.18	0.18	0.90	0.38
Spacing*WaterTrt	3	0.78	0.26	1.29	0.36
Block*Spacing	6	1.48	0.25	1.23	0.40
Block*WaterTrt	2	0.72	0.36	1.79	0.25
Error	6	1.21	0.20		

Table 6.1. F-tests of fixed effect of dead branches biomass in the fifth growing season.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.01	0.00	0.11	0.89
Spacing	3	0.29	0.09	50.70	**<.0001**
WaterTrt	1	0.02	0.02	0.32	0.59
Spacing*WaterTrt	3	0.00	0.00	0.88	0.61
Block*Spacing	6	0.00	0.00	0.79	0.32
Block*WaterTrt	2	0.00	0.00	1.37	0.50
Error	6	0.01	0.00		

Table 7.1. F-tests of fixed effect foliage biomass in the fifth growing season.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.53	0.27	0.17	0.84
Spacing	3	24.14	8.03	5.25	**0.00**
WaterTrt	1	1.06	1.06	0.69	0.44
Spacing*WaterTrt	3	7.85	2.62	1.71	0.26
Block*Spacing	6	2.37	0.39	0.26	0.93
Block*WaterTrt	2	0.54	0.27	0.18	0.84
Error	6	9.18	1.53		

Table 8.1. F-tests of fixed effect of Aboveground net primary production (ANPP) in the fifth growing season.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	21.13	10.56	0.61	0.56
Spacing	3	226.07	75.36	4.35	**0.02**
WaterTrt	1	2.04	2.04	0.12	0.74
Spacing*WaterTrt	3	38.74	12.91	0.61	0.54
Block*Spacing	6	21.98	3.66	0.17	0.97
Block*WaterTrt	2	92.64	46.32	2.17	0.19
Error	6	127.85	21.31		

Table 9.1. F-tests of fixed effect of mortality rate in the fifth growing season.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	89.11	44.55	2.53	0.05
Spacing	3	740.70	246.95	14.01	**0.00**
WaterTrt	1	10.42	10.42	0.59	0.47
Spacing*WaterTrt	3	21.03	7.01	0.40	0.78
Block*Spacing	6	35.83	5.97	0.34	0.91
Block*WaterTrt	2	3.21	1.60	0.09	
Error	6	105.77	17.63		

Table 10.1. Results of ANOVA post hoc Tukey adjustment test showing the statistical significance (p values) among contrasting planting density treatments (10000, 5000, 2500 tree ha^{-1}) for total wood biomass, stem biomass, foliage biomass, live and dead branches biomass, ANPP, mortality rate. (significant p-values in bold). Pr > |t| for H0: LSMean(i)=LSMean(j).

	i/j	1250	2500	5000	10000
Total wood biomass	1250		**0.04**	**<.0001**	**<.0001**
	2500			**0.00**	**<.0001**
	5000				0.74
Stem biomass	1250		**0.04**	**<.0001**	**<.0001**
	2500			**0.00**	**<.0001**
	5000				0.56
Foliage biomass	1250		0.27	**0.00**	**0.00**
	2500			0.09	0.09
	5000				1.00
Live branches	1250		0.28	**0.00**	**0.00**
	2500			**0.00**	**0.00**
	5000				0.99
Dead branches	1250		**0.03**	**<.0001**	**<.0001**
	2500			**0.00**	**<.0001**
	5000				0.49
ANPP	1250		0.46	0.13	**0.02**
	2500			0.83	0.23
	5000				0.67
Mortality rate	1250		**0.00**	**<.0001**	**0.00**
	2500			0.97	0.51
	5000				0.31

F tests of soil variables (significant *p* values < 0.05 in bold)

Table 11.1. F-tests of fixed effect of water-stable fractional soil aggregates (53μm-0.25mm).

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Block	2	0.01	0.00	0.86	0.44
Spacing	3	0.02	0.00	1.06	0.40
Block*Spacing	6	0.02	0.00	0.61	0.72
Error	12	0.07	0.00		

Table 11.2. F-tests of fixed effect of water-stable fractional soil aggregates (0.25-0.50mm).

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Block	2	0.014	0.00	0.91	0.43
Spacing	3	0.003	0.00	0.23	0.88
Block*Spacing	6	0.03	0.00	0.68	0.67
Error	12	0.09	0.00		

Table 11.3. F-tests of fixed effect of water-stable fractional soil aggregates (0.50-1mm).

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Block	2	0.00	0.004	0.08	0.92
Spacing	3	0.03	0.01	1.30	0.32
Block*Spacing	6	0.05	0.00	1.14	0.39
Error	12	0.09	0.00		

Table 11.4. F-tests of fixed effect of water-stable fractional soil aggregates (1-2mm).

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Block	2	0.00	0.00	0.19	0.83
Spacing	3	0.02	0.00	1.66	0.23
Block*Spacing	6	0.01	0.00	0.54	0.77
Error	12	0.04	0.00		

Table 11.5. F-tests of fixed effect of water-stable fractional soil aggregates (>2mm).

Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
Block	2	0.03	0.02	0.67	0.52
Spacing	3	0.01	0.00	0.19	0.90
Block*Spacing	6	0.07	0.01	0.43	0.84
Error	12	0.31	0.02		

Table 11.6. F-tests of fixed effect among water-stable fractional soil aggregates groups.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.00	0.00	0.09	0.91
Spacing	2	0.00	0.00	0.36	0.69
Group	8	4.55	0.57	85.28	**<.0001**
Block*Spacing	4	0.00	0.00	0.14	0.96
Block*Group	16	0.08	0.00	0.73	0.76
Spacing*Group	8	0.02	0.00	0.42	0.91
Error	76	0.51	0.01		

Table 11.7. F-tests of fixed effect of mean weight diameter of soil aggregates for all tree plots.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.73	0.37	0.69	0.52
Spacing	3	0.40	0.13	0.25	0.86
Block*Spacing	6	1.32	0.22	0.41	0.86
Error	12	6.40	0.53		

Table 12.1. F tests of fixed effects of saturated hydraulic conductivity (Ksat).

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.43	0.21	1.07	0.37
Spacing	3	4.11	1.37	6.87	**0.00**
Block*Spacing	6	2.15	0.36	1.80	0.18
Error	12	2.39	0.20		

Table 13.1. F tests of fixed effects of soil bulk density.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.01	0.00	1.50	0.26
Spacing	3	0.00	0.00	0.50	0.69
Block*Spacing	6	0.02	0.00	1.19	0.37
Error	12	0.04	0.00		

Table 14.1. F tests of fixed effects of soil porosity.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.00	0.00	0.39	0.68
Spacing	3	0.00	0.00	1.94	0.18
Block*Spacing	6	0.01	0.00	1.28	0.33
Error	12	0.01	0.00		

Table 15.1. F tests of fixed effects of soil field capacity.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.01	0.00	3.78	0.05
Spacing	3	0.02	0.01	9.70	**0.00**
Block*Spacing	6	0.01	0.00	3.31	0.04
Error	12	0.00	0.00		

Table 16.1. F tests of fixed effects of permanent wilting points.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.00	0.00	0.21	0.82
Spacing	3	0.01	0.00	12.27	**0.00**
Block*Spacing	6	0.01	0.00	9.03	0.00
Error	12	0.00	0.00		

Table 17.1. F tests of fixed effects of plant available water.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.00	0.02	0.43	0.09
Spacing	3	0.01	0.00	10.84	**0.00**
Block*Spacing	6	0.01	0.00	5.12	0.00
Error	12	0.02	0.00		

Table 18.1. F tests of fixed effects of macropores.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.00	0.00	1.19	0.34
Spacing	3	0.00	0.00	1.89	0.18
Block*Spacing	6	0.00	0.00	0.35	0.90
Error	12	0.00	0.00		

Table 19.1. F tests of fixed effects of mesopores.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.00	0.00	5.09	**0.03**
Spacing	3	0.00	0.00	4.76	**0.02**
Block*Spacing	6	0.00	0.00	2.17	0.12
Error	12	0.00	0.00		

Table 20.11. F tests of fixed effects of micropores.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	0.00	0.00	2.82	0.10
Spacing	3	0.01	0.00	7.44	**0.00**
Block*Spacing	6	0.00	0.00	1.21	0.37
Error	12	0.00	0.00		

Table 21.1. F tests of fixed effects of total soil organic C.

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Block	2	20.16	10.08	0.70	0.53
Spacing	3	101.82	33.94	2.37	0.17
Block*Spacing	6	45.61	9.52	1.44	0.35
Error	12	86.10	14.34		

Table 22.1. Soil texture of tree plots using the USDA classification.

Sample ID	Sand %	Silt %	Clay %	USDA Class.
Blk 1 0.5A	77.3	20.2	2.5	loamy sand
1A	54.1	39.2	6.7	sandy loam
2A	69.3	20.2	10.5	sandy loam
4A	68.3	27.1	4.7	sandy loam
Blk 2 0.5A	71.4	24.4	4.2	sandy loam
1A	60.6	31.7	7.7	sandy loam
2A	70.9	24.9	4.2	sandy loam
4A	50.2	40.8	9.0	Loam
Blk 3 0.5 A	72.6	24.4	3.0	sandy loam
1A	59.2	34.0	6.7	sandy loam
2A	50.3	45.1	4.7	sandy loam
4A	46.3	47.2	6.4	sandy loam

Soil texture of control plots derived using the particle size analysis test. Values were classified using the USDA soil textural triangle.

Table 23.1. Mean values of water-stable soil aggregates of SRWC with American sycamore.

Planting density	**Aggregated silt - clay fraction**	**Fractional soil aggregates**					**Mean weight diameter**
Ha^{-1}		53µm-0.25mm	0.25-0.5mm	0.5 -1 mm	1-2 mm	2-8 mm	mm
10000	0.93± 0.01	0.05± 0.01	0.08±0.01	0.15±0.03	0.07±0.01	0.58±0.06	3.13±0.61
5000	0.96± 0.02	0.07± 0.02	0.08±0.02	0.08±0.02	0.05±0.01	0.58±0.05	3.20±0.56
2500	0.95± 0.01	0.07± 0.01	0.10±0.03	0.10±0.03	0.07±0.01	0.60±0.06	3.07±0.66
1250	0.90± 0.02	0.10± 0.02	0.10±0.03	0.12±0.03	0.05±0.01	0.53±0.07	2.87±0.79

Values are means and SEs of aggregated silt-clay fraction, fractional soil aggregates sizes and the mean weight diameter of soils in an American sycamore plantation in the piedmont of North Carolina. Four planting density treatments were used in the study: 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}), 4.0 x2.0m

(1,250 ha^{-1}). There was no significant treatment effect on the water-stable soil aggregates and its mean weight diameter (Significance level: P<0.05).

Table 24.1. Mean values of soil hydraulic properties of SRWC with American sycamore.

Planting density (Ha^{-1})	**Porosity** ($m^3\ m^{-3}$)	**Field capacity** ($m^3\ m^{-3}$)	**Permanent wilting point** ($m^3\ m^{-3}$)	**Plant available water** (%)	**Saturated hydraulic conductivity** (mm^{-day})
10000	0.38±0.01[a]	0.21±0.01[b]	0.03±0.00[b]	18	2.20±0.23[a]
5000	0.37±0.01[a]	0.28±0.01[a]	0.05±0.00[a]	23	1.12±0.15[b]
2500	0.40±0.01[a]	0.30±0.02[a]	0.05±0.00[a]	25	1.68±0.02[ab]
1250	0.38±0.01[a]	0.28±0.02[a]	0.05±0.01[a]	23	1.32±0.37[b]

Same lowercase letters within a column indicate no significant difference between treatments. Values are means and SEs of soil porosity, field capacity, permanent wilting point, plant available water and saturated hydraulic conductivity. Four planting density treatments were used in the study: 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}), 4.0 x 2.0m (1,250 ha^{-1}). (Significance level: P<0.05).

Table 25.1. Soil organic C and percent carbon, δ13C concentration, total soil carbon and bulk density for each planting density treatment and their standard error.

Planting Density (Ha^{-1})	**Carbon** (%)	**δ13C per mill** (‰)	**Total Soil C** ($Mg\ ha^{-1}$)	**Bulk density** ($Mg\ m^{-3}$)
10000	1.01	-25.16	16.03± 0.5	1.59± 0.02
5000	1.50	-25.58	24.07± 1.4	1.60± 0.02
2500	1.34	-25.56	20.95± 3.8	1.58± 0.03
1250	1.36	-25.57	21.55± 1.0	1.59± 0.03

Values are means and SEs of percent C, δ13C concentration, total soil organic C and bulk density of an American sycamore plantation in the piedmont of North Carolina. Four planting density treatments were used in the study: 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}), 4.0 x 2.0m (1,250 ha^{-1}). There was no significant treatment effect on total soil organic C and bulk density (Significance level: P<0.05).

Table 26.1. Key soil properties driving aboveground biomass productivity and stool mortality of American sycamore.

Tree variables	**Best soil model predictors**	R^2	**Intercept**	**F value**	**P value**
Total wood biomass		0.26	28.04		
	Field capacity			20.68	**< 0.001**
	Mesopores			9.18	**< 0.05**
	Ksat			4.4	**< 0.01**
ANPP		0.33	5.02		
	Field capacity			45.27	**< 0.001**
	Ksat			16.24	**< 0.001**
	Bulk density			14.86	**< 0.001**
Mortality rate		0.55	4.29		
	Field capacity			22.92	**< 0.001**
	Bulk density			7.32	**< 0.01**
	Mesopores			6.88	**< 0.01**

Generalized additive model (GAM) analysis to predict and rank soil variables (field capacity, mesopores, Ksat and bulk density) according to their ability to explain the variations in total woody biomass productivity, aboveground net primary productivity and tree mortality rate (significant $p < 0.05$ values in bold).

Table 27.1. Results of ANOVA post hoc Tukey adjustment test showing the statistical significance (p values) among wet-stable fractional soil aggregates groups (significant $p < 0.05$ values in bold). *Group 1=53µm-0.25 mm, group 2=0.25-0.50 mm. group 3=0.50-1 mm, group 4=1 – 2 mm, group 5=2-8mm.* Pr > |t| for H0: LSMean(i)=LSMean(j).

	i/j	**Group 1**	**Group 2**	**Group 3**	**Group 4**	**Group 5**
Fractional soil aggregates	Group 1		1	0.99	0.99	**<0.001**
	Group 2			1	0.89	**<0.001**
	Group 3				0.73	**<0.001**
	Group 4					**<0.001**

Table 28.1. Results of ANOVA post hoc Tukey adjustment showing the statistical significance (p values) between contrasting planting density treatments (1250, 2500, 5000 and 10000 trees ha^{-1}) for significant soil variables in the study (significant *p <0.05* values in bold). Pr > |t| for H0: LSMean(i)=LSMean(j).

	i/j	**1250**	**2500**	**5000**	**10000**
Ksat	1250		0.52	0.86	**0.02**
	2500			0.19	0.22
	5000				**0.01**
Field capacity	1250		0.61	0.10	**0.01**
	2500			0.72	**0.00**
	5000				**0.01**
Permanent wilting point	1250		0.96	0.87	**0.00**
	2500			0.99	**0.00**
	5000				**0.00**
Plant available water	1250		0.28	0.51	**0.00**
	2500			0.78	**0.01**
	5000				**0.00**
Mesopores	1250		0.10	0.61	0.12
	2500			0.53	0.15
	5000				**0.01**
Micropores	1250		0.88	0.95	**0.02**
	2500			0.10	**0.01**
	5000				**0.01**

APPENDIX B: FIGURES

Figure 1.1. Aerial view of the study site from Google earth.

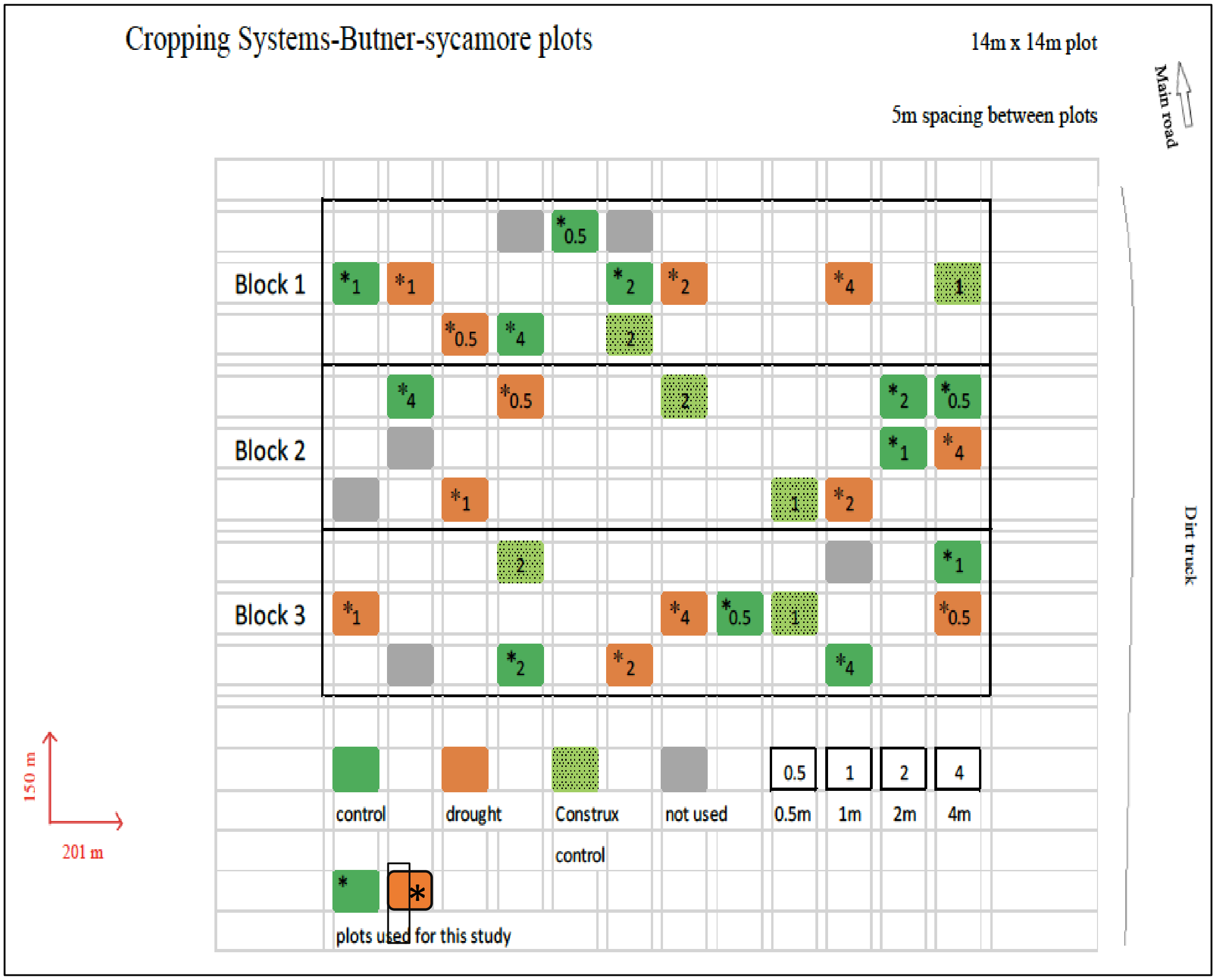

Figure 2.1. Schematic representation of the randomized complete block design of the study site. The asterisk (*) represent the tree plots used.

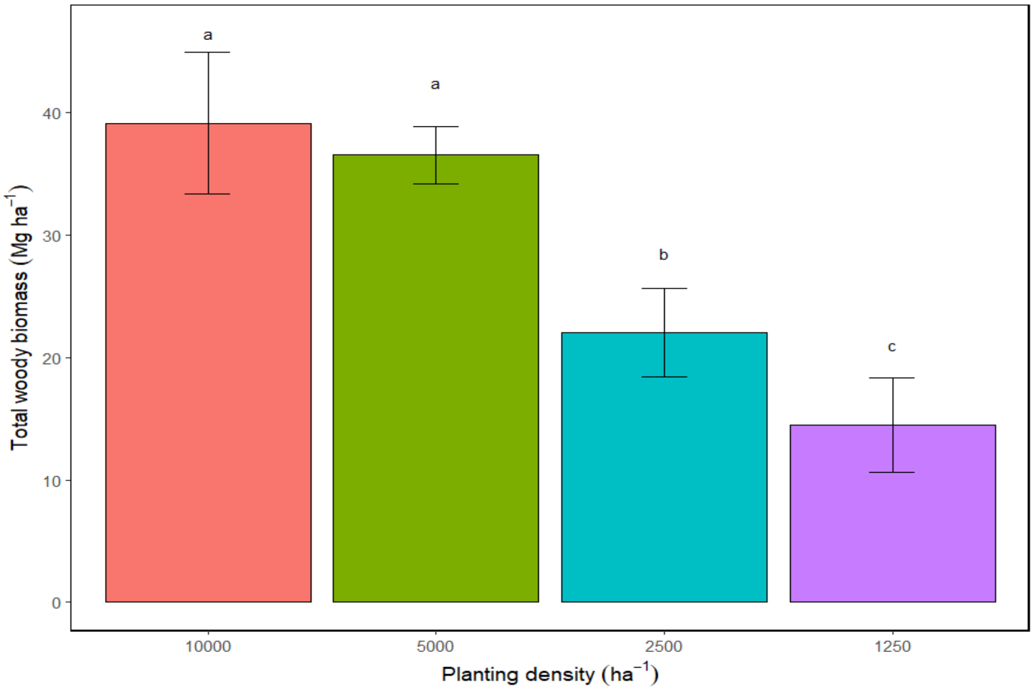

Figure 3.1. Total aboveground woody biomass (Mg ha^{-1}) by planting density (10,000, 5,000, 2,500 and 1,250 tph) for the fifth growing season of the second rotation. Vertical bars represent the standard error of the mean. Differing small letters on bars indicating statistical significance.

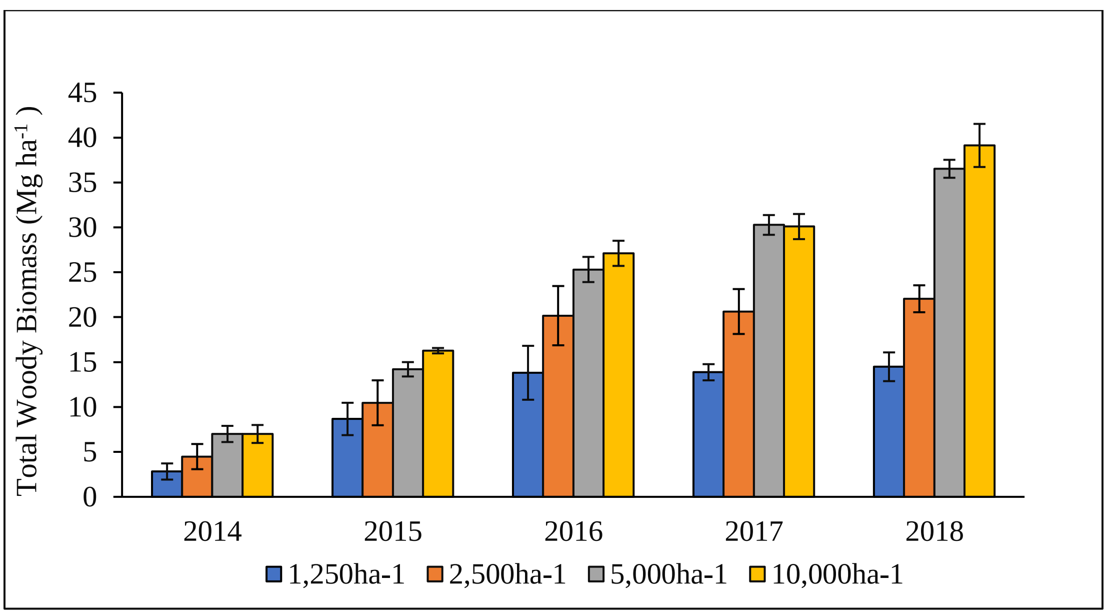

Figure 4.1. Cumulative sycamore total woody biomass (Mg ha^{-1}) following each growing season by planting density for the second rotation. Vertical bars represent the standard error of the mean.

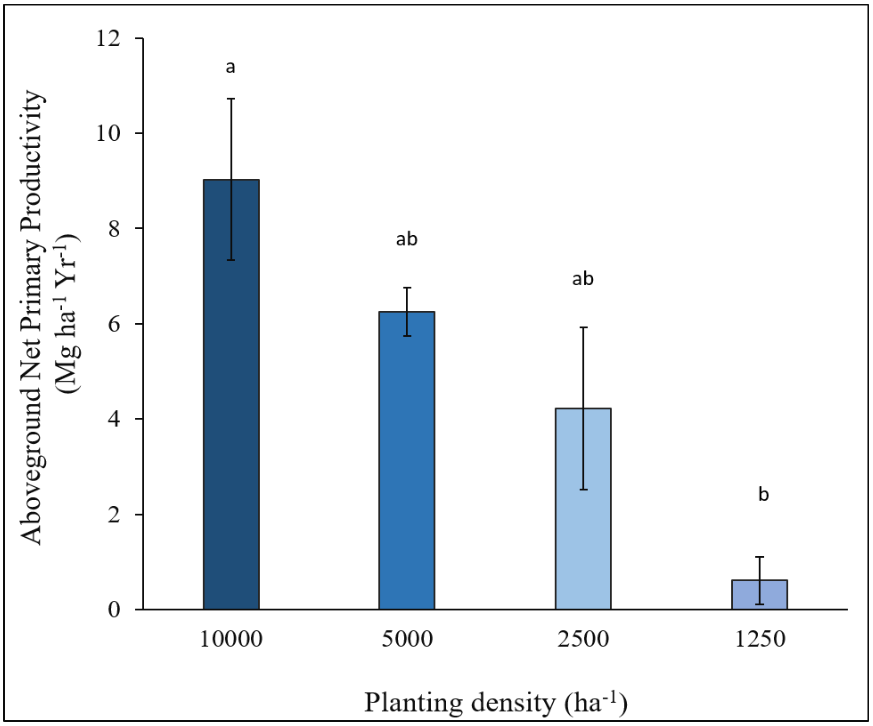

Figure 5.1. Above ground net primary production (ANPP) of wood (Mg ha^{-1}yr^{-1}) by planting density for the fifth growing season of the second rotation. Vertical bars represent the standard error of the mean. Differing small letters on bars indicating statistical significance.

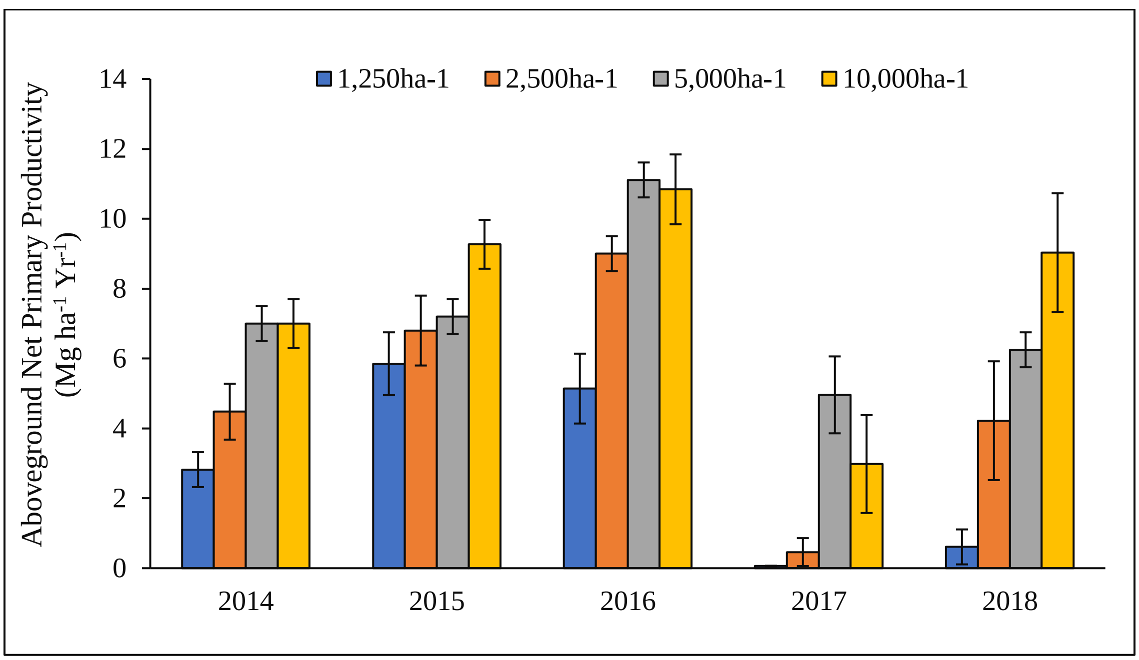

Figure 6.1. Above ground net primary production (ANPP) of wood (Mg ha^{-1}yr^{-1}) following each growing season by planting density for the second rotation. Vertical bars represent the standard error of the mean.

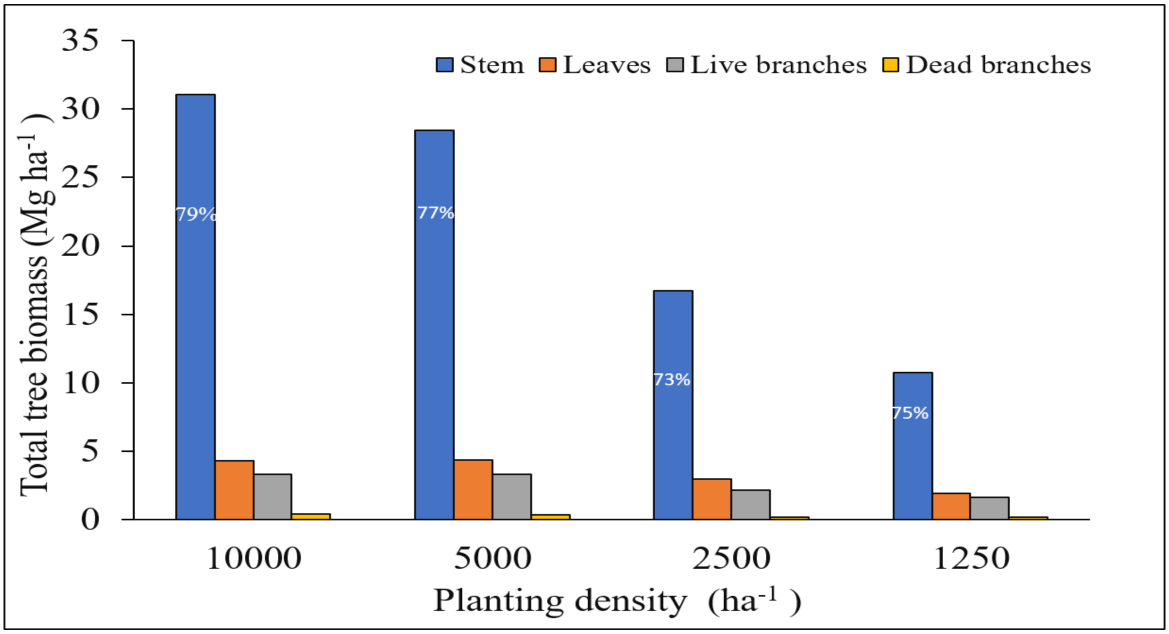

Figure 7.1. Mean total aboveground biomass (Mg ha $^{-1}$) of the trees partitioned into stem, leaves, live and dead branches by planting density for the fifth growing season of the second rotation.

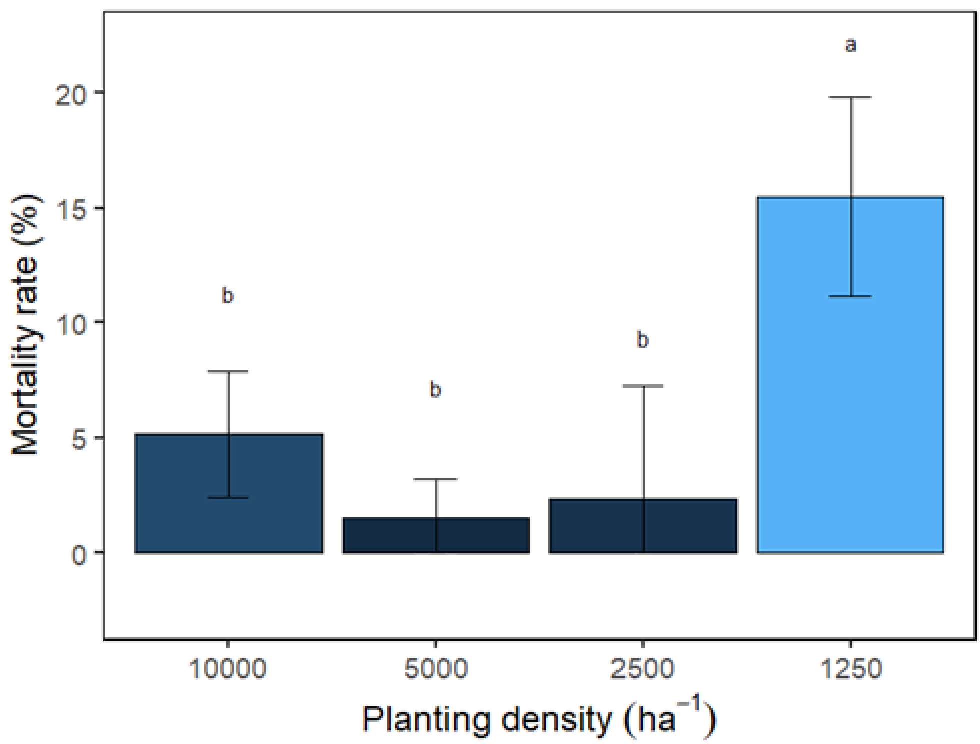

Figure 8.1. Stool mortality rate by planting density for the fifth growing season of the second rotation. Vertical bars indicating standard error of the mean. Differing small letters on bars indicating statistical significance.

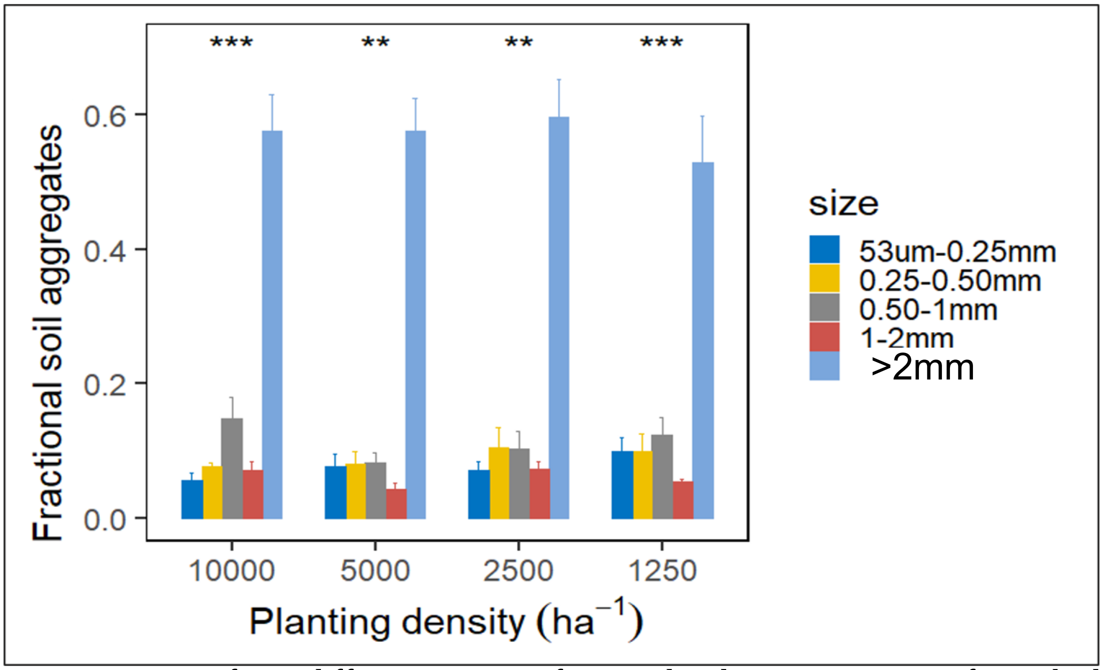

Figure 9.1. Significant differences among fractional soil aggregates group for each planting density (significant *p* values at '*** < 0.001', '** < 0.01').

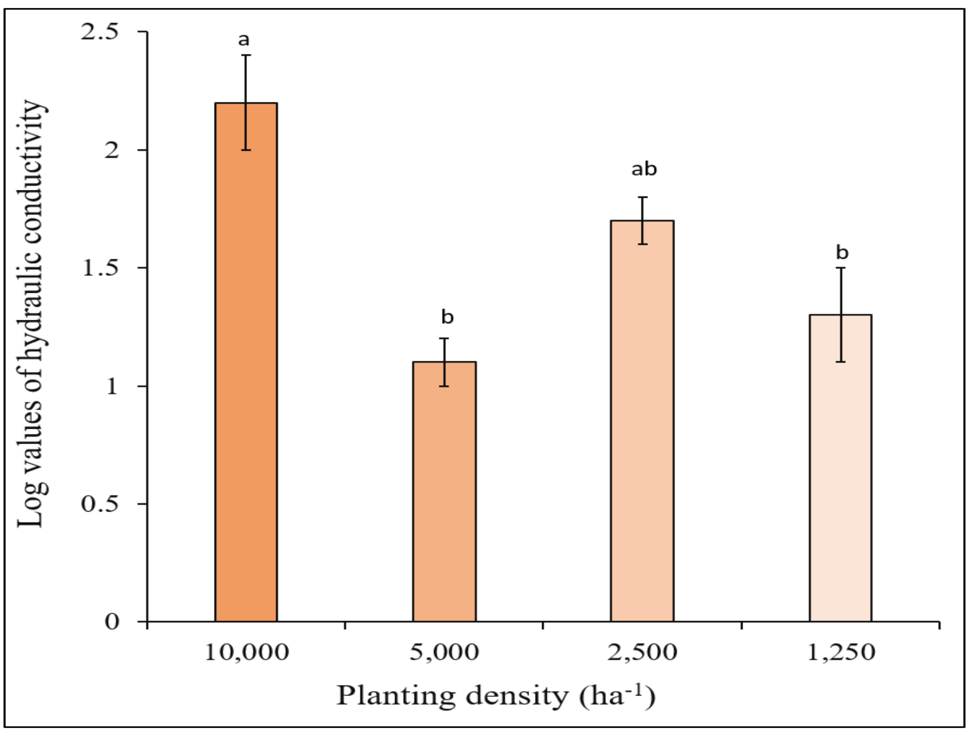

Figure 10.1. Saturated hydraulic conductivity (Ksat) for each planting densities with vertical bars indicating standard error of the mean. Differing small letters on bars indicating statistical significance.

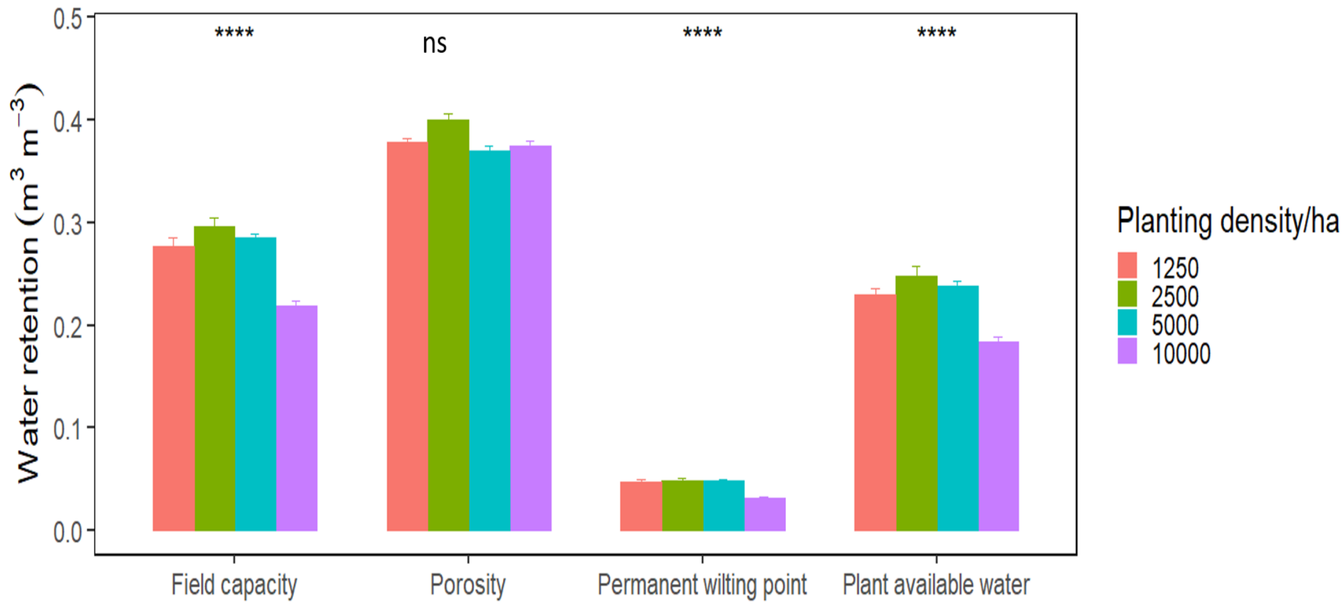

Figure 11.1. Soil field capacity, soil porosity, permanent wilting point and plant available water results for planting density treatments. (significant *p* values = '*** < 0.001', 'ns not significant).

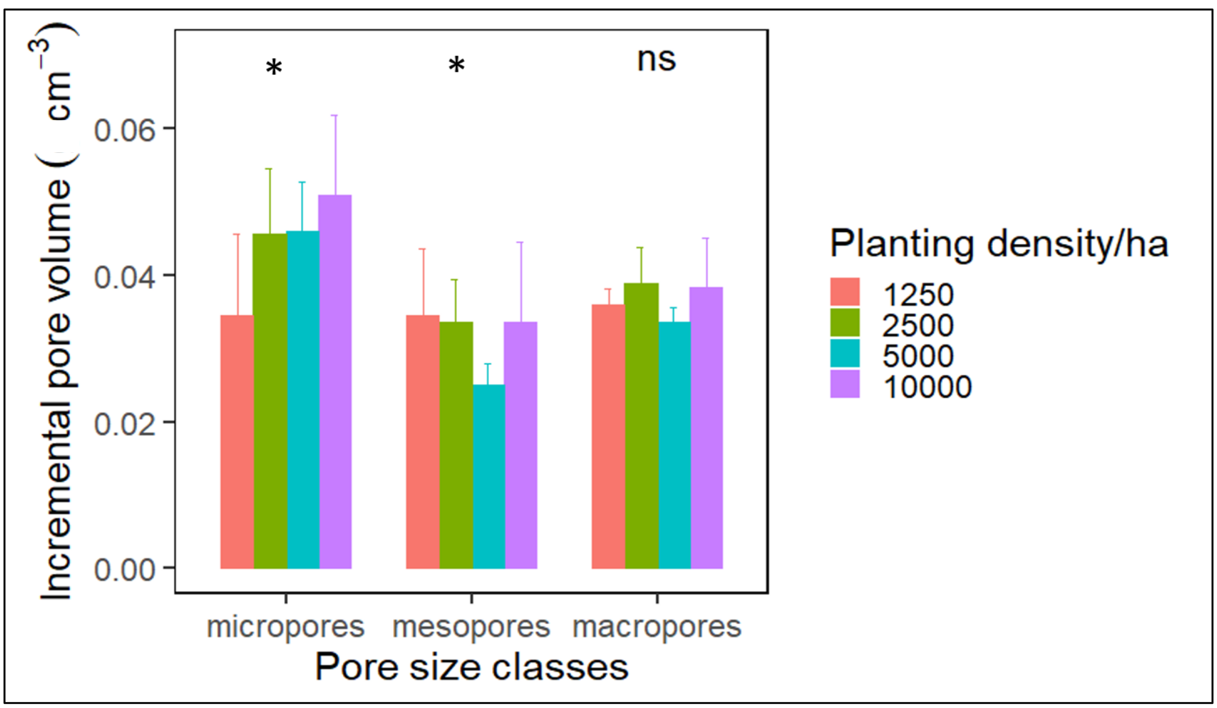

Figure 12.1. Pore size distribution for planting density treatments. Pore size classes were distinguished at 0.009mm, 0.003mm and 0.04mm respectively (Luxmoore, 1981). (significant *p* values = '* < 0.05', 'ns not significant).

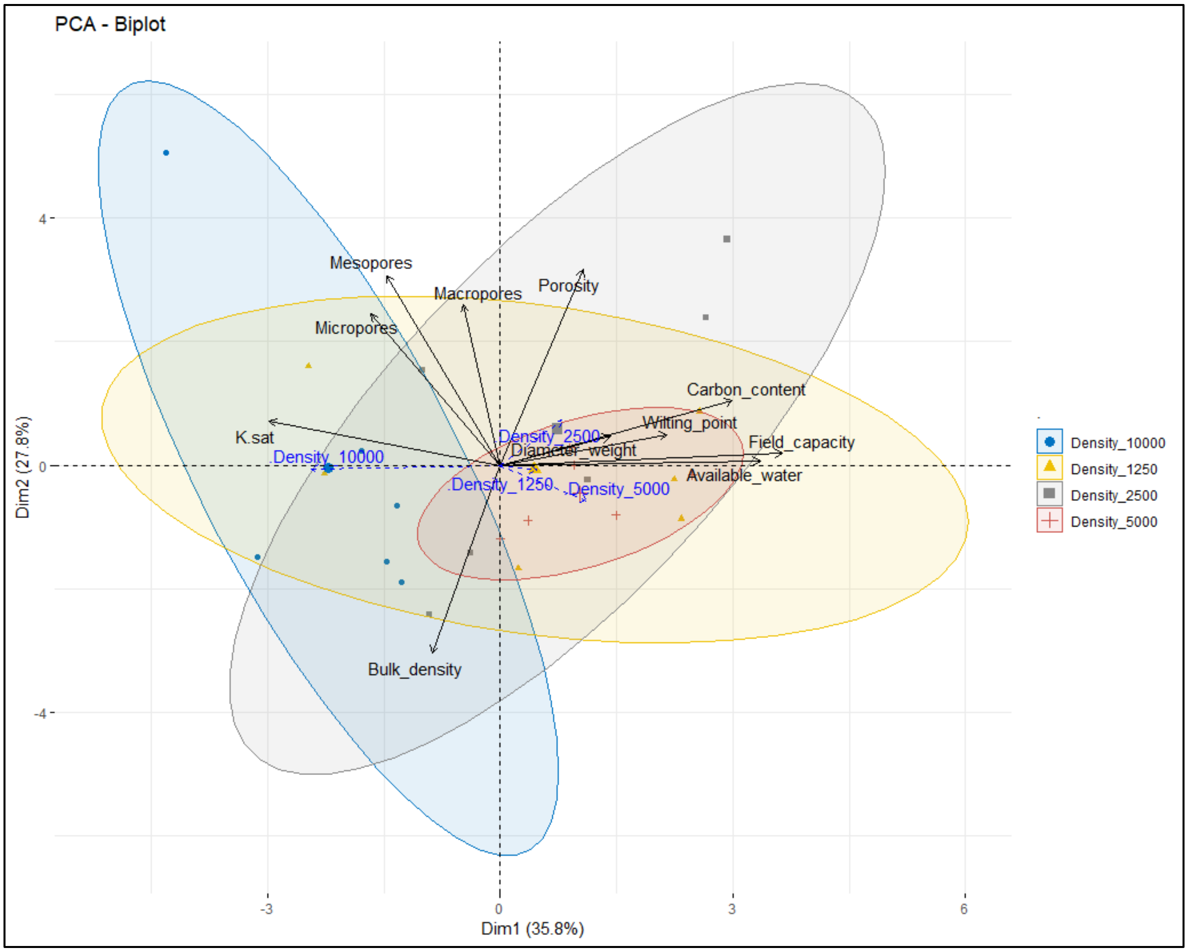

Figure 13.1. Principal component analysis (PCA) of major soil properties. Positively correlated soil properties are grouped together while negatively correlated variables are positioned on opposite sides of the plot origin (opposed quadrants). Planting densities were superimposed as categorical variables.

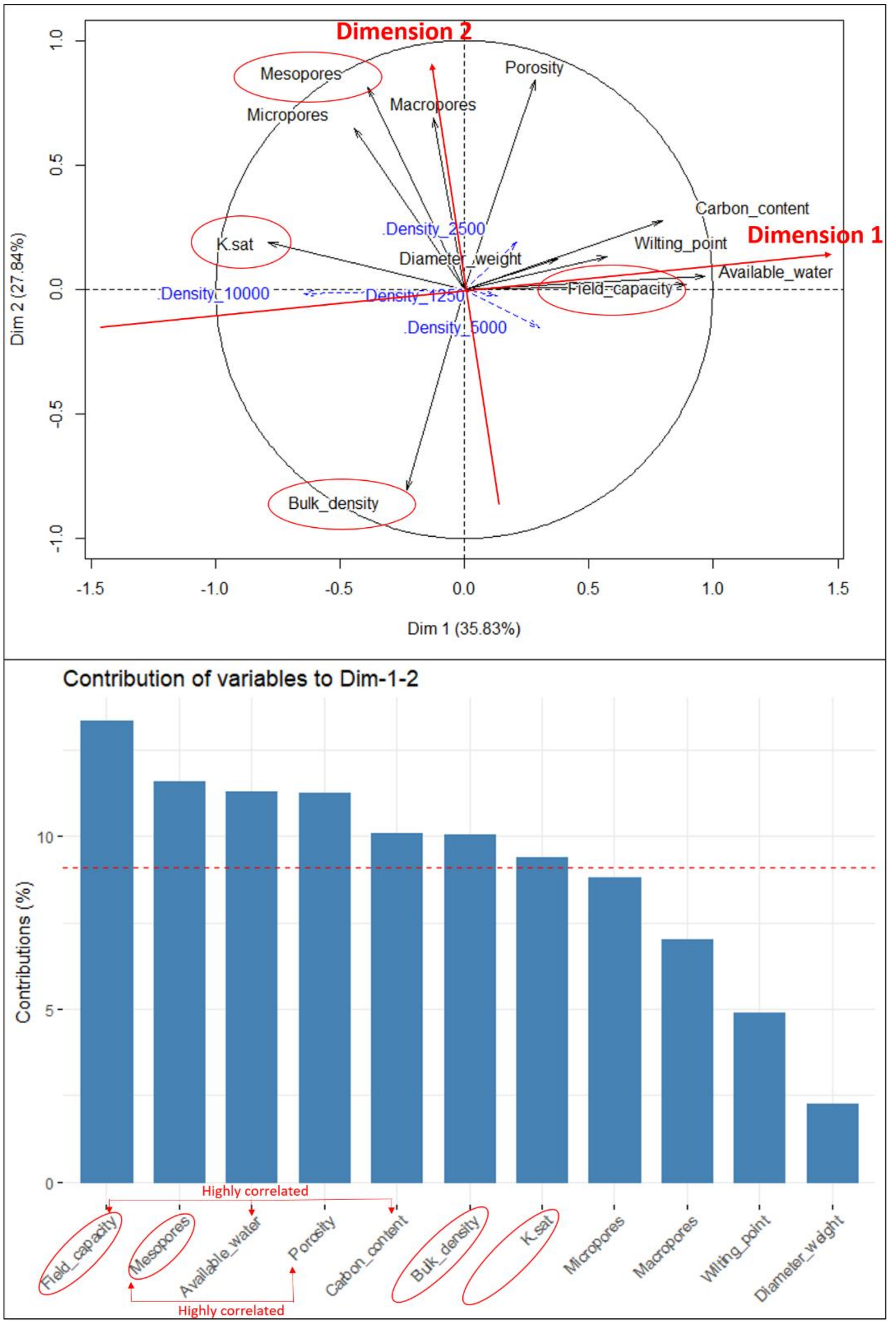

Figure 14.1. PCA circle and the relative contribution of each variable in this 2-dimensional PCA circle. The red dashed line on the bar graph indicates the average contribution. For a given component, a variable with a contribution larger than this cut-off was considered important in contributing to the component. Variables that are correlated with Dimensions 1 and 2 are the most important variables in explaining the variability in the dataset. Variables that do not correlate with any dimensions are variables with low contribution that were removed to simplify the overall analysis. In cases where two or more highly correlated variables appeared above the cut-off line, only one among them, preferably the one with the highest contribution can be chosen to avoid multicollinearity problem.