Root Biomass Distribution and Soil Physical Properties of Short-Rotation Coppice American Sycamore (*Platanus occidentalis* L.) Grown at Different Planting Densities

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Abstract: Short rotation woody crops (SRWCs) provide sustainable, renewable biomass energy and offer potential ecosystem services, including increased carbon storage, reduced greenhouse gas emissions, and improved soil health. Establishing SRWCs on degraded lands has potential to enhance soil properties through root and organic matter turnover. A better understanding of SRWC planting density and its associated root turnover impacts on soil–air–water relations can improve management. In this study, we investigate the effects of planting density for a low-input American sycamore SRWC (no fertilization/irrigation) on soil physical properties for a degraded agricultural site in the North Carolina piedmont. The objectives were (1) to estimate the distributions of coarse and fine root biomass in three planting densities (10,000, 5000, and 2500 trees per hectare (tph)) and (2) to assess the effects of planting density on soil hydraulic properties and pore size distribution. Our results show that planting at 10,000 tph produced significantly higher amounts of fine root biomass than at lower planting densities ($p < 0.01$). In the 25,000 tph plots, there was significantly higher amounts of coarse root biomass than for higher planting densities ($p < 0.05$). The 10,000 tph plots had lower plant available water capacity but larger drainable porosity and saturated hydraulic conductivity compared with lower planting densities (<0.05). The 10,000 tph plots total porosity was more dominated by larger pore size fractions compared with the 5000 and 2500 tph. Generally, our findings show similar patterns of soil hydraulic properties and pore size distributions for lower planting densities. The results from 10,000 tph indicate a higher air-filled pore space at field capacity and more rapid drainage compared with lower planting densities. Both characteristics observed in the 10,000 tph are favorable for aeration and oxygen uptake, which are especially important at wet sites. Overall, the results suggest that improved soil health can be achieved from the establishment of American sycamore SRCs on marginal lands, thereby providing a green pathway to achieving environmental sustainability with woody renewable energy.

Keywords: bioenergy trees; wet marginal sites; root biomass; pore size distribution; water retention components; saturated hydraulic conductivity

1. Introduction

Short Rotation Woody Crops (SRWCs) are becoming a fundamental component of regional and national energy systems providing essential ecosystem services, such as biomass supplies, carbon sinks, and healthy soils [1]. 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 [2–4]. Soil can act as a buffer for hydrologic and biogeochemical processes to reduce the impacts of the ever-changing weather variability and limited water availability due to global climate

change [5]. 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 [6].

The productivity and stability of SRWCs on marginal sites have received considerable attention [1,7–9]. However, the given definition of a marginal site remains variable and dependent on the surrounding factors of the site such as the soil survey classifications and yield estimates [10,11]. General descriptions range from abandoned agricultural lands unsuitable for crop production due to poor soil health, fallow lands, degraded and eroded lands, water-logged sites, contaminated lands, former landfills, wastewater, and sludge treatment lands [7,8,12–14]. For this study, our site is considered marginal due to the highly eroded soils, water-logged hydrology, and decline in agricultural crop productivity resulting from unsustainable farming practices [15].

Changes in global climate patterns accentuate wet sites and other uncertain, unpredictable changes that increases abiotic stresses, affecting plant growth and survival [16,17]. In the United States, 16% of water-logged sites are considered marginal, and 10% of the agricultural lands in Russia and of the irrigated croplands of India, Pakistan, Bangladesh, and China are also considered marginal [18,19]. Opportune, appropriate cropping and management system practices using marginal lands can improve soil quality and crop productivity while reducing the need to over-exploit agricultural lands [7–9,20–22]. Research emphasizes the use of SRWCs to enhance soil biodiversity and environmental quality through root dynamics, fine root mortality, and turnover [1,23,24]. Short rotation woody crops can improve soil water retention due to the high concentration of soil organic matter [25]. Organic matter added as tree biomass and from root activity can increase water-stable aggregate proportions and can improve other physical soil properties at a much greater rate than might be achieved with conventional cropping practices alone [26].

Roots are often separated into the size classes of "fine" (<2 mm diameter) and "coarse" (>2 mm diameter), with attributed or assumed differences in branching order, functional roles, nutrient concentrations, and decomposition dynamics [27,28]. Although the 2 mm break point does not provide accurate delineation of root functional traits [29], it is practical in terms of root sorting and thus is often applied in field studies. Fine roots play an important role in the belowground biomass production of natural and managed ecosystems by their rapid turnover that recycles nutrients, water, and organic matter through the soil to the soil surface [30–32]. Coarse roots provide strong support systems to the fine root networks and plant structure in addition to transporting nutrient and water resources to the aboveground structures [27,33]. Roots can modify soil physical properties as significant drivers of soil structure and soil pore formation [34,35]. Root density (e.g., g root m^{-3} soil), root growth, and root spatial distributions are prominent factors affecting soil physical properties, particularly soil saturated hydraulic conductivity, soil porosity, water retention, and air-filled capacity [35–37]. Root biomass distributions within the soil profiles can be obstructed by high soil bulk density and influenced by the soil texture, thereby affecting water and nutrient uptake of trees [38,39]. Plant roots also act as binding agents with soil organic matter [40] in soil aggregates to create relative pore spaces: large macropores (root channels, earthworm holes, and shrinkage cracks), mesopores, and micropores [41]. When roots grow, they may obstruct large pore spaces, dividing them into small micropores [42,43]. After the root decays, root-induced macropores are formed with inter-channel connectivity that facilitate water movement through the soil profile [44–47]. These effects elucidate the need to better understand the complexity of the interactions between roots and soil physical properties, and the potential for management to improve ecosystem services.

This study investigated the effects of the root biomass of a low-input American sycamore SRWC (no fertilization/irrigation/herbicides) on soil physical properties at an upland site in the Piedmont region of North Carolina. We hypothesized that tree fine root biomass would be higher at a higher planting density (e.g., number of trees per hectare), while coarse root biomass would be higher at a lower planting density. We expected that

this would influence the distribution of soil pores such that higher planting density would have more macro-pores in relation to the total porosity, while lower planting density would have higher micro-porosity. We further expected that higher planting density would have significant effects on soil water and air properties (soil porosity components) compared with lower planting density. To test these hypotheses, we cultured an American sycamore SRWC with three planting densities (10,000 trees per hectare, 5000 trees per hectare, and 2500 trees per hectare (tph)) for nine years and quantified the distribution of root biomass and soil physical properties.

2. Materials and Methods

2.1. Study Site

The study site is located on North Carolina Department of Agriculture and Consumer Services land near Butner, North Carolina (36°7′58.2″ N, 78°48′26.49″ W) in the Piedmont physiographic region of North Carolina (Figure 1). Meteorological data from a nearby station indicate a mean annual precipitation of 1412 mm, mean annual high temperature of 21 °C, and mean annual low temperature of 7.8 °C from 2010 to 2013. Between 2014 and 2018, mean annual precipitation was 1398 mm, mean annual high temperature was 21.6 °C, and mean annual low temperature was 9.7 °C (https://www.ncdc.noaa.gov/cag/) (accessed on 29 August 2021) [48]. The site is considered marginal land, that is, ancient, highly weathered soils common to the region [15]. The soil comprised Creedmoor sandy loam (fine, mixed, semiactive, thermic Aquic Hapludults on a 2–6% slope and made of 13% clay and 62% sand) with a bulk density of 1.52 g cm^{-3} (USDA NRCS Web Soil Survey, http://websoilsurvey.sc.egov.usda.gov/) (accessed on 13 October 2021) [49].

Figure 1. Aerial view of the study site.

2.2. Experimental Design and Treatments

The study site was originally established to quantify the effects of planting density and simulated 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*) under short rotation coppice

culture. Bare-root seedlings were purchased from the North Carolina Forest Service Tree Seedling store and hand planted to establish the site in January 2010. However, after two growing seasons, sweetgum, tuliptree, and poplar all suffered extremely high mortality despite replanting and competition control efforts [8]; therefore, the current study continued to research sycamore alone. During the first and second growing seasons, inter-rows were mowed, and glyphosate herbicide was applied three times (total) to help the trees become established, but no other inputs were applied thereafter.

A completely randomized block design study was used, consisting of three blocks as replicates: three levels of planting density (0.5 × 2.0 m (10,000 trees per hectare [tph^{-1}]), 1.0 × 2.0 m (5000 tph^{-1}), 2.0 × 2.0 m (2500 tph^{-1})) that were randomized within each block, amounting to nine plots in total, each 14 m × 14 m in size. After nine years of SRWC growth, including two harvest events and subsequent tree re-sprouting [7], we sampled soil physical properties by collecting intact soil cores of 7.6 cm diameter × 7.6 cm depth for analysis of bulk density, water retention, and saturated hydraulic conductivity. A total of 18 samples were taken from two positions between the second and sixth rows of trees in the alleys of each planting density treatment. Loose soil samples were also taken at 0 to 10 cm depths with a shovel for soil texture analysis. To account for spatial heterogeneity, data from all soil cores within a plot were aggregated.

2.3. Root Biomass

Root biomass (fine and coarse) was determined in each plot by collecting five replicate soil cores (5 cm diameter, 15 cm deep) in August 2017 and February 2018. Five soil cores per plot were collected randomly between tree rows, core samples were mixed to form a single composite sample, and a total of 45 soil cores were collected to analyze root biomass. The soil samples were soaked in distilled water to loosen attached soil particles, and fine roots (<2 mm) and coarse roots (>2 mm), were extracted manually by wet sieving in the laboratory. Roots were dried at 70 °C to constant mass and then weighed.

2.4. 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 saturated hydraulic conductivity (*Ksat*) measurement. Constant head was introduced into the system with a Marriotte bottle. The height of water ponding 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 follows:

$$Ksat = \frac{VL}{AtH}$$

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); and *t* = time (s).

2.5. Low-Pressure Water Retention

Following hydraulic conductivity measurements, core samples were re-saturated. Soil cores were arranged into a low-pressure chamber system to determine the 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 and 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. The volume of water was back calculated to estimate the volumetric water content at 100, 25, and 0 cm water applied pressure. The soil field capacity was estimated at 333 cm, and the soil total porosity was estimated at 0 cm.

2.6. 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 for 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. The water content at this pressure was estimated as the lower limit of plant available water (PWP) since water retention corresponds mostly to water in small pores and adsorbed on surfaces. Plant available water was estimated as the difference between water retention at field capacity (FC) and permanent wilting point (PWP). Drainable porosity (DP), which is also the air-filled pore space at field capacity, was estimated as the difference between total porosity and field capacity (FC).

2.7. Pore Size Distribution

The pore size class distribution was estimated from the water retention data by converting the heads (333 cm, 100 cm, and 25 cm) to pore diameter size classes. The resulting pore size classes were 0.0009 mm (micropores), 0.003 mm (mesopores), and 0.01 mm (macropores) [50]. The water-retention pressure head was related to pore size distribution using the capillary equation:

$$h = 0.3 \text{ cm}^2/d$$

where h is pressure head (cm) and d is diameter (cm).

2.8. Statistical Analysis

Before analysis, all data were checked for compliance with the assumptions of ANOVA. An analysis of variance (ANOVA) for a randomized complete block design was used to test for planting density treatment effect using the *aov* function, and the *lm* function was used to fit the linear model in R (R version 3.4.4 (Vienna, Austria)). A further post hoc analysis was conducted with the Tukey adjustment for least square means (LSMeans) using a significance level of $p < 0.05$.

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

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

where Y_{ijk} is the dependent variables of coarse root, fine roots, total porosity, plant available water, drainable porosity, saturated hydraulic conductivity, bulk density, macropores, mesopores and micropores. α_i is the effect due to planting density (i = 2500, 5000, and 10,000 tph). β_j is the 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.

3. Results

3.1. Fine and Coarse Root Biomass

The distribution of coarse root biomass (CRB), fine root biomass (FRB), and total root biomass (TRB) showed disparity between the three planting densities. Using the variance propagation technique, our result showed that the contributions of coarse roots to the total root biomass were 65%, 67%, and 63% for the 10,000 tph, 5000 tph, and 2500 tph, respectively. The contribution of fine root biomass to the total root biomass was lower than coarse roots, with only 34%, 33%, and 37% for 10,000 tph, 5000 tph, and 2500 tph, respectively (Figure 2). The lowest planting density, 2500 tph, had higher CRB compared with the higher planting densities. The 10,000 tph treatment had the highest fine root biomass compared with the lower planting densities, with 316.7 ± 11.1, 238.9 ± 11.0, and 208.8 ± 14.2 g biomass m^{-3} in the 10,000, 5000, and 2500 tph treatments, respectively

(Figure 2). A post hoc analysis of the means showed that FRB in the 10,000 tph was significantly different from the 5000 tph and 2500 tph treatments ($p < 0.001$). Likewise, coarse root biomass (CRB) among planting densities was significantly different ($p < 0.01$, $p < 0.05$).
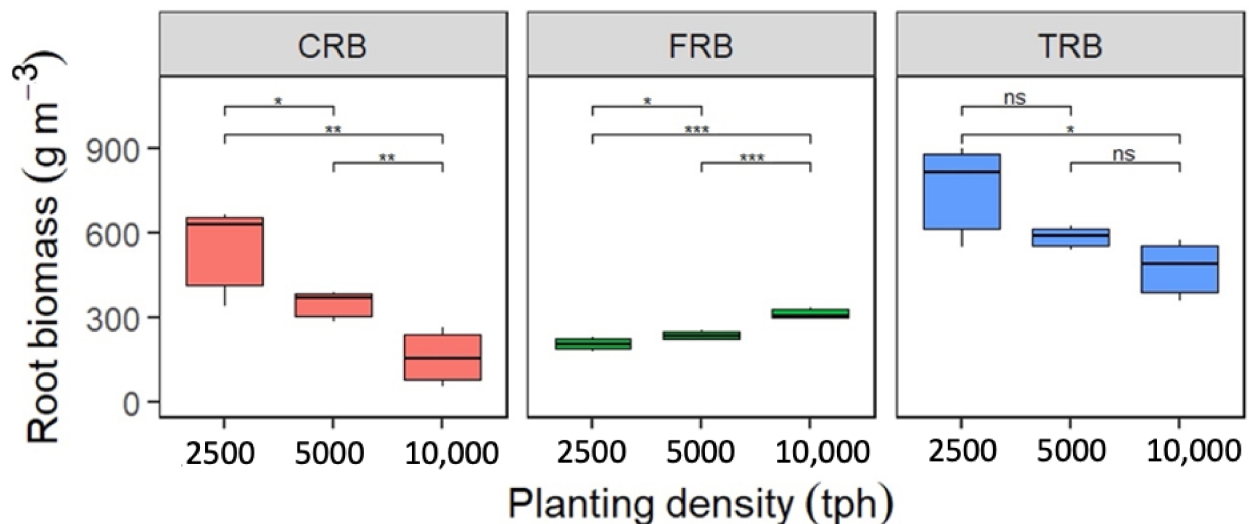

Figure 2. Variation in coarse root biomass (CRB), fine root biomass (FRB), and total root biomass (TRB) across the three different planting densities (2500 trees per hectare (tph), 5000 tph, and 10,000 tph). In the boxplots, the thick line shows the median; the box extends to the upper and lower quartiles; and dashed lines indicate the nominal range. Significant p values at *** < 0.001, ** < 0.05, and * < 0.1).

3.2. Soil Water Retention

The 10,000 tph treatment had significantly lower water retention at field capacity, that is, at 333 cm water applied pressure, compared with the 5000 and 2500 tph ($p < 0.05$). The 10,000 tph treatment had 0.21 m^3 m^{-3} water retention at field capacity compared with 0.28 m^3 m^{-3} and 0.30 m^3 m^{-3} of the 5000 tph and 2500 tph, respectively (Figure 3 and Table 1). The water retention curve of the 10,000 tph dropped significantly with gradually increasing applied pressure compared with the 5000 and 2500 tph, whereas the latter exhibited very similar water retention curves (Figure 3). Likewise, the 10,000 tph had a lower permanent wilting point of 0.03 m^3 m^{-3} compared with the other three planting densities at ~0.05 m^3 m^{-3} (Tables 1 and 2).

Table 1. Mean values of soil physical properties in the three planting densities.

Planting Density (tph)	Field Capacity (m^3 m^{-3})	Drainable Porosity (m^3 m^{-3})	Permanent Wilting Point (m^3 m^{-3})	Plant Available Water (%)	Total Porosity (m^3 m^{-3})	Bulk Density (Mg m^{-3})
10,000	0.21 ± 0.01 [a]	0.16 ± 0.03 [a]	0.03 ± 0.00 [a]	18	0.38 ± 0.01 [a]	1.59 ± 0.02 [a]
5000	0.28 ± 0.01 [b]	0.09 ± 0.01 [b]	0.05 ± 0.00 [b]	23	0.37 ± 0.01 [a]	1.60 ± 0.02 [a]
2500	0.30 ± 0.02 [b]	0.10 ± 0.03 [b]	0.05 ± 0.00 [b]	25	0.40 ± 0.01 [a]	1.58 ± 0.03 [a]

Same lowercase letters within a column indicate no significant difference between treatments. Values are means and SEs of field capacity (FC), drainable porosity (DP), permanent wilting point (PWP), plant available water (PAW), total porosity, and bulk density for three planting density treatments in the study at $p < 0.05$.

Table 2. Pairwise comparison of slopes of macropores, mesopores, macro- + mesopores, micropores, field capacity (FC), plant available water (PAW), drainable porosity (DP), total porosity (TP), permanent wilting point (PWP), and saturated hydraulic conductivity (Ksat) based on planting density.

		Planting Density		
Variables		**Comparison of Slopes**		
		10,000	5000	2500
Macropores	10,000			
	5000	-		
	2500	-	-	
Mesopores	10,000			
	5000	**		
	2500	**	-	
Macro- + Mesopores	10,000			
	5000	*		
	2500	*	-	
Micropores	10,000			
	5000	*		
	2500	*	*	
Saturated hydraulic conductivity	10,000			
	5000	*		
	2500	-	-	

Significant differences between SMA slopes for different seasons or planting densities are shown by (*) and (-) symbols. Significance level: *, 0.01–0.05; **, 0.01–0.001; (-), non-significant relationships. The rectangular blocks going from top left to bottom right shows that each variable perfectly correlated with itself.
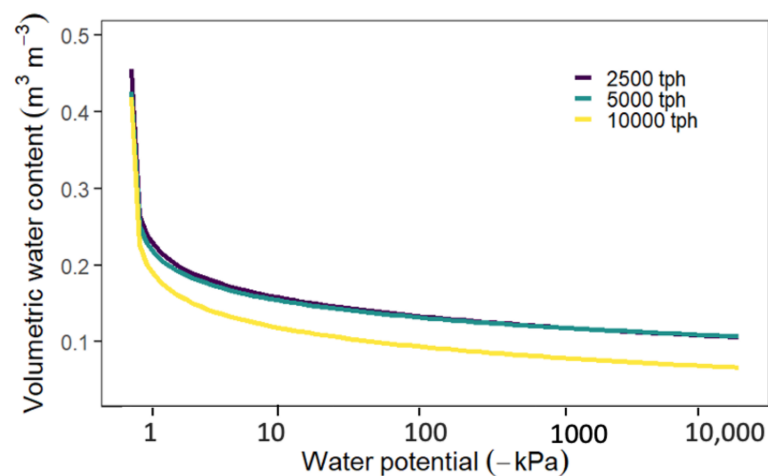

Figure 3. Soil water-retention curve showing the relationship between water content and water potential for the three planting densities (2500 trees per hectare (tph), 5000 tph, and 10,000 tph). Water potential was plot on a log base 10 scale.

3.3. Soil Pore Size Distribution

There were significant differences among planting density treatments for the distribution of micropores, mesopores, and meso- + macropores relative to the overall mean (Figure 4). The results showed a higher range of micropore fractions relative to the total porosity in the three planting densities, ranging from 71% to 80%, compared with the larger pore size fractions, ranging from 5% to 19%. As we hypothesized, the 10,000 tph treatment with the highest fine root biomass density had a high macro-porosity and a low micro-porosity compared with the other two planting densities. It had a significantly higher amount of mesopores, 11% ($p < 0.01$), and macro + meso pores, 28% ($p < 0.05$), and the lowest amount of micropores, 71%, compared with the 5000 and 2500 tph treatments ($p < 0.05$; Figure 4). The macropore and mesopore portions differed slightly at lower planting densities (5000 and 2500 tph), but when summed, the macro- + mesopore fractions

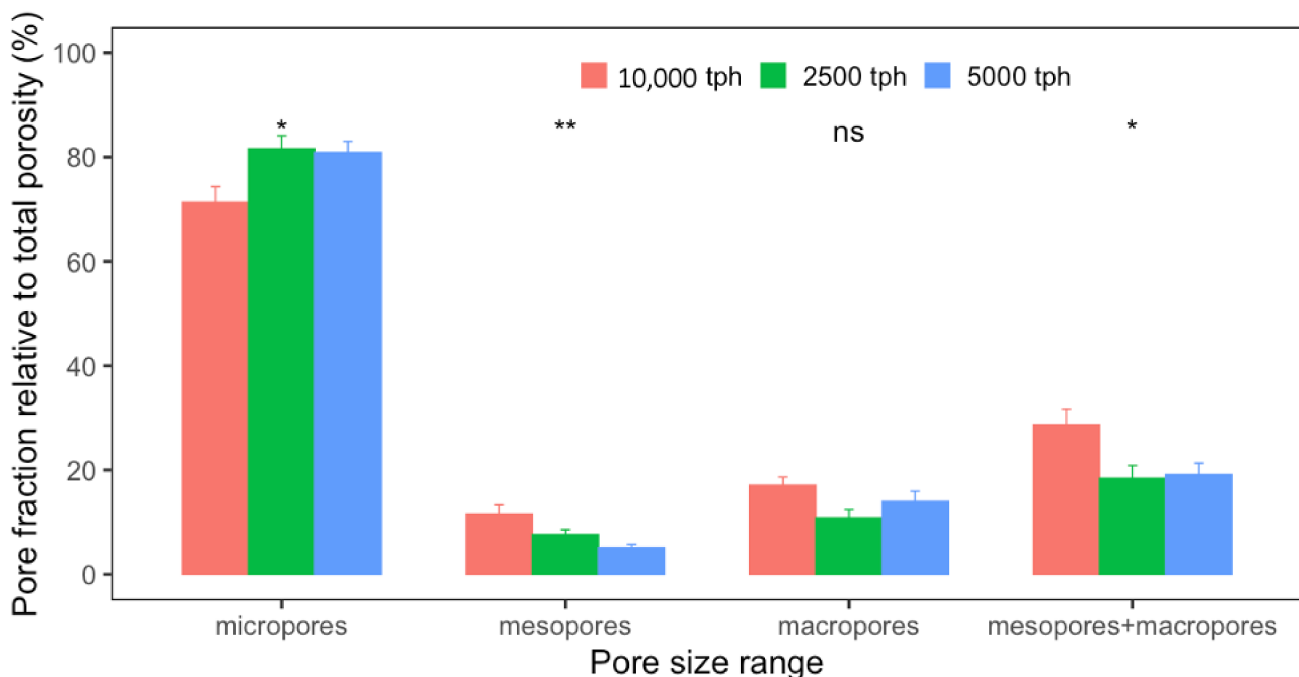were similar at 19% and 18%, respectively. The total porosity did not differ by planting density treatment.

Figure 4. Pore size fraction distribution by planting density treatments (2500 trees per hectare (tph), 5000 tph, and 10,000 tph) indicated by the different colors. Pore size classes were distinguished at 0.009 mm, 0.003 mm, and 0.04 mm for micropores, mesopores, and macropores, respectively (Luxmoore, 1981). Mean pore fraction relative to total porosity (%) per planting density was used in the analysis and error of the mean indicated on each bar (Significant *p* value = * < 0.05 and ns, not significant).

3.4. Soil Porosity Components

Due to the low FC and PWP recorded in the 10,000 tph (Table 1), it had the lowest plant available water (PAW), 18%, compared with the other two treatments, 23% and 25% in the 2500 tph and 5000 tph, respectively ($p < 0.001$; Table 1). Conversely, the 10,000 tph treatment had the highest DP, 16%, compared with the lower planting densities of 9% to 10% (Figure 5) ($p < 0.01$). The results showed a general trend of FC decreasing with increasing tree planting density from 2500 tph to 10,000 tph, while the drainable porosity (DP) increased (Figure 5).

3.5. Relationships among Root Biomass Distribution, Saturated Hydraulic Conductivity, and Water Retention

Water retention and hydraulic conductivity (Ksat) exhibited opposing responses to increasing root biomass, and the relationships were affected by planting density and root fraction. The 10,000 tph treatment had a significantly higher saturated hydraulic conductivity (Ksat) of $10^{2.2}$ cm day^{-1} compared with the other two planting densities, at $10^{1.1}$ and $10^{1.7}$ cm day^{-1} for the 5000 and 2500 tph treatments, respectively ($p < 0.5$; Figure 6; Table 1). Further analysis showed that water retention and Ksat were dependent on the presence of coarse or fine roots. With increasing coarse root biomass, water retention increased while Ksat decreased. The opposite was the case with fine root biomass: water retention decreased while Ksat increased as fine root biomass increased. In the 10,000 tph treatment, Ksat increased due to the increase in fine root biomass. Even with the lowest amount of coarse root biomass in this planting density, Ksat was shown to still increase. However, the 10,000 tph treatment had the lowest water retention regardless of having the highest fine root biomass and the lowest coarse root biomass. On the other hand, the

2500 tph treatment had high water retention with low fine root biomass and high coarse root biomass, but Ksat decreased with high coarse root biomass and increased even with a low fine root biomass (Figure 6).
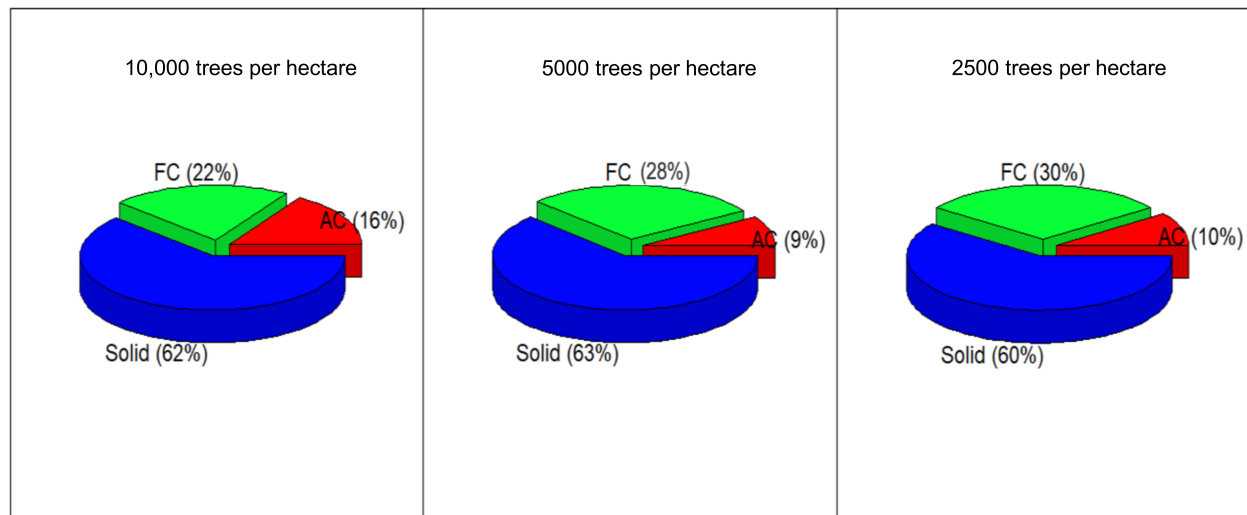

Figure 5. Distribution fractions of field capacity ((FC): remaining water in soil after saturation and drainage) and air-filled pore space at field capacity (AC) also termed drainable porosity ((DP): amount of water drainage from pores by gravity between saturation to field capacity) in the three planting density treatments (10,000, 5000, and 2500 trees per hectare). Solid represents the mineral and organic matter proportion of the soil.
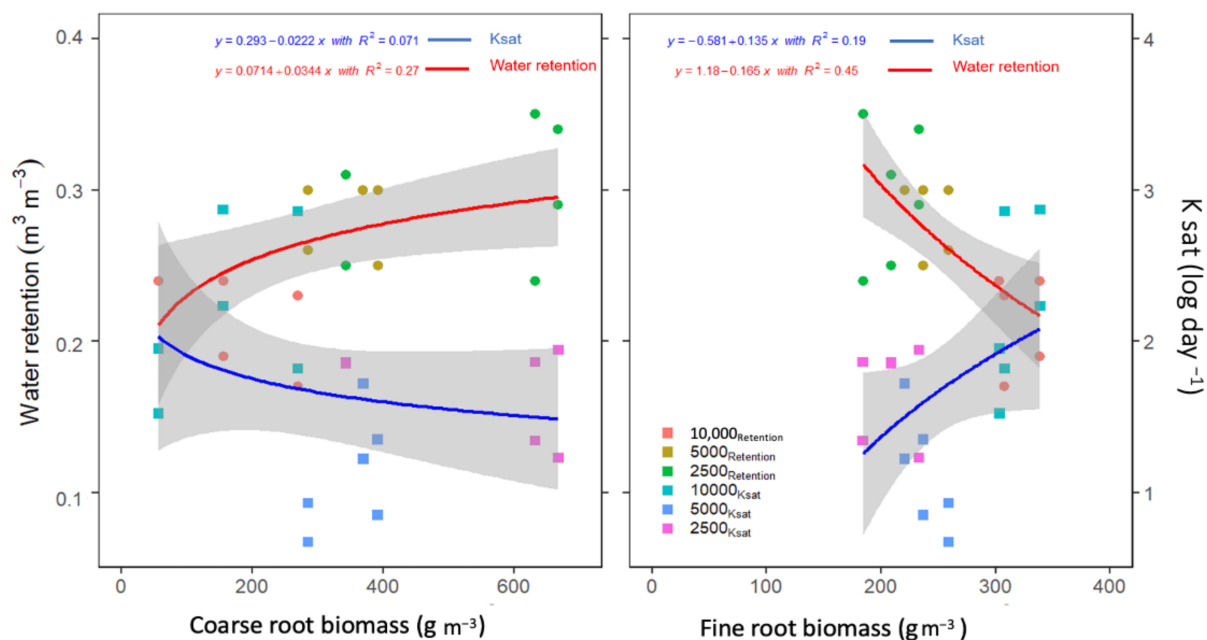

Figure 6. The trend of water retention and saturated hydraulic conductivity (Ksat) as coarse and fine root biomass density increased in the three planting density treatments (10,000, 5000, and 2500 trees per hectare).

4. Discussion

4.1. Effects of Planting Density on Coarse and Fine Root Biomass

Planting density is an important management consideration that determines the above-and belowground partitioning of biomass in SRWC plantations, influences forest ecosystem function, and has economic implications [51–53]. Furthermore, the impacts

of planting density on root biomass partitioning may influence tree nutrient and water uptake [54,55]. In this study, we found that the partitioning of coarse and fine roots differed in the different planting density treatments, where the lower planting densities produced more coarse roots while the higher planting density produced more fine root biomass (Figure 2). The CRB represented more proportion of the TRB, where CRB ranged from 160 to 648 g biomass m^{-3}, while FRB ranged from 208 to 316 g biomass m^{-3}, and the variance proportion technique further confirmed this result. This shows that the coarse roots drive the total root biomass in the sycamore plantation, which may result in more root carbon storage in lower planting densities. Our results conformed with the study of Berhongaray et al. (2017) [56], where there was more distribution of coarse root biomass than fine root biomass in a poplar and willow SRWC plantation. Belowground inputs from roots, microorganisms, and tree litter contribute to the soil carbon storage, which can be stored for decades depending on climatic and anthropogenic conditions [57,58]. However, the stored carbon in the coarse roots may not have a great effect on soil health such as the fine roots due to the high turnover of fine roots, facilitating water, carbon, and nutrient cycling in forest ecosystems [24,56,59]. Though, we did not measure roots turnover in this study, we assumed that, when the number of trees per unit area is high, the competition for belowground resources is higher, which may cause an overlap of roots that are short-lived and increase roots turnover, as reported by other studies [59,60]. Similar to our results, in a SRWC study of poplar, fine root biomass was higher when planted at narrow spacing (e.g., higher density) compared with wider spacing [53]. The high density of coarse root biomass in the tree plots are representative of the standing stocks of aboveground biomass, where they have been suggested to be correlated to tree size and tree age [61]. This is a positive result of American sycamore SRWC, as this reduces the effects of soil compaction, which is important for restoring abandoned agricultural fields [62].

4.2. Impacts of Coarse and Fine Roots Biomass on Soil Pore Size Distribution and Total Porosity

There was significant effect of planting density on pore size distribution but not on soil total porosity. The distribution of pore fractions and sizes in the three planting densities can also be attributed to the presence of either coarse or fine roots in each of the treatments. This was due to the interaction of roots with the soil ecosystem, supporting the formation of soil aggregates and creating and occupying pore spaces that affects pore size distribution and pore connectivity [34,63–65]. Further analysis to understand the relationship between sizes of roots and pore size distribution showed similar trends between coarse and fine roots in each planting density (Figure 7). This similarity in the relationship between coarse and fine roots with pore size distribution could be related not only to the rooting density but also to the pore volume as well as the tendency for roots to grow along pre-existing pathways [66,67]. For example, in the 2500 and 5000 tph treatments, micro porosity increased as CRB and FRB increased, while the larger pore sizes (macropores and mesopores) decreased. The significant relationships between roots biomass and pore size explains the importance of root and soil characteristics on pore size distribution [65]. Our results show R^2 values of 0.62, 0.65, 0.68, and 0.68 for the relationships between coarse roots and pore size distribution for macropores, mesopores, macro + mesopores and micropores, respectively (Figure 7) and, similarly, for the fine roots and pore size distribution (R^2 = 0.72, R^2 = 0.52, R^2 = 0.68, and R^2 = 0.68) of macropores, mesopores, macro + mesopores, and micropores, respectively (Figure 7).
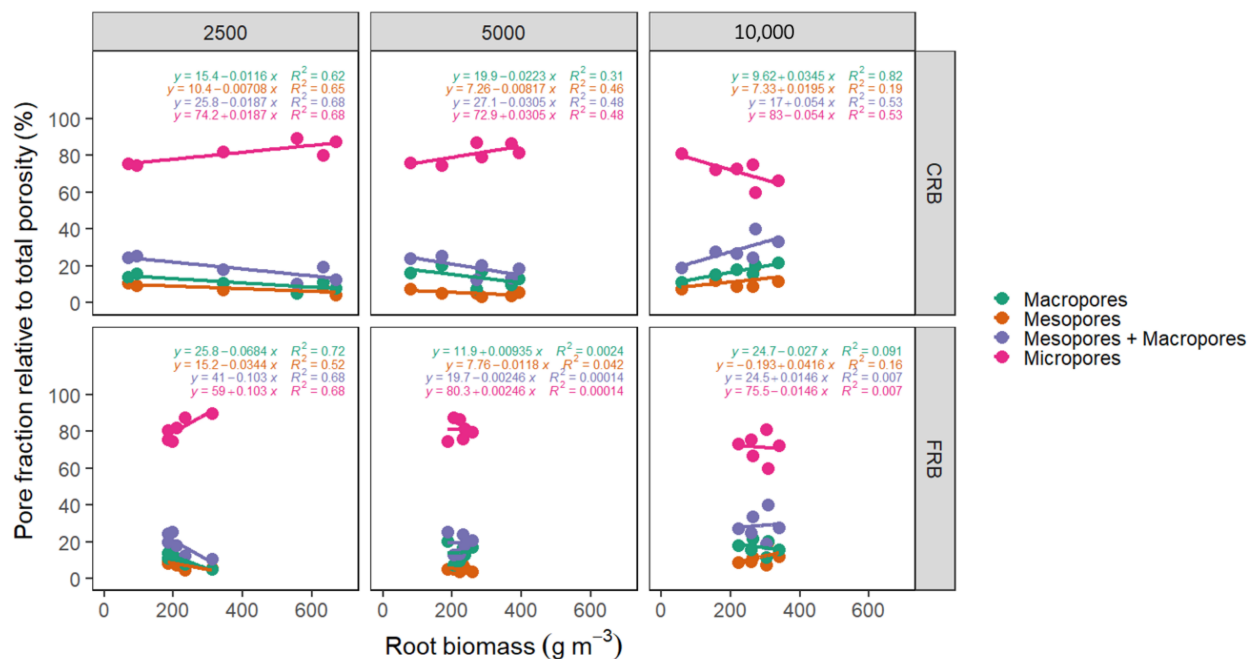
Figure 7. Relationships among coarse and fine root biomass density with macropores, mesopores, macro- + mesopores, and micropores with the pore size fraction as a factor in the three planting densities (2500 trees per hectare (tph), 5000 tph, and 10,000 tph). Each pore size fraction is assigned different colors. Linear regression lines were colored according to pore size fraction. Mean pore fraction relative to total porosity (%) per planting density was used in the analysis.

In particular, the 10,000 tph treatment showed a distinct trend, where micropores decreased as CRB and FRB increased, while the larger pores increased with an increase in CRB, but only mesopores showed a marginal increase as FRB increased ($R^2 = 0.16$). The weak relationships between FRB and pore size distribution in the highest planting density, that is, with macropores ($R^2 = 0.09$), meso + macropores ($R^2 = 0.007$), and micropores ($R^2 = 0.007$), indicates that other significant factors contributed to the intra-aggregate porosity besides the fine roots [68]. These other factors driving pore sizes could be mechanical effects (e.g., axial and radial pressures during soil penetration, and crack formation from wetting–drying cycles) [65,69], biochemical (e.g., exudation and rhizosphere microbes), and abiotic effects [65].

The 10,000 tph treatment presented a higher mesopore and macro + mesopore content with a respective decrease in micropores in contrast with the other two planting densities. This may be due to the higher microbial and nutrient activity that enhance stable soil aggregates and, hence, larger pore spaces [70,71]. A high macropore fraction in relation to the soil total porosity has also been associated with weed roots and root decay in the soil top layer [72]. In addition, the decay and easy buckling of fine roots in high planting densities, noted for increased intra-specific competition, may result in larger pore sizes in the soil [44,66]. This phenomenon of larger pore sizes observed in the 10,000 tph planting density could be important for the rapid drainage of waterlogged sites or excess water accumulated from heavy rainfall events or excessive irrigation. In contrast, other studies suggest that fine roots grow along existing pore spaces created by aggregated soil particles obstructing pores, while coarse roots physically shift soil aggregates forming larger pore spaces [73–76]. Lu et al. (2020) [76] found that fine roots in high planting densities reduced macropores in a review of root induced changes on soil hydraulic properties, and Bodner et al. (2014) [65] also found that coarse roots induced macropores while investigating the effects of coarse and fine roots on pore size distribution. The contradictions in these findings of root size fractions on soil pore size distributions highlights the challenge of correctly estimating micro and macro porosity and the need for more root-pore modeling work. As mentioned, although total porosity did not differ by planting density, differences

in pore size distribution did impact the soil air–water properties, particularly the 10,000 tph treatment, which had high macro porosity, showing an opposite trend in most of the properties tested compared with the lower planting densities.

4.3. Roots and Pore Size Distribution on Saturated Hydraulic Conductivity

Plant roots and pore size distribution are considered to be directly involved in the improvement and management of soil hydraulic properties [42,77–79]. Saturated hydraulic conductivity (Ksat) is one of the most important soil physical properties determining soil health, as it expresses the rate of water movement in response to a hydraulic gradient, yet it is highly variable due to biological, chemical, and physical soil processes [80,81]. As hypothesized, planting density affected the soil water properties in that the 10,000 tph planting density had a significantly higher Ksat and a significant decrease in soil water retention with applied pressure (Table 1 and Figure 6). Notably, this planting density had significantly higher mesopore and macro- + mesopore size fractions compared with the other two planting densities. Changes, such as an increase in Ksat, have been attributed to large pore spaces caused by root decay as well as fine roots that occupy pore spaces, impacting the formation of soil aggregates and hydraulic process [82–85]. Accordingly, Rasse et al. (2000), Schwarzel et al. (2011), and Germann and Beven (1982) [86–88] reported high macro porosity in their studies that resulted in a high Ksat. Perhaps, the 10,000 tph produced more tree litter, more organic inputs, and possibly more root activity [26,89,90], all of which help to improve soil structure, creating larger pore spaces in the soil and thus an increased rate of Ksat [91]. The high rate of Ksat in the 10,000 tph also plays an important role with the ease at which pores distribute rainfall for the water infiltration rate in soil. Given their size, larger pores increase the rate at which water drains or passes through the pores; hence, they are often filled with air and determine soil aeration. For sustainable management, the roots of SRWCs established on marginal lands (e.g., degraded agricultural land) can be used as a natural management tool to loosen soil compaction and to improve the root penetration of subsequent crops when the land is returned to agriculture. It also enhances the soil structural porosity and improves the soil permeability, water retention capacity, and saturated hydraulic conductivity of the land.

4.4. Roots and Pore Size Distribution on Water-Retention Components

Water and gas exchange are crucial processes mediated by soil physical properties. The opposing trends of water retention and aeration are such that an increase in one parameter causes a decrease in the other, which may or may not be desirable depending on the management objective and mechanical resistance [92]. According to Ng and Leung (2012), Ng and Pang (2000), and Romero et al. (1999) [93–95], water retention in soil is highly dependent on pore size distribution. In the current study, more micropores relative to total porosity led to higher plant available water capacity in the lower planting densities (5000 and 2500 tph), while more meso- + macropore fractions increased drainable porosity in the 10,000 tph (Figures 3 and 4). Riquelme et al. [77] also found a water-retention capacity on fields with a higher micropore fraction in contrast with the SRWC field with a higher macropore content. This is consistent with the greater water-retention capacity of fine texture soils compared with coarse texture [96], conferred by the greater matric forces of smaller pore size.

The high drainable porosity observed in the 10,000 tph is favorable for soil aeration and root oxygen uptake, which could be especially important at wet sites, such as becoming increasingly widespread in coastal areas under climate change, where altered hydrology due to sea level rise and extreme storm events result in prolonged hydroperiods [97]. In addition, the trees take up water more efficiently when the soil is more aerated. While this effect on soil hydraulic properties could be argued to decrease ecosystem resilience during times of drought, previous studies at our site have shown no negative effects on growth of experimentally simulated drought [8].

Short rotation woody crops have been shown to increase plant available water in the topsoil layer (0–10 cm) due to the accumulation of soil organic matter, root channels, earthworm burrows, and a high proportion of water-stable soil aggregates [90]. The 5000 and 2500 tph planting densities of American sycamore in the current study had higher plant available water, which in general should be good for SRWC, since the productivity of willow, polar, and hybrid aspen have been reported to be positively correlated with plant available water [98–100]. Trees grown at high planting densities were shown to have higher root water uptake, which markedly reduced the soil water content as induced suction increased and approached the field capacity at 25 kPa [101]. Perhaps, the low permanent wilting point results from this study (0.03–0.05 m m^{-3}) will provide a greater buffering of plant stress to low soil water content during times of drought.

5. Conclusions

There are remarkable impacts of planting density on root systems of short rotation woody cropping of American sycamore, with consequences for soil physical properties important to soil gas exchange and the movement and storage of water. The highest planting density, 10,000 tph, had more fine root biomass distribution, while the lower planting densities had more coarse root biomass distribution. The former also had more macro porosity while the two lower planting densities, 5000 and 2500 tph, had more micro porosity. Consequently, the 10,000 tph planting density showed significant differences in soil water and air properties compared with the other treatments, such as having the lowest plant available water, highest saturated hydraulic conductivity, and highest drainable porosity. The result from our study suggests that planting at 10,000 tph may be favorable for the restoring soil physical properties of intensively managed farmland soils or sites that are marginal and wet, such as those prevalent in coastal areas subject to altered hydroperiod, by improving gas exchange and by facilitating drainage. This implies that despite land being marginal, wet, or eroded, the establishment of SRWC American sycamore can either improve the soil water retention capacity or the soil drainable porosity depending on present or future management objectives, farmer or stakeholder interests, and the site conditions. This study provides a structure for other studies to build upon in assessing the impacts of SRWC American sycamore on soil health for sustainable management. We recommend that further investigations into SRWC root biomass partitioning effects on soil physical properties be conducted on multiple sites with diverse soil textures as well as sampling deeper soil profiles. We conclude 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 aboveground woody biomass productivity.

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