Productivity of low-input short-rotation coppice American sycamore (*Platanus occidentalis* L.) grown at different planting densities as a bioenergy feedstock over two rotation cycles

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Abstract

Short rotation coppice culture of woody crop species (SRWCs) has long been considered a sustainable method of producing biomass for bioenergy that does not compete with current food production practices. In this study, we grew American sycamore (*Platanus occidentalis* L.) for nine years corresponding to two rotation cycles (first rotation (FR) = 2010 – 2014, second rotation (SR) = 2015 – 2019). This was done at varying tree planting densities (1250, 2500, 5000, and 10000 trees per hectare (tph)) on a degraded agricultural landscape under low-input (e.g. no fertilizer and low herbicide application) culture, in the Piedmont physiographic region of eastern North Carolina. Tree productivity was proportional to planting density, with the highest cumulative aboveground wood biomass in the 10,000 tph treatment, at 23.2 ± 0.9 Mg ha^{-1} and 39.1 ± 2.4 Mg ha^{-1} in the first and second rotations, respectively. These results demonstrate increasing productivity under a low-input SRWC management regime over the first two rotations. Biomass partitioning was strongly affected by planting density during FR, allocating less biomass to stems relative to other plant parts at low planting density (44 to 59 % from 1250 to 10000 tph, respectively). This effect disappeared during SR, however, with biomass partitioning to stems ranging from 74 to 79 % across planting densities. Taken together, our results suggest that American sycamore has the potential to be effectively managed as a bioenergy feedstock with low input culture on marginal agriculture lands.

Keywords

Sustainable bioenergy, low-silvicultural input, degraded land, woody biomass partitioning, short rotation woody crops

1. Introduction

Renewable energy such as solar energy, wind energy and bioenergy derived from biomass are alternative sources that could reduce GHG emissions, thereby supporting goals of the Paris Agreement [1]. This agreement aims to mitigate climate change in the 21st century by decreasing CO_2 from the atmosphere and limiting temperature increase in this century to 2 °C [2, 3]. The focus of the current study is on cellulosic bioenergy, a renewable energy source produced from a variety of plant materials including herbaceous perennial crops, crop residues and woody bioenergy species. Biomass-based energy can offset the effects of GHG emissions on the environment, as well as enhance domestic economic development by supporting rural communities and industries involved in bio-based products [4].

There are long-term data on the biomass productivity of corn and perennial grasses because of extensive research on these species compared to woody bioenergy species [5, 6]. However, when corn and perennial grasses are grown solely for ethanol production, this can increase production costs greatly, add carbon to the atmosphere during fertilization and tillage, and can stress water resources [5, 7, 8]. A more sustainable bioenergy feedstock would be plants that can be grown with minimal agricultural/silvicultural inputs, which decreases costs and the environmental footprint. Trees, especially species that coppice vigorously after harvesting, have great potential as bioenergy feedstocks. Trees produce deep, extensive root systems to access soil resources and withstand many environmental stresses. Fine root mortality and turnover provide biochemically complex carbon inputs to the soil, in contrast to the shallow root systems of many annual crops [5, 9, 10]. Furthermore, the production of woody biomass is energy efficient, requiring minimal inputs such as pesticides and fertilizers [6, 11]. 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 [12]. The US Department of Energy considered wood to be the major potential source of renewable biomass energy because wood burns highly efficiently, with relatively low emissions of sulfur dioxide and methane, making woody fuel preferable to coal and natural gas [13, 14]. Some environmental organizations have argued that the increasing demand for wood pellets will lead to loss of old growth forests and loss of forest biodiversity [15, 16]. However, other researchers suggest that a strong wood pellet market will encourage forest planting/regrowth and reduce GHG emissions over multiple cycles of forest harvest [17, 18]. The thriving wood pellet industry in the Southeastern US has emerged as an alternative to the decline of pulp and paper production, sustaining high employment and regional economic stability [19]. In addition, the implementation of the European Union Renewable Energy Directive has prompted the development of wood pellet manufacturing facilities in the southeastern US [20, 21], accompanied by a local growing demand for woody biomass [22, 23]. Therefore, wood pellet production provides an opportunity if economically sustainable biomass production rates of 8 – 10 Mg ha^{-1} yr^{-1} can be achieved over multiple growing rotations [24, 25], offering economic diversification for landowners and rural communities [26, 27, 28].

SRWCs with a fast growth rate and optimal productivity at age 3 – 5 years can provide a continuous supply of biomass, as they re-sprout into multiple stems after coppicing. The genera *Populus* L. and *Salix* L. are the most widely investigated SRWC candidate trees in the southeastern US [5, 29]. However, many species of these genera are highly susceptible to pests and diseases, and do not establish well on marginal lands, hence requiring high input culture [6, 11, 30]. On the other hand, 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, resilience to adverse conditions and the ability to establish on marginal lands [6, 11, 12]. It has fast growth with medium wood density, excellent coppice ability, and thin bark (thus low ash content) and can thrive on highly degraded agricultural lands [31, 32]. Degraded agricultural land has been described as lands not suitable for agricultural cultivation due to poor crop productivity, abandoned croplands, and pasturelands with environmental liabilities [33]. American sycamore was once considered one of the most promising hardwood plantation species in the Southeastern US, however, there has been a decline in the study of American sycamore. This is partly due to its susceptibility to *Xylella sp.* (Pierce's disease for grapes) and *Ceratocystis sp.*, as well as the occurrence of an anthracnose disease that resulted in high mortality in plantations of 13 years or more [34, 35]. 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 stems. As such, current research focuses on growing the species in SRWC for bioenergy in multiple short rotations of under 5 years each [6, 11].

Although planting at high density increases (short-term) productivity, it also requires more resources and larger economic investment. However, this initial increased planting cost may be compensated for by a decreased need for weed control in the first growing season compared to wider spaced trees. Closely spaced American sycamore trees have been shown to rapidly shade out competing vegetation [11]. Furthermore, planting trees at wider spacing has been shown to reduce inter-specific competition, causing less efficient nutrient-use and inability to shade out competing vegetation, which could increase stool mortality [6]. Higher planting densities produce smaller individual trees, higher total aboveground biomass, more partitioning to stem wood relative to branches, and are generally favored for SRWC [6, 12]. This suggests that short rotation coppicing of American sycamore may be a regionally appropriate source of bioenergy feed stocks to meet current and future demands. Studies on the effect of planting density on SRWC productivity have involved high inputs such as fertilization, irrigation or both [32, 36 – 38]. Excluding our previous work [6], we know of no other studies that have investigated the effects of planting density on the productivity and growth response of American sycamore over multiple rotations under a low input cultural regime. In the current study, we quantify productivity of low-input American sycamore SRWC (no fertilization/irrigation/herbicides) over multiple rotations on an infertile, eroded soil in the Piedmont of North Carolina. An allometric approach that scales to the stand level [39] was used to quantify aboveground biomass production and examine the effects of planting density and coppicing on biomass productivity, stool mortality, and patterns of biomass partitioning. We hypothesized that productivity would be proportional to planting density, and that high planting density would result in greater biomass partitioning to stems due to competition for light, and greater stool mortality (greater intra-specific competition). We also hypothesized that productivity would not be reduced between the first and the second rotation, demonstrating the sustainability of American sycamore as a bioenergy feedstock.

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, Granville county, North Carolina (36° 7’58.20” N 78°48’26.49” W) in the Piedmont physiographic region of North Carolina. The soil is classified as an Altavista silt loam and a Creedmoor sandy loam (fine, mixed, semi active, 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} and a field capacity of around 29% (USDA NRCS Web Soil Survey, http://websoilsurvey.sc.egov.usda.gov/). The site is considered marginal land, that is, ancient, highly weathered soils of the Ultisol soil order with declining productivity due to historical unsustainable farming practices and resulting soil erosion common to the region [40]. Weather data from a nearby station indicate a mean annual precipitation of 1412 mm, mean annual high temperature of 21 ºC, and mean annual low temperature of 7.8 ºC from 2010 – 2013. Between 2014 – 2018, mean annual precipitation was 1398 mm, mean annual high temperature was 21.6 ºC and mean annual low temperature was 9.7 ºC. The precipitation for 2017 (1218 mm) was markedly low compared to the other years in the second rotation, particularly year 2018 of 1738 mm (https://www.ncdc.noaa.gov/cag/) .

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 (http://nc-forestry.stores.yahoo.net/sycimpied1yr.html) and hand planted in January 2010, to establish the experiment. During the first and second growing seasons of the study, in-between tree rows were mowed, and glyphosate herbicide was applied thrice to help the trees get established, but no other inputs were applied thereafter. A 4 x 2 completely randomized block design study was used, consisting of three blocks as replicates, four levels of planting density (0.5 x 2.0 m (10,000 tph^{-1}), 1.0 x 2.0 m (5,000 tph^{-1}), 2.0 x 2.0 m (2,500 tph^{-1}), and 4.0 x 2.0 m (1,250 tph^{-1}). Planting densities were randomized within each block, with two levels of drought per planting density (20 % reduction and control) randomized within each block as well, amounting to 24 plots in total, each 14 m x 14 m in size. 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. Consistent with the previous study on this site [5], the effect of the throughfall reduction treatment (drought) was not significant for tree variables quantified (P=0.5). Therefore, data were averaged over drought treatment for all analyses of the current study and will not be discussed for the remainder of the paper. After two growing seasons, the sweetgum, tulip tree, and poplar had high mortality despite replanting and competition control efforts. In contrast, American sycamore experienced very minimal mortality (<3%), and therefore, the study continued with that species alone. The trees were harvested/coppiced in March 2014, ending the first rotation (FR) and beginning the second rotation (SR) with no additional weed control or other inputs. The trees were then harvested/coppiced again in March of 2019 to complete the SR and begin the third rotation (TR) with no additional inputs.

2.3. Inventory and biomass allometry measurements

In FR, tree heights, basal diameter, and diameter at breast height (DBH, mm) were recorded for all trees in the plots. The relationship between DBH and plant dry mass was derived [6] to estimate the aboveground biomass of individual trees in each treatment plot and were summed to the plot level (kg plot^{-1}) and subsequently scaled to the ecosystem level (Mg ha^{-1}). Edge trees were excluded from the analysis to minimize edge effects. Woody biomass aboveground net primary productivity (ANPPwood, Mg ha^{-1} yr $^{-1}$) was calculated as the difference in aboveground wood biomass between successive years [6].

For the first three growing seasons of SR (2014 – 2016), DBH of all dominant shoots (Fig. 1) were recorded for every tree. The diameters were converted into basal area (BA) and summed to give total BA to weight ratio. These measurements allowed for development of allometric biomass regressions to scale the biomass for the main shoots to the whole tree (Table 1). For the fourth and fifth growing seasons of the SR (2017 and 2018), DBH was measured on the three dominant shoots of each tree for allometric analysis. For the fifth growing season, one individual shoot from each of the planting densities in each block was harvested with a chainsaw, measured, and weighed (12 shoots total). Branches were partitioned into live and dead, and weighed to derive individual diameter to weight ratio. Fresh samples of stems and branches were weighed green, dried at 70 °C and reweighed to measure dry weight and derive water content. Tree diameters were converted into BA and summed to give total BA to weight ratio, excluding trees growing on the edge of plots to avoid edge effects. Biomass regression equations (Table 1) were used to quantify biomass/productivity of all individual trees and components (stem wood, live branches, dead branches) per 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 were between 10 – 58 mm. Total foliage biomass was calculated by subtracting the sum of the other predicted components (stem weight, live and dead branches) from total tree biomass. Aboveground net primary production (ANPP) was derived by difference between successive years.

2.4. Statistical analysis

Analysis of variance (ANOVA) for a randomized complete block design was used to test for planting density, drought, and interactive effects. Block was considered as fixed effect to account for the effects of slope at the field site, and significant interactions between Block and treatments was counted as error. Tukey adjustment for least square means (LSMeans) was conducted in case of significant differences between treatments. Statistical analysis was performed with PROC GLM in SAS statistical software (SAS Institute, Cary, NC) using a significance level of $P < 0.05$.

3. Results

3.1. Suitable planting density for total woody biomass of American sycamore

There were significant effects of tree planting density on aboveground biomass productivity in all years from 2010 to 2018. Published biomass data from the first rotation cycle [6] indicated that the 10,000 tph treatment produced the highest aboveground biomass at 23.2 ± 0.9 Mg ha^{-1}, followed by the 5,000 tph treatment at 19.6 ± 1.6 Mg ha^{-1}, but the difference between these treatments was not significant ($P > 0.05$) (Fig. 2). The 2,500 tph treatment had a biomass of 12.3 ± 2.5 Mg ha^{-1}, which was also not significantly different from the 1,250 tph treatment, with the lowest biomass of 8.4 ± 1.6 Mg ha^{-1}. By the end of the second rotation, mean cumulative aboveground biomass in the 10,000 tph treatment was 39.1 ± 2.4 Mg ha^{-1} and 36.5 ± 0.9 Mg ha^{-1} in the 5,000 tph treatment, which were not significantly different from one another, but were significantly greater than the two lower planting densities ($P < 0.05$). The 2,500 tph treatment had a cumulative biomass of 22.1 ± 1.5 Mg ha^{-1}, which was significantly greater than the 1,250 tph treatment, which had the lowest biomass of (14.5 ± 1.6 Mg ha^{-1}) ($P < 0.001$) (Fig. 2).

In SR, the 10,000 tph treatment increased total biomass 11 % between the third and fourth growing seasons (27.1 to 30.1 Mg ha^{-1}), and had the highest percentage growth increase at 30 % (30.1 to 39.1 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 (25.3 to 30.3 Mg ha^{-1}) between the third and fourth growing seasons, and a 20.6 % increase (30.3 to 36.5 Mg ha^{-1}) between the fourth and fifth growing seasons. The 2,500 and 1,250 tph treatments had the lowest growth percentage increases. Between the third and fourth growing seasons, the 2,500 tph had 2.3 % increase in total biomass (20.2 to 20.6 Mg ha^{-1}), and a 6.9 % increase between the fourth and fifth growing seasons (20.6 to 22.0 Mg ha^{-1}). The 1,250 tph treatment had the least percentage increase at only 0.43 % (13.8 to 13.9 Mg ha^{-1}) in aboveground total tree biomass between the third and fourth growing seasons, and 4.4 % increase (13.9 to 14.5 Mg ha^{-1}) between the fourth and fifth growing seasons (Fig. 2). The higher planting densities in SR had significantly smaller tree basal diameter ($P < 0.05$) with the 10,000 tph and 5,000 tph with basal diameter ranging from 1,500 to 1,800 mm^{-2} and 2,300 – 2,500 mm^{-2}respectively compared to the lower planting densities ($P < 0.05$). The 1,250 tph produced significantly bigger tree basal diameter ranging between 8,000 – 10,000 mm^{-2} (Fig. 3).

3.2. Aboveground Net Primary Productivity (ANPP) dynamics

The third growing season of the first rotation (year 2012) had the highest ANPP across all planting densities, with the highest occurring in the 10,000 tph treatment at 12.7 Mg ha^{-1} yr $^{-1}$. In the second rotation, the third growing season (2016) again showed the highest ANPP across the planting densities, where the 10,000 and 5,000 tph treatments produced 10.8 and 11.1 Mg ha^{-1} yr $^{-1}$ respectively, compared to the lower planting densities. The year 2017 had the lowest ANPP (Table 2). After the five growing seasons of the second rotation, the highest ANPP was recorded in the 10,000 tph treatment, with an average of 9.0 Mg ha^{-1} yr $^{-1}$ and lowest was in the 1,250 tph planting density at 0.6 Mg ha^{-1} yr $^{-1}$ (Fig. 4; Table 2).

3.3. Biomass partitioning

Planting density treatments affected partitioning of biomass components (stem wood, live branches, dead branches, and foliage mass), with the highest planting density treatments producing significantly more biomass in all plant parts. In all planting density treatments, stem wood made up the majority of total biomass in both rotations, followed by leaf mass. Over the two rotations, the partitioning of biomass to stem wood ranged from 44 – 79 % (Table 3). At the end of the first rotation, total aboveground biomass was partitioned as 59 %, 57 %, 51 % and 44 % stem wood in the 10,000, 5,000, 2,500 and 1,250 tph treatments, respectively (Fig. 5; Table 3). At the end of the second rotation, stem wood ranged from 74 to 79 % of total aboveground biomass, from the lowest to the highest planting density treatments, with differences remaining statistically significant ($P < 0.001$) while dead branch biomass was the lowest component regardless of planting density, at about 1 % of the total biomass. Foliage and live branches ranged between 11 % to 14 % and 9 % to 11 % respectively from the lowest to highest planting density treatments (Fig. 5).

Coppicing of the stands during the first harvest fundamentally changed patterns of biomass partitioning. At the end of the FR, the lowest planting density allocated 31 % of total aboveground wood to live branches and 44 % to stems, compared to an average of 11 % in live branches and 56 % in stems for the other planting density treatments. By the end of SR, all planting densities had similar patterns of biomass partitioning, with an average of 10 % in live branches and 77 % in stems (Fig. 5; Table 3).

3.4. Stool mortality

At the end of SR, the 1,250 tph had significantly higher stool mortality, at 15 % of the total trees planted, compared to the other planting densities ($P = 0.01$). The other three planting density treatments had minimal mortality (ranging from 1 - 5 %) with no significant differences between them ($P > 0.05$), with the 10,000 tph recording the 5 %. Planting density treatments showed a general relationship of decreasing mortality with increasing tree diameter, but this was significant only for the 1,250 tph treatment (Fig. 6).

4. Discussion

American sycamore SRWC in the southeastern US has great potential to help meet the growing demand for alternative energy and achieve the United States mandate to increase biofuel production [30]. This study confirmed that planting density strongly affects the amount of total aboveground biomass produced by American sycamore and its partitioning into stem, leaves, live and dead branches, and above all that productivity is maintained over multiple rotations of SRWC culture, without the need for replanting (Fig. 2, Fig. 5 and Table 3). In this study, high planting densities of sycamore in short rotation lengths increased biomass productivity, indicating great potential to help meet future demands for woody feedstocks and diversify agricultural economics of landowners [12]. Adoption of this planting establishment (short-rotation coppice of sycamore) can contribute to the growing demand of wood pellets in the southeast of the US, that is expected to reach 11.6 Mt from a starting point of 0.5 Mt in 2010 [20, 41]. Further, the successful establishment of sycamore plantations on degraded lands [6, 11, 12] can help address loss of natural timberlands, following the permitted woody biomass for biofuels production credit under RFS2 (U.S Congress, 2007) limiting wood bioenergy feedstocks from natural forest stands [42].

Our study showed relatively high ANPP of American sycamore at 11.0 Mg ha^{-1} yr^{-1} in the third growing season of the second rotation (Table 2), even on degraded agricultural land without fertilizer, herbicides and/or irrigation. This reduces concerns of the loss of agricultural land being used for bioenergy production [12] and provides economic and environmental advantages due to the use of minimal inputs. When compared to other studies that have estimated the effects of planting density on biomass production of SRWC and used irrigation, fertilizer and/or herbicides [12, 43, 44], thus reducing both economic and environmental benefits. In a study conducted in Poland that incorporated lignin and fertilization as soil amendments [45], the biomass productivity of poplar matched the productivity of sycamore in our study with no fertilizer inputs (Fig. 7). Another economic advantage of American sycamore compared to other bioenergy crops is its resilience under environmental stress [11]. During this study, sycamore seedlings survived weather extremes and intense competition with agricultural weeds, where several other prominent candidate SRWC species experienced very high mortality under the low-input management regime [6]. On a former agricultural soil in South Carolina, sycamore survived weed competition and performed better than sweetgum in growth and biomass productivity in their first seven growing seasons [36]. Sycamore also out-grew sweetgum on a former pine forest site in Georgia [46]. These results are similar to the outcome of sweetgum, tulip tree and poplar establishments of our study, where these other tree species did not successfully establish despite competition control and repeated planting efforts [6]. Although unplanned, this outcome is evidence of the capacity of American sycamore to establish successfully, tolerate environmental stress, and maintain productivity under low input culture, all of which are necessary for woody bioenergy crops to be economically competitive with other land uses [5, 11].

Ultimately, we found increasing total biomass production during the first three years of both rotations, followed by a decline in subsequent years, and significantly higher biomass production of SR relative to FR (Figs. 2 and 3). We have found this “hysteresis effect” of American sycamore SRWC productivity in a totally unrelated study at a geographically distant field site [11], and it appears to be a real biological phenomenon (e.g. not driven by climate or site factors). In economic terms, this may suggest an optimal harvest age of 3 y, since productivity peaks at that age. However, the quality of the wood produced in subsequent years is high and the overall amount and quality of feed stocks produced may thus be higher at 4 or even 5 y of age. Although, our experience suggests individual tree diameters become too large to facilitate efficient mechanized harvesting after this amount of time. Other authors have shown that planting fast growing species on adequate sites for the optimal rotation length can improve economic performance [12]. In the current study, the total woody biomass productivity at the end of each growing season in the second rotation was higher than each growing season of the first rotation due to the pre-existing root systems/stool from the previous rotation after coppicing. Studies have shown increased productivity of sycamore after coppicing because of stored sugars in the roots [36], allowing shoots to sprout quickly from the stool, hence, producing a large amount of biomass quickly. This is further evidence that sycamore is a good candidate for bioenergy SRWC, with increasing productivity through multiple rotations [44].

The establishment of bioenergy trees at high planting densities increases intraspecific competition and nutrient-use efficiency, leading to higher biomass productivity in shorter rotation lengths to meet feedstock demands [46]. In the current study, the high-density planting treatments (10,000 tph and 5,000 tph) had the smallest size individual trees, but the highest total biomass yield compared to the lower density planting treatments (Fig 2, Fig 3, and Table 2). Further, the productivity of the 5,000 and 10,000 tph treatments were not statistically different over most years of the study, meaning that establishment costs can be substantially decreased with no loss in revenues by planting at the lower density. Planting density also influenced intraspecific competition, resulting in higher biomass partitioning to stem wood relative to other plant parts at higher densities [6, 47]. In all four planting densities of both rotations, stem wood had by far the highest proportion of total aboveground biomass. Foliage biomass was similar in both rotations due to canopy closure (e.g. light limitation), and by the end of the second rotation it ranged from 1.9 to 4.3 Mg ha^{-1} across planting densities. In studies by Burkes et al. [48] and Wood et al. [49], investigating the relationship between stand density and leaf biomass, they also reported little change in the leaf mass allocation at different planting densities. With the increased biomass allocation to stem wood and live branches and less to dead branches in the second rotation compared to the first rotation (Fig. 5), it would be interesting to see what the trend will be in the third rotation (plateau or increase). An additional advantage of coppicing American sycamore is that it 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 which in early research was reported to limit sycamore plantation success [35]. The current study is now in its third rotation (to be harvested again in 2022), and the health and productivity show no sign of diminution. Multiple rotations of hardwood SRWC also improves the environmental footprint of bioenergy SRWC by avoiding the energy-use and expense involved with plantation establishment and may increase ecosystem C storage due to decreased site disturbance [50].

Our results show 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 ha^{-1} yr^{-1}. The ANPP of 11.1 Mg ha^{-1} yr^{-1} in the third growing season of the second rotation is higher than the result of a similar study in Belgium (fourth growing season of fourth rotation) (Fig. 7) [51]. Where sixteen-year old poplar trees (10,000 tph) were established without fertilizer, herbicides or irrigation [51]. With an average biomass productivity of over 9.0 Mg ha^{-1} yr^{-1}, the performance of sycamore in this study is within productivity range of other tree species [11-12, 45, 51-53], including establishments that applied fertilizers, lignin and irrigation (Fig. 7). *Eucalyptus* spp, and loblolly pine (*Pinus taeda*) are tree species that could also rival our estimates of sycamore ANPP, with the former having mean ANPP of 17.5 Mg ha^{-1} yr^{-1} under high-input silviculture [5], and the latter about 15.0 Mg ha^{-1} yr^{-1} [54]. However, *Eucalyptus* spp are not indigenous to the southeastern US, while loblolly pine, though indigenous to this region, does not have coppicing ability. Non-native species could be susceptible to infections, diseases, and may not be environmentally favorable [55]. Furthermore, since loblolly pine trees are used as bioenergy feedstocks and considered for ethanol production [5, 12, 56], the lack of coppicing ability of the pine trees would increase production costs as replanting is required after every rotation. In addition, the higher lignin content and 5-C sugars of pines results in lower enzymatic hydrolysis efficiency and lower ethanol yields compared to hardwoods, such as American sycamore [56]. These limitations of other species do not apply to American sycamore for plantation establishment in the southeastern US.

In the current study, the 1,250 tph treatment had the highest stool mortality, at 15 % of the number of planted stools, by the end of the second rotation. It is uncertain why this occurred, but perhaps intense competition with competing weeds due to the high light environment after coppicing played a role. Although stool mortality in the 10,000 and 5,000 tph treatments were not statistically different, the relationship between stool mortality and mean tree diameter (Fig. 6) showed high mortality in the 1,250 tph and 10,000 tph which declined with increasing tree size (DBH). The impact of each tree dying in the 1,250 tph was higher than in the denser stands, maybe because the large size of the trees in this spacing density was a contributing factor, or maybe because when trees died, the remaining trees were not able to take advantage of the extra space. In longer rotations, the impact of mortality may even out as the trees may eventually occupy open growing space. The stool mortality is another benefit of establishing American sycamore at 5,000 tph planting density, compared to higher and lower levels. The low mortality in the 5,000 tph treatment, along with its high total woody biomass of 36.0 Mg ha^{-1}, by the end of the rotation, which was statistically not different from the 10,000 tph treatment (39.0 Mg ha^{-1}), suggests this planting density may be best for efficient productivity. Establishment costs could 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.

5. Conclusions

American sycamore SRWC produced total woody biomass of up to 39.0 Mg ha^{-1}, with average ANPP of up to 9.0 Mg ha^{-1} yr^{-1} by the end of the second rotation with minimal silvicultural inputs. An advantage of the second (and subsequent) rotation(s), is that it produced more biomass than the first rotation, and had no costs associated with new plantation establishment, such as labor, seedlings, herbicides, and fertilization. This illustrates the advantage of coppiced SRWCs over pines, which would have to be re-planted with each rotation. 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 good productivity under low input regimes, even on marginal land, with the potential to produce environmentally sustainable and competitive woody biomass feedstocks.

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Figures

Figure 1

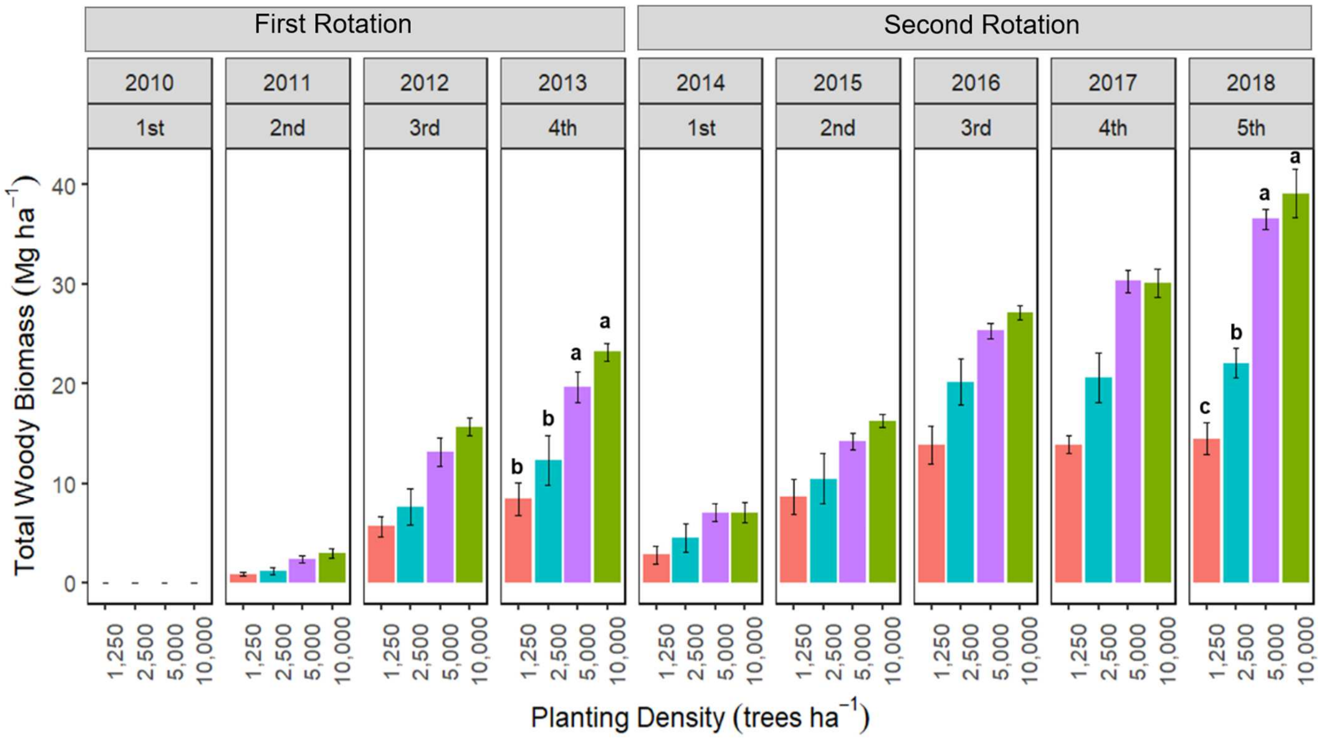

First Rotation
Second Rotation
2010
2011
2012
2013
2014
2015
2016
2017
2018
1st
2nd
3rd
4th
1st
2nd
3rd
4th
5th
Total Woody Biomass (Mg ha^{-1})
0
10
20
30
40
b
b
a
a
c
b
a
a
1,250
2,500
5,000
10,000
Planting Density (trees ha^{-1})

Figure 2

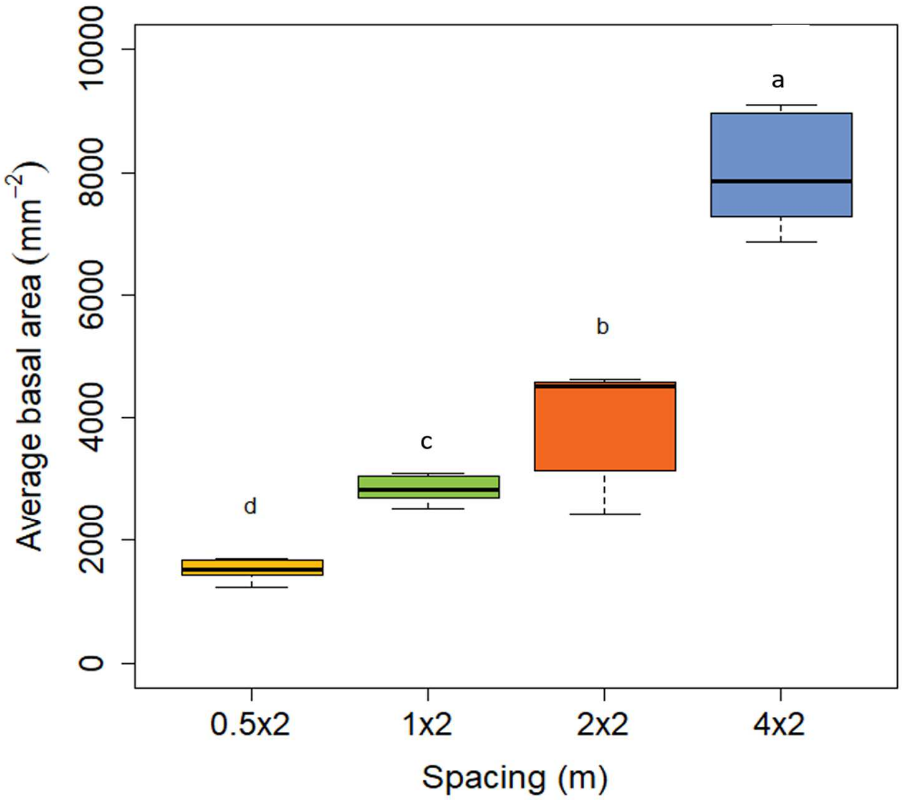

Average basal area (mm^{-2})
0
2000
4000
6000
8000
10000
a
b
c
d
0.5x2
1x2
2x2
4x2
Spacing (m)

Figure 3

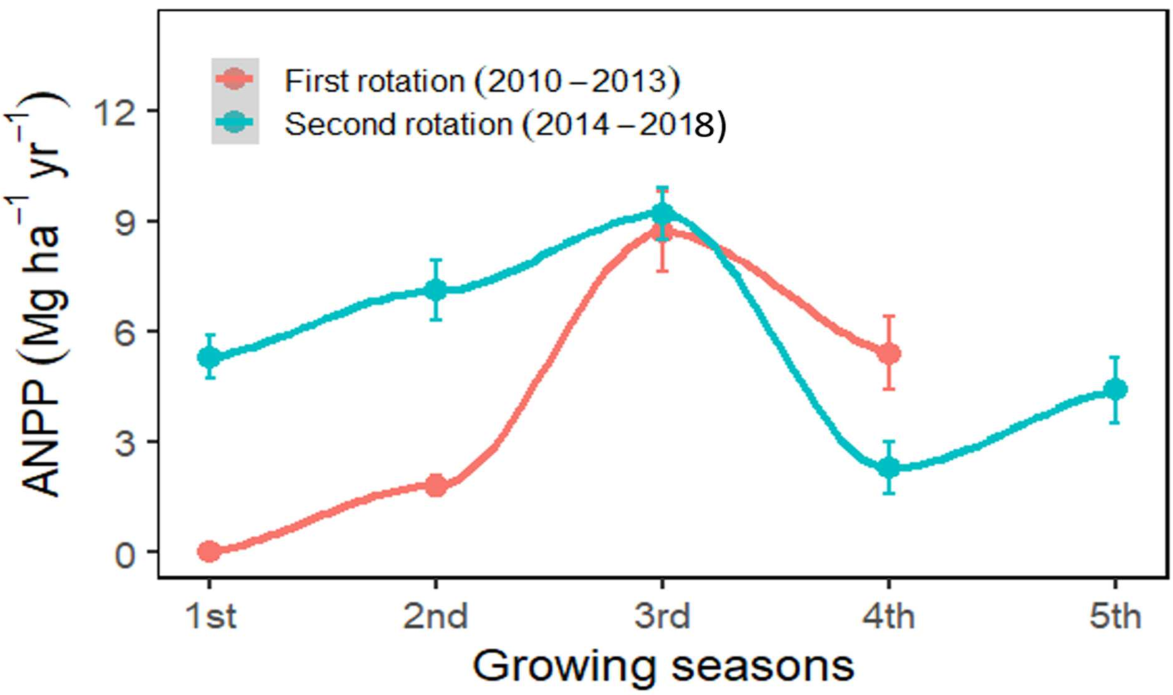

First rotation (2010 – 2013)
Second rotation (2014 – 2018)
ANPP (Mg ha^{-1} yr^{-1})
0
3
6
9
12
1st
2nd
3rd
4th
5th
Growing seasons

Figure 4

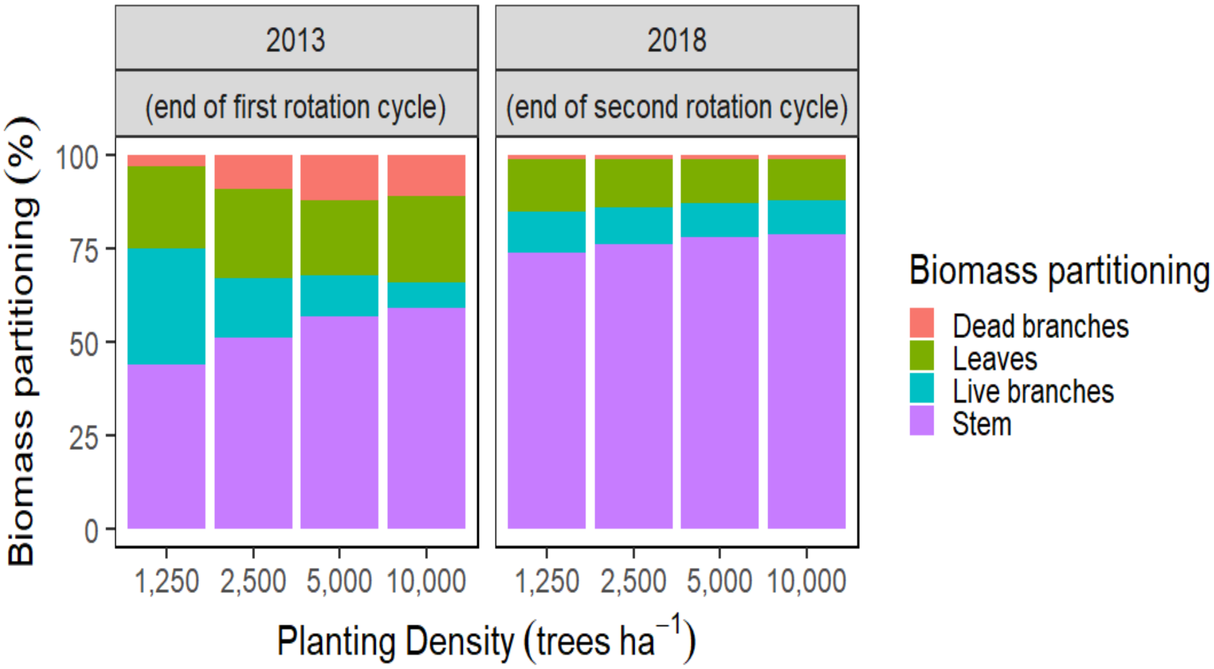

2013
(end of first rotation cycle)
2018
(end of second rotation cycle)
Biomass partitioning (%)
100
75
50
25
0
1,250
2,500
5,000
10,000
Planting Density (trees ha⁻¹)
Biomass partitioning
Dead branches
Leaves
Live branches
Stem

Figure 5

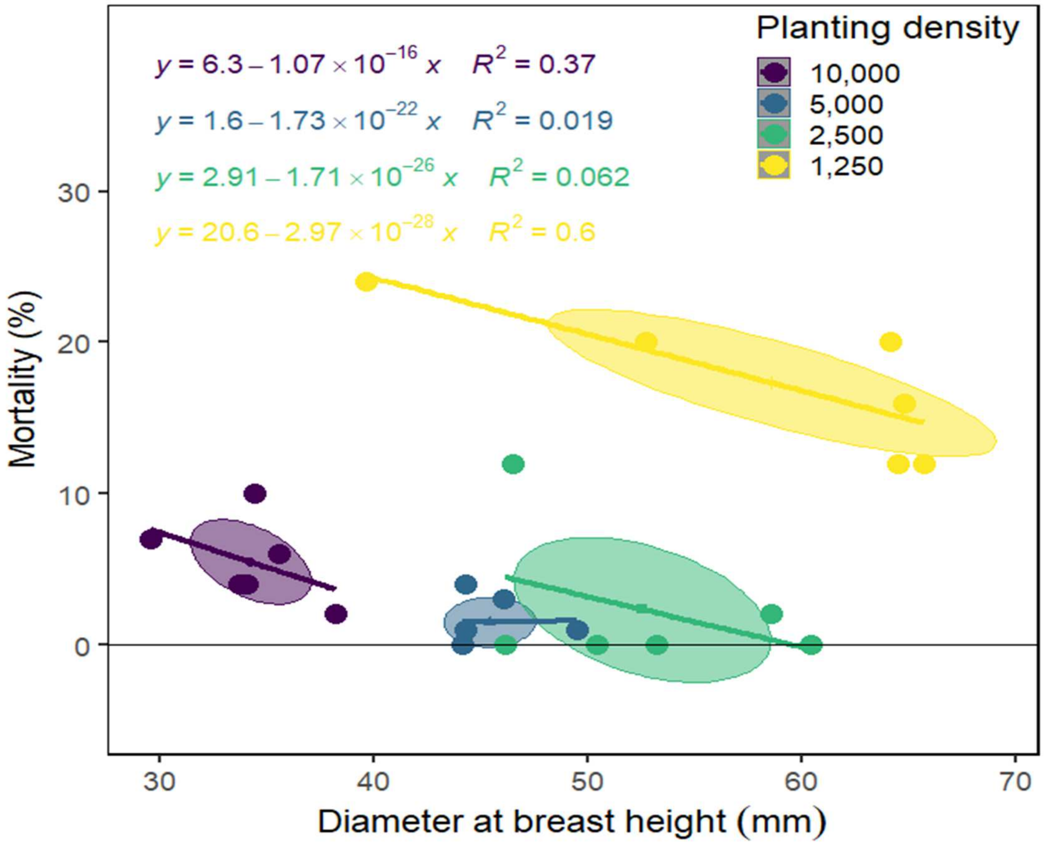
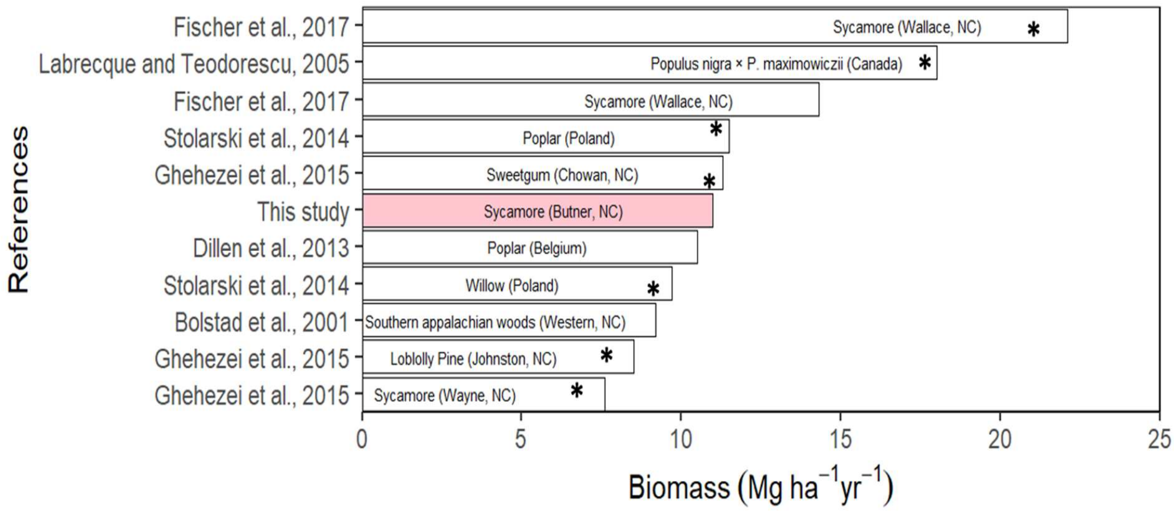

$y = 6.3 - 1.07 \times 10^{-16}\,x \quad R^2 = 0.37$
$y = 1.6 - 1.73 \times 10^{-22}\,x \quad R^2 = 0.019$
$y = 2.91 - 1.71 \times 10^{-26}\,x \quad R^2 = 0.062$
$y = 20.6 - 2.97 \times 10^{-28}\,x \quad R^2 = 0.6$
Planting density
10,000
5,000
2,500
1,250
Mortality (%)
30
20
10
0
30
40
50
60
70
Diameter at breast height (mm)

Figure 6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Fischer et al., 2017
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This study
Dillen et al., 2013
Stolarski et al., 2014
Bolstad et al., 2001
Ghehezei et al., 2015
Ghehezei et al., 2015
Sycamore (Wallace, NC) *
Populus nigra × P. maximowiczii (Canada) *
Sycamore (Wallace, NC)
Poplar (Poland) *
Sweetgum (Chowan, NC) *
Sycamore (Butner, NC)
Poplar (Belgium)
Willow (Poland) *
Southern appalachian woods (Western, NC)
Loblolly Pine (Johnston, NC) *
Sycamore (Wayne, NC) *
0
5
10
15
20
25
Biomass (Mg ha^{-1}yr^{-1})

Figure 7

Tables

Table 1: Biomass regression equation used to estimate productivity of American sycamore. Adapted from Boone, 2017 [57]

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

Table 2: Average (standard error) Aboveground Net Primary Productivity (ANPP) (Mg ha^{-1} y^{-1}) for each planting density (trees per hectare, tph). Year 2013 ends the first rotation (FR = 2010 – 2013) and year 2014 begins the second rotation (SR = 2014 – 2018). 2010 represents the year of establishment, hence, there are no available data for that year.

	ANPP							
	First Rotation (2010 – 2013)			Second Rotation (2014 – 2018)				
Planting density (tph)	2011	2012	2013	2014	2015	2016	2017	2018
10,000	2.98	12.69	7.49^{a}	7.00	9.27	10.84	2.98	9.03^{a}
	(0.45)	(0.74)	(0.82)	(0.70)	(0.70)	(0.75)	(1.40)	(1.70)
5,000	2.34	10.83	6.46^{a}	7.00	7.20	11.11	4.96	6.25^{a}
	(0.37)	(1.21)	(1.24)	(0.50)	(0.51)	(0.47)	(1.11)	(0.50)
2,500	1.18	6.45	4.69^{b}	4.48	5.99	9.70	0.46	1.42^{b}
	(0.34)	(1.60)	(1.16)	(0.80)	(1.00)	(0.66)	(0.21)	(1.00)
1,250	0.88	4.76	2.80^{c}	2.82	5.85	5.14	0.06	0.61^{b}
	(0.21)	(0.99)	(0.92)	(0.50)	(0.91)	(1.09)	(0.01)	(0.40)

Different superscript letters indicate significant differences between planting density treatments ($P < 0.05$) at the end of each rotation.

Table 3: Mean total aboveground biomass (Mg ha $^{-1}$) of the trees partitioned into stem, leaves, live and dead branches by planting density at the end of the first (2013) and the second (2018) rotation. Year 2013 is adapted from Domec et al., 2017 [5].

Year	Tree planting density (ha $^{-1}$)	Stem (Mg ha $^{-1}$)	Leaves (Mg ha $^{-1}$)	Live branches (Mg ha $^{-1}$)	Dead branches (Mg ha $^{-1}$)
2013	10,000	17.83 (0.67)	7.10 (0.92)	1.87 (0.06)	3.25 (0.13)
	5,000	13.60 (1.07)	5.04 (0.63)	2.61 (0.17)	2.87 (0.33)
	2,500	8.38 (1.67)	3.72 (0.69)	2.49 (0.42)	1.63 (0.39)
	1,250	4.84 (0.94))	2.61 (0.60)	3.34 (0.64)	0.19 (0.05)
2018	10,000	31.08 (1.81)	4.32 (0.28)	3.31 (0.24)	0.41 (0.02)
	5,000	28.43 (0.71)	4.32 (0.13)	3.4 (0.11)	0.37 (0.01)
	2,500	16.71 (1.08)	2.96 (0.32)	2.16 (0.10)	0.22 (0.01)
	1,250	10.77 (1.13)	1.95 (0.72)	1.62 (0.20)	0.14 (0.01)

Values in bracket represent the standard error of the mean