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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

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Abstract Short-rotation woody crops (SRWC) grown for bioenergy production are considered a more sustainable feedstock than food crops such as corn and soybean. However, to be sustainable SRWC should be deployed on land not suitable for agriculture (e.g., marginal lands). Here we quantified productivity and energy yield of four SRWC candidate species grown at different planting densities (1250, 2500, 5000, and 10,000 trees ha^{-1}) under a low-input regime on a marginal site in the Piedmont of North Carolina and responses to reduced water availability. By the end of the first growing season, 75 to 100% tree mortality occurred in all tested species (*Liquidambar styraciflua*, *Liriodendron tulipifera*, and *Populus nigra*) except American sycamore (*Platanus occidentalis*), the productivity of which was positively affected by planting density, but unaffected by the throughfall reduction treatment. After 4 years of growth, the 10,000 trees ha^{-1} sycamore treatment produced smaller individual trees but the largest amount of total tree biomass (23.2 ± 0.9 Mg ha^{-1}), which, although greater, was not significantly different from the 5000 trees ha^{-1} treatment (19.6 ± 1.5 Mg ha^{-1}). The two highest planting density treatments had similar aboveground net primary productivity (ANPP$_{wood}$) of 7.2 Mg ha^{-1} year^{-1}. By contrast, in the 1250 and 2500 trees ha^{-1} treatments, ANPP$_{wood}$ was significantly lower, ranging from 3.4 to 5.4 Mg ha^{-1} year^{-1}. Stem wood made up a majority of the biomass produced regardless of spacing density, but live branch biomass weight increased with decreasing planting density, comprising up to 31% of total aboveground biomass in the 1250 trees ha^{-1} treatment. Gross energy yield reached 140 GJ ha^{-1} year^{-1} for the 10,000 trees ha^{-1} treatment. Given this productivity, American sycamore could potentially yield 2400 (±380) L ethanol ha^{-1} year^{-1} over the first 4-year rotation. This study demonstrated that of the four species tested, only American sycamore grown on marginal land under low inputs (no fertilizer, no irrigation, limited weed control) had the capacity to successfully establish and maintain SRWC productivity, which might compare favorably with other fast-growing tree and grass species that typically require high inputs.

Keywords American sycamore · Bioenergy · Degraded land · Bioethanol · Productivity · Short-rotation woody crops

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Introduction

Currently, about 91 million barrels of crude oil per day are used to meet the energy needs of the world and this demand is projected to reach over 110 million barrels by 2030 [1]. In total, world energy consumption is projected to increase by

1.4% each year from roughly 550 quadrillion Btu in 2016 to 815 quadrillion Btu in 2040 [2]. In addition to the negative climate effects of massive production and consumption of fossil fuels [3], there will be a dramatic depletion of crude oil reserves as world population continues to grow [4]. Consequently, governments have begun to consider energy sources alternative to fossil fuels by exploring diversification of renewable energy technologies, such as fuel produced through biological processes [1, 5]. Most of the current biofuel production in USA is based on utilizing grain ethanol extracted from agricultural feedstocks or by converting starch into sugars primarily from edible corn and soybeans [6]. However, it is debated whether these feedstocks, which compete with the global food supply, are feasible or even ethical to use for bioenergy [7, 8]. In addition, there are serious concerns about the sustainability and climatic feedbacks of ethanol derived from corn and soybeans [6]. Not only is this a carbon intensive process but also expensive and inefficient, with over 80% of the operating cost in production coming from fertilizer inputs [9, 10]. Second-generation biofuels are renewable fuels that come from cellulosic woody biomass. Trees grown as a feedstock for bioenergy are considered a more sustainable substitute for petroleum because this renewable resource is manufactured without depleting food supplies, provides more energy than is used to produce it, and contributes environmental benefits such as the reduction of greenhouse gas emissions and soil restoration [9, 11]. While woody biomass combustion generates less energy per unit mass compared to fossil fuels, they cycle atmospheric CO_2, whereas fossil fuels release geologically stored carbon [12, 13].

As some southern US states strive to meet renewable energy goals, land owners may be provided an opportunity to use abandoned or nonarable lands not suited for field crops. These degraded farmlands, classified as “marginal lands,” are characterized by low productivity due to unsustainable cropping or because they are prone to flooding, drought, or erosion [14–16]. Based on soil and land use data, marginal agricultural land comprises 10% of the area of the Southeastern USA, and in North Carolina alone represents over 1 million hectares, with at least 500,000 ha being rapidly exploitable [17, 18]. To complement production of wood pellets, the state of North Carolina has implemented an energy strategic plan that includes the production of 10% liquid ethanol used for biocarburant to be derived locally from woody crops [19]. Conversion of marginal lands to cellulosic woody biomass could potentially meet this goal and limit the growing controversy of displacing land suitable for food production [20, 21]. Planting woody plants on marginal land could also rebuild soil organic matter, recycle nutrients, and provide vegetative cover [22], as well as increase landscape heterogeneity and biodiversity [23, 24]. Therefore, better understanding of woody crop optimization under environmental stress in a low-input system, and its effects on biomass production for bioenergy, is needed.

Much of the bioenergy research has been done on a few herbaceous perennial crops such as giant miscanthus (*Miscanthus giganteus* Keng.), reed canary grass (*Phalaris arundinacea* L.), and switchgrass (*Panicum virgatum* L.) and on a few woody species such as hybrid poplars (*Populu*s spp.) and willows (*Salix* spp.) [25–29]. Unlike corn and switchgrass, for which long-term data on productivity are available, data for perennial woody plants managed as bioenergy crops are still limited. Short-rotation woody coppice culture (SRWC) has the potential to provide a sustainable supply of bioenergy if trees grow fast enough to allow rotation times between 4 and 8 years, as compared to several decades for traditional silviculture [25–27]. The genera *Populus* and *Salix* have been the most widely investigated SRWC [28–30]. However, many fast-growing species of these genera are not native to the Southeastern USA because they cannot tolerate marginal lands, summer droughts, and high temperature [31–33]. Of the native southeastern species, American sycamore has the potential to out-produce others like black locust [22], cottonwood [34], yellow poplar [29], and sweet gum [35]. However, research on full rotation viability and productivity of American sycamore is still limited, with early studies focusing on suitability for the pulp and paper industry or from mature stands that overestimated the potential output of SRWC systems [36, 37]. Recently, American sycamore has shown promise for SRWC culture by being resilient to highly degraded agricultural areas [22, 38], even though its widespread use may be sensitive to water availability at establishment [34, 39]. Previous work has explored American sycamore as a wood energy crop for co-fired powerplants, with little investigation into productivity, stress tolerance, energy value, and potential ethanol yield, leaving many unanswered questions about the full energetic potential of this prospective bioenergy species.

When growing trees for rapid biomass production, there is a tradeoff between the cost of increasing planting density and the gain in productivity. Trees grown at high density require a larger initial economic investment but will result in faster site occupation, shading out competing vegetation and decreasing the need for weed control [35, 37]. However, smaller individual trees may not be appropriate as energy source or pulpwood. Trees smaller than 10 cm diameter cannot be harvested efficiently with conventional equipment [25] and pulp mills may be unwilling to accept smaller material because of low fiber quality relative to older wood [40]. Currently, there are no known studies that directly quantify the effect of planting density of tree spacing on the growth response and the energy value of sycamore grown primarily as a source of bioenergy.

In the current study, we report the results of SRWC field trials of four species at a marginal site in the Piedmont of North Carolina. The main objective of this experiment was originally to investigate low-input culture of four candidate hardwood species (*Liquidambar styraciflua* L., *Platanus* *occidentalis* L., *Liriodendron tulipifera* L., and *Populus nigra* L. × *Populus maximowiczii* A. Henry), exploring the effects of planting density on tree productivity and energy yield, and drought tolerance using a 20% throughfall removal treatment. However, with no fertilization or irrigation, and little competition control, only American sycamore exhibited almost 100% survival, and the other three species experienced very high mortality soon after establishment. Therefore, in this paper, we report an in-depth analysis of the productivity potential only for this native southeastern hardwood species, and only briefly mentioning the species that did not survive in the interest of providing a complete assessment of the bioenergy potential of the tested species under the specific experimental conditions.

Materials and Methods

Study site, experimental design, and treatment description

The study site was established in January of 2010 to determine the effects of planting density and water availability on stand-level aboveground biomass productivity of sweetgum (*L. styraciflua*), American sycamore (*P. occidentalis*), tuliptree (*L. tulipifera*) and the hybrid poplar 'NM6' (*P. nigra* × *P. maximowiczii*) grown as a short-rotation coppice culture in the Piedmont of North Carolina (Fig. 1). The site was located on North Carolina Department of Agriculture land in Granville County (36° 7′ 57.6798″ N, 78° 48′ 25.704″ W). Elevation is approximately 86 m above sea level. Between 2010 and 2013, mean annual precipitation was 1412 mm and mean annual temperature was 21.0 °C in summer and 7.8 °C in winter. The soil was comprised of 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} and a field capacity of around 29% (USDA NRCS Web Soil Survey, http://websoilsurvey.sc.egov.usda.gov/). At site establishment, bare-root seedlings purchased from the North Carolina Forest Service Tree Seedling Store (http://nc-forestry.stores.yahoo.net/sycimpied1yr.html) were hand planted. There was a single application of glyphosate herbicide between rows at planting. The application of glyphosate and mowing for weed control was however repeated three times during the first and second growing seasons. At the end of the first growing season (2010), 75–100% tree mortality occurred in all species except American sycamore, which experienced about 5% mortality regardless of treatments. High rates of seedling death were the consequence of extreme cold in winter and wet soils in spring 2010, followed by a dry summer (National Climatic Data Center, accessed 10/12/2016). Consequently, at the beginning of the second growing season, sweetgum, tuliptree, and poplar trees were replanted in the original experimental design but they again suffered very high mortality by the end of the second growing season, because of extreme summer temperature and despite the significant effort at competition control. The year 2011 was indeed the third warmest year on record at our site, and the 10th across North Carolina with maximum temperatures reaching 40 °C for a week straight. The exception was again sycamore, which experienced almost no mortality during the second year (<3%). Accordingly, the experiment continued as a productivity trial for sycamore alone, and no further attempts were made at establishing the other species. Trees were harvested after the fourth growing season in winter 2013–2014.

The experiment was set up as a randomized complete block design with a 4 × 2 factorial of planting density (1250, 2500, 5000, and 10,000 trees ha^{-1}) in control and a 20% throughfall reduction treatment, replicated in three blocks for a total of 24 plots (Fig. 1). They were 25, 50, 100, and 200 trees in the 1250, 2500, 5000, and the 10,000 trees ha^{-1} plots, respectively. Using the 1250 trees ha^{-1} plots as references, planting density treatments were established at the initial planting by reducing the planting distance by 2, 4, and 8 within the row for the 2500, 5000, and 10,000 planting density plots, respectively. Water reduction treatments were installed in February/March, 2012, before the third growing season. The throughfall reduction treatment was composed of vinyl rain gutters that covered 20% of the soil surface. Gutters were deployed below the tree canopy but elevated between 30 and 60 cm above the soil (to minimize soil-related artifacts) to move water gravimetrically off of the plots. Gutters were placed between tree-rows, leaving 50 cm spacing on both sides and an aisle width of 100 cm (Fig. 1). Throughfall reduction plots were surrounded by back-filled, plastic lined trenches 1 m deep to prevent lateral flow of soil water into/out of the plots and to contain tree roots within the treatment. Soil volumetric water content (VWC) was measured in each plot just after the throughfall reduction treatment was installed using time domain reflectometry probes (FieldScout TDR 300, Spectrum Technologies, Aurora, IL, USA) inserted at 25 cm depth. Each combination of planting density and water treatment was assigned randomly to each replication (Fig. 1).

Tree Growth and Aboveground Biomass

Basal diameter (BD, mm) measurements, taken 10 cm above the ground line, were recorded for every tree in every plot at the initial planting (2010) and at the end of the first and second

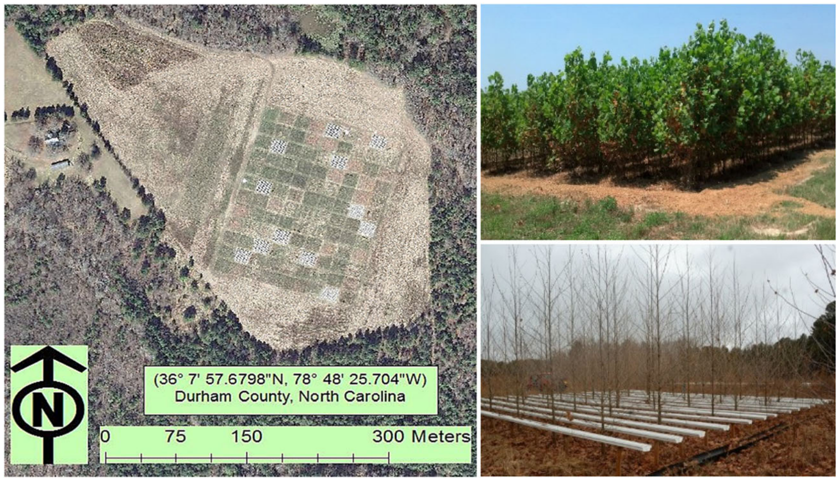

Fig. 1 American sycamore (*Platanus occidentalis*) site located at a North Carolina Department of Agriculture experiment station. In the *left image*, the *white squares* represent the throughfall reduction plots. American sycamore occupied 24 plots (of the 96 total) at this field, whereas the remainder was for the three species that did not survive (*Liquidambar styraciflua*, *Liriodendron tulipifera*, and *Populus nigra*). The *right panels* show the trees during the third growing season and the design of the throughfall reduction treatment

growing seasons. At the end of the third and fourth growing seasons, trees were tall enough so that both BD and diameter at breast height (DBH, mm) were recorded for every tree. Across both years and treatments, a common linear relationship relating BD to DBH was derived:

$$\mathrm{BD} = 1.19\ \ \mathrm{DBH} + 8.79; R^2 = 0.95 \quad (1)$$

Tree height (Ht, cm) of all trees was measured at the initial planting (2010) and at the end of the first and second growing seasons. Height at the end of the fourth growing season (2013) was measured on a subsample of 104 destructively harvested trees (26 trees per planting density treatment), because they were too tall to be measured directly. Tree heights of the remaining trees at the end of the fourth growing season were estimated using the resulting planting density specific regression equations of the general form Ht = m ln(DBH) + b, with an average R^2 of 0.75 and standard error of 0.09 (see Supplementary Table 1 for fitted parameters for each planting density). Heights of trees at the end of the third growing season (2013) were estimated using planting density specific regression equations developed from the measured height and BD from the end of the second and fourth growing seasons. The height and basal diameter equation followed the form Ht = m BD + b and had an average R^2 of 0.83 with standard error of 0.03 (Supplementary Table 2).

Partitioning differences between the planting densities was investigated by quantifying the different components of total aboveround biomass (stem wood, dead branches, live branches, and foliage mass). At the end of the fourth growing season, four to six trees were randomly harvested from within the interior of each plot (to mitigate edge effects) and used to develop allometric biomass regressions (same trees used for height measurements). Harvested allometry trees were separated into stem wood, dead branches, and live branches. The fresh mass (kg) of all components was measured in the field using a FG7750 Pelouze digital hanging scale (Rubbermaid Commercial Products, LLC, Winchester, VA, USA). From each stem wood sample, three subsamples of 10 cm each were collected, representative of the top, middle, and base of the stem and 20 to 30 10-cm-long segments of dead and live branches were also collected on each harvested tree. To determine water content (%), defined as fresh mass minus dry mass divided by dry mass, the subsamples from each component were dried to constant weight at 70 °C and weighed. Total dry mass of each component from each harvested tree was calculated by multiplying the total fresh mass by the subsample moisture content [41]. An allometric approach was used to quantify aboveground biomass for all trees in the experimental plots, including edge-buffer trees, although these were excluded from plot-level estimates of productivity. Quartic polynomial equations were fitted for each different spacing and throughfall reduction treatment using the harvested trees by regressing the natural logarithm of tree dry mass (stem wood, dead branches, live branches in kg) against DBH (in cm):

$$\text{Plant dry mass} = e^{\left(a + b(\mathrm{DBH}) + c(\mathrm{DBH})^2\right)} \quad (2)$$

Relationships between DBH as the independent variable and plant dry mass were used to calculate individual aboveground standing biomass for all trees in each treatment plot in the third and fourth growing seasons (Supplementary Table 3). All plant dry mass components were summed to the plot level (kg plot^{-1}) and scaled to Mg ha^{-1}. To minimize edge effects, the outermost (buffer) rows of the plots were excluded. Woody biomass aboveground net primary productivity (ANPP$_{\mathrm{wood}}$ in Mg ha^{-1} year^{-1}) was calculated from the difference in aboveground wood biomass between 2013 and 2012 (fourth and third growing seasons).

Specific Leaf Area and Leaf Area Index Measurements

Forest floor litter collection was done at the end of the fourth growing season to estimate stand leaf area index (LAI). Leaf litter was collected from one 0.25m^2 litter trap per plot placed in the area between the rows of trees. Samples were separated into leaves and twigs by hand and then oven-dried to constant mass at 70 °C. The total litter mass collected divided by the area of the litter baskets provided an estimate of annual leaf litter mass production per square meter. A subsample of fresh leaves was collected from each plot to determine specific leaf area (SLA in cm^2 g^{-1}). Special care was taken to retrieve samples from various levels of the canopy to ensure that any variation in age and light environment would be accounted for. Leaf area was estimated using ImageJ [42] and the same leaves were then dried at 70 °C to constant mass so that SLA could be calculated. Projected LAI for each plot was calculated as the product of SLA and dry leaf mass per ground area.

Growth Efficiency

Growth efficiency describes the amount of biomass (aboveground wood biomass in our case) created per unit of LAI [43]. To determine growth efficiency for the fourth growing season (the last year of growth), the $ANPP_{wood}$ was divided by LAI in each plot.

Wood Density

From the stem wood subsamples taken from the field and dried in the lab, a 2.5-cm segment from each middle stem wood sample was extracted. Samples were dried to constant mass at 65 °C and wood density (kg m^{-3}) of each sample was then calculated as the ratio of dry mass to dry volume that was determined by water displacement.

Energy Value

From the middle section of the stem subsamples, 0.4–0.7 g of wood were extracted. These were then kept in the drying oven at 65 °C to ensure uniform moisture content. Subsamples were run through an 1108 oxygen combustion vessel (Parr Instrument Company, Moline, IL, USA) to determine the energy value (calorific value) of the wood according to DIN 51900-3 (German Institute for Standardization, Germany).

Gross energy yield (GEY) was calculated as the product of wood energy value and $ANPP_{wood}$. In addition, we converted $ANPP_{wood}$ into the annual volume of liquid ethanol that could potentially be produced (in liter ha^{-1} year^{-1}) using the recent published ethanol yield value of 0.36 L ethanol kg^{-1} for American sycamore [44]. We also compared this ethanol volume produced to other several key SRWC and non-woody crops adapted to the Southeastern USA and established on either marginal or highly productive lands. We used published values of productivity and species-specific ethanol yields from other American sycamore stands [22, 29] and from *Populus* spp. [32, 33, 45–47], southern yellow pines [38, 48, 49], switchgrass [21, 50], giant miscanthus [51, 52], and maize [53, 54].

Statistical Analysis

All data were analyzed with a mixed model analysis of variance (ANOVA) for a randomized complete block design conducted in the MIXED procedure of the SAS/STAT software v9.4 (SAS Institute, Inc., Cary, NC, USA). ANOVA was used to test for planting density, throughfall exclusion and interactive effects. Block was first considered as fixed effect to account for the very clear effects of slope on soil water content, and the interaction between block and treatments was counted as error. We then tested for block effects and interactions. If block was significant but did not show an interaction with either treatment, we simplified the model by treating block as a random factor to consider consistent upslope-downslope differences in water availability. Least square means were generated from the MIXED procedure, and multiple comparisons among means were calculated using least square differences. The mixed model was also used to determine which treatment applications had a significant effect on LAI, growth efficiency, and wood density. A probability level of $P < 0.05$ was considered to indicate significant differences.

Results

At the end of the first growing season (2010), and again after replanting (2011), more than 75% tree mortality occurred in sweet gum, tuliptree, and the hybrid poplar NM6. However, American sycamore experienced only 5%and 3% mortality at establishment in 2010 and 2011, respectively, and so regardless of treatments. Therefore, we are only reporting results for this hardwood species.

Across seasons, soil VWC in the 0–20 cm soil layer decreased linearly by 7–9% ($P < 0.03$) from the lowest to highest planting density (Fig. 2). Throughfall reduction treatment decreased VWC only toward the end of the growing season ($P = 0.03$), whereas in spring no difference was observed. The effect of throughfall reduction increased with planting density (Fig. 2). However, there was no effect ($P > 0.21$) of the throughfall reduction treatment on any of the parameters studied including LAI, wood density, and tree biomass (Supplementary Table 4).

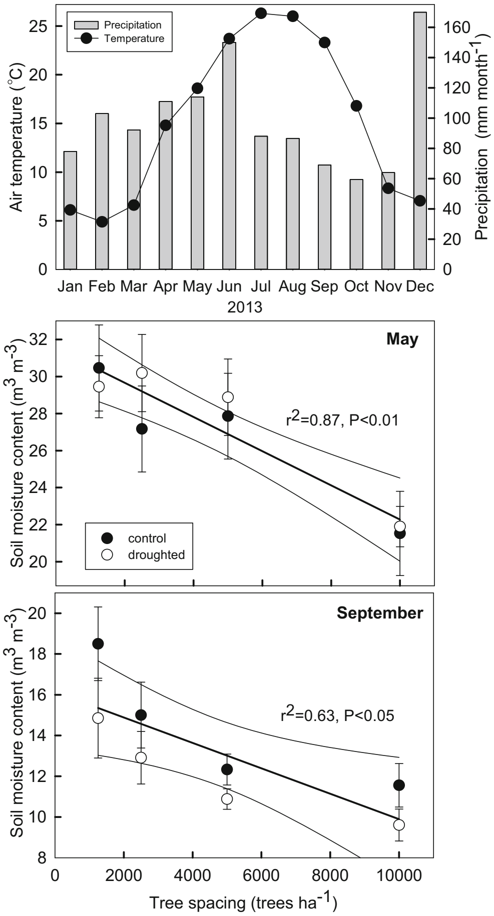

Fig. 2 Site monthly patterns in mean air temperature and precipitation, as well as mean soil moisture at 20 cm (with standard error bars) for different sycamore planting densities in control and droughts plots

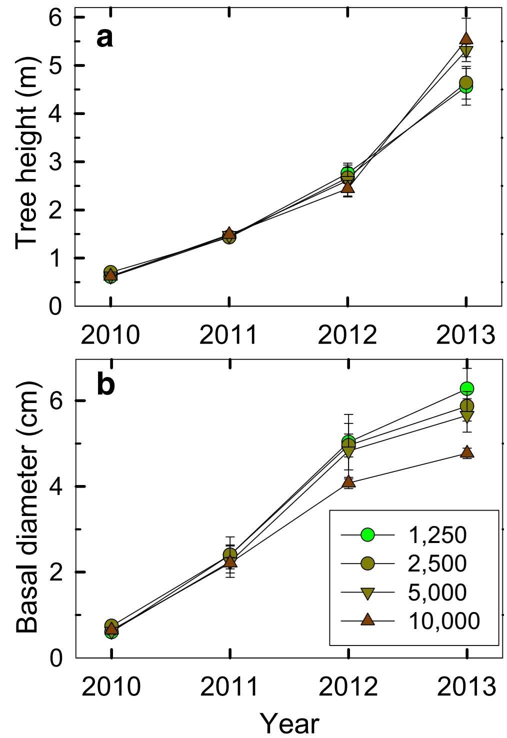

Fig. 3 Average height (**a**) and basal diameter measurements (**b**) for different planting densities throughout the first rotation (*bars* represent standard error of the mean)

Through the first three growing seasons, average American sycamore height for each of the spacing treatments was not significantly different ($P = 0.39$). In the last growing season, differences in average height between the planting density treatments became evident (Fig. 3a). Similarly, basal diameter measurements for the first two growing seasons were not significantly different ($P > 0.45$). However, in the third and fourth growing seasons, the 1250 trees ha^{-1} density treatment had the largest basal diameter and the 10,000 ha^{-1} density treatment had the smallest diameters on average (Fig. 3b).

There was no significant effect of age or location in the canopy on specific leaf area (SLA; $P > 0.05$), with a mean SLA of 167.1 ± 4.7 cm^2 g^{-1}. Stand LAI in year four (2013) was strongly correlated with planting density (Fig. 4), ranging from 5.81 (± 1.01) for the lowest planting density plot (1250 trees ha^{-1}) to 11.86 (±1.54) for the highest density plot (10,000 trees ha^{-1}). Throughfall reduction did not show any significant effect on LAI ($P = 0.41$) (Fig. 4; Supplementary Table 4).

Although the mean growth efficiency was nearly 20% higher at the high than low planting densities, this difference was not statistically significant ($P = 0.22$; Table 1). The effect of planting density on wood density was the opposite as for LAI, with wood density decreasing significantly ($P = 0.003$) with increasing planting density (Table 1).

Total tree biomass nearly tripled from lowest to highest planting density ($P < 0.001$, Table 2), whereas throughfall reduction treatment had no effect ($P > 0.21$; Supplementary Table 4). By the end of the fourth year, the highest planting density treatment (10,000 trees ha^{-1}) had reached total above-ground wood biomass of 23.2 ± 0.9 Mg ha^{-1}, compared to 8.4 ± 1.6 Mg ha^{-1} at the lowest planting density plots (Supplementary Fig. 1, Table 2). Specifically, there was no significant difference between the amount of total tree

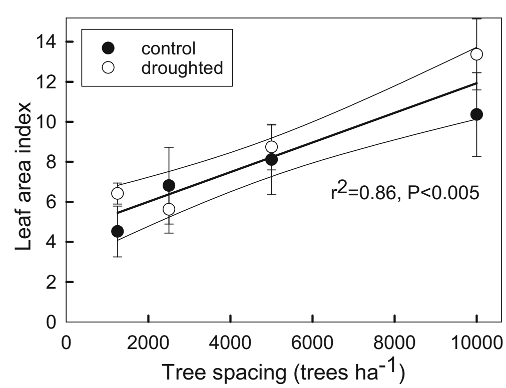

Fig. 4 Relationship between leaf area index and sycamore planting density for control and droughted plots (*bars* represent standard error of the mean)

Table 1 Mean values (SE) of leaf area index (LAI), growth efficiency, and wood density (average of control and droughted treatments)

Tree planting density	LAI	Growth efficiency ($Mg\ m^{-2}\ ha^{-1}\ year^{-1}$)	Wood density ($kg\ m^{-3}$)
10,000 ha^{-1}	11.86 (1.54) ^{a}	0.53 (0.07) ^{a}	598.2 (1.3) ^{d}
5000 ha^{-1}	8.42 (1.04) ^{b}	0.57 (0.08) ^{a}	622.9 (11.4) ^{c}
2500 ha^{-1}	6.22 (1.15) ^{bc}	0.49 (0.07) ^{a}	651.8 (11.2) ^{b}
1250 ha^{-1}	5.81 (1.01) ^{c}	0.44 (0.06) ^{a}	685.0 (10.3) ^{a}

The superscript letters indicate significant differences between planting density treatments ($P < 0.05$)

biomass produced between the 10,000 and 5000 trees ha^{-1} nor between the 2500 and 1250 trees ha^{-1} treatments (Table 2). Relative biomass increment in the last year of the study was 47–49% in the two highest planting density treatments and 61–65% in the two lower planting density treatments (Supplementary Fig. 1). Stemwood biomass increased progressively with planting density (Table 2), whereas stemwood productivity (ANPPwood) differed only between the three lower planting density treatments and was the same ($P = 0.72$) at 7.2 Mg ha^{-1} $year^{-1}$ for the 5000 and 10,000 trees ha^{-1} treatments (Fig. 5). Dead branch biomass followed the same pattern as total tree biomass, whereas live biomass differed only in the 10,000 trees ha^{-1} planting density treatment.

Stem wood made up a majority of the biomass produced, regardless of planting density (Fig. 6). The 10,000 and the 5000 trees ha^{-1} treatments had similar biomass partitioning, with 57–59% biomass in stem wood and 30–31% in branches and leaves (Fig. 6). The 2500 trees ha^{-1} plots resembled the denser spacing treatment in that the stem wood still made up a majority of the biomass proportion at 51%. In the widest spacing treatment, the stem wood still made up a majority of the biomass produced but it was no longer more than half. Live branch biomass mass increased with decreased planting density and comprised up to 31% of the total biomass in the 1250 trees ha^{-1} plots (Fig. 6). Regardless of spacing, dead branches were the smallest component of the total biomass produced (4–12%) and decreased with decreased planting density (Fig. 6).

As planting density did not affect wood energy value, with a global average of 19.3 ± 0.2 MJ kg^{-1}, GEY increased proportionally with standing biomass, with values reaching 140 GJ ha^{-1} $year^{-1}$ for the 10,000 trees ha^{-1} planting density treatment (Fig. 5). American sycamore managed for biomass yield with few inputs could potentially produce 2400 (±380) L ethanol ha^{-1} $year^{-1}$ over the first rotation (Fig. 7).

Discussion

Our results show that SRWC of American sycamore on currently under-utilized marginal lands could help achieve US bioenergy mandates and minimize the amount of diverted agricultural land. Over the first 4-year rotation of the current study, we demonstrated that American sycamore produced over 7 Mg ha^{-1} $year^{-1}$ on a marginal site (e.g., eroded Piedmont soils) in North Carolina with no fertilizer or irrigation inputs, suggesting great potential as a viable SRWC bioenergy crop. Although these yields are less than production rates shown for other SRWC systems with high inputs (10–18 Mg ha^{-1} $year^{-1}$ [45, 55]), and from the ambitious goals of the US Department of Energy (20–25 Mg ha^{-1} $year^{-1}$ [56]), they are consistent with a wide range of low-input SRWC species reported in the literature [28, 29]. Further, these yields would be immediately attainable given available (marginal) land, biomass production/processing technologies, and existing workforce in rural communities. Moving forward, we anticipate even higher yields after coppicing the system due to the already developed root systems [37]. In addition, SRWC systems may confer ecosystem services that can help restore degraded agricultural soils by increasing soil organic carbon, and consequent improvement of physical and chemical properties [9, 33]. Previous research has made significant strides in determining the growth potential of SRWC, including effects of planting density, however most of this work used high inputs (irrigation, fertilizer, herbicide) [22, 34–36, 38,

Table 2 Average values and their associated standard error (SE) for total tree, stem wood, dead branches, live branches, and leaf biomass at harvest when the trees were 4 years old (average of control and droughted treatments)

Tree planting density	Total tree ($Mg\ ha^{-1}$)	Stem wood ($Mg\ ha^{-1}$)	Dead branches ($Mg\ ha^{-1}$)	Live branches ($Mg\ ha^{-1}$)	Leaf mass ($Mg\ ha^{-1}$)
10,000 ha^{-1}	23.16 (0.89)^{a}	17.83 (0.67)^{a}	3.25 (0.13)^{a}	1.87 (0.06)^{a}	7.10 (0.92)^{a}
5000 ha^{-1}	19.62 (1.56)^{a}	13.60 (1.07)^{b}	2.87 (0.33)^{a}	2.61 (0.17)^{b}	5.04 (0.63)^{b}
2500 ha^{-1}	12.32 (2.47)^{b}	8.38 (1.67)^{c}	1.63 (0.39)^{b}	2.49 (0.42)^{b}	3.72 (0.69)^{bc}
1250 ha^{-1}	8.44 (1.65)^{b}	4.84 (0.94)^{d}	0.19 (0.05)^{c}	3.34 (0.64)^{b}	2.61 (0.60)^{c}

The superscript letters indicate significant differences between planting density treatments ($P < 0.05$)

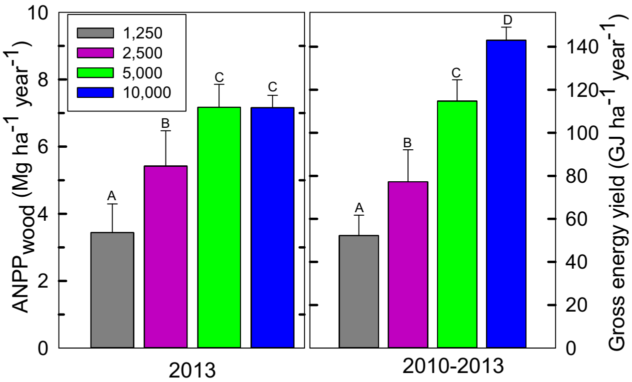

Fig. 5 Effect of planting density on aboveground net primary productivity ($ANPP_{wood}$; Mg ha^{-1} year^{-1}) during the last growing season (2013). Mean annual gross energy yield over the entire rotation is also given. *Bars with different letters* are significantly different ($P < 0.05$)

57], potentially decreasing economic returns and environmental benefits.

This study is also unique in assessing American sycamore SRWC tolerance to climatic stress under field conditions via a 20% throughfall reduction treatment that was effective in decreasing soil VWC (Fig. 2). Although there is some uncertainty in projections of future precipitation regimes, there is widespread agreement that there will be increased drought stress in the coming decades [28], and therefore, it is essential to evaluate the resilience of SRWC bioenergy systems to decreased water availability. In the current study, there was no effect of

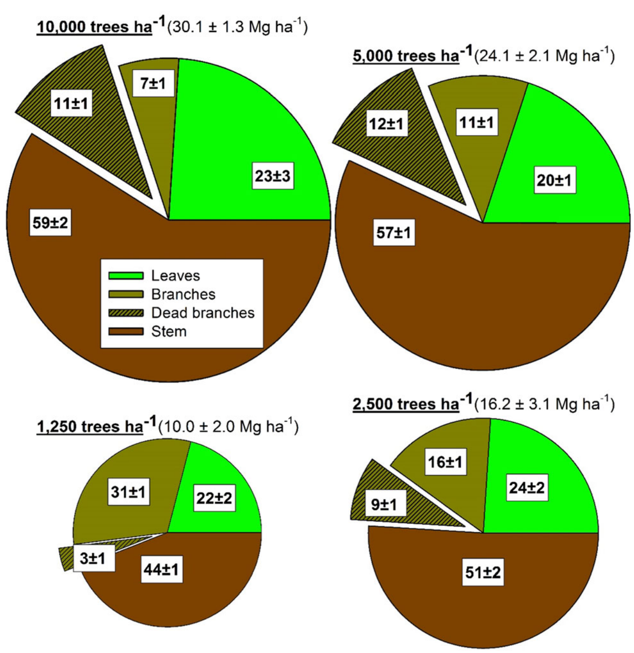

Fig. 6 Biomass partitioning between leaves, live branch, dead branch, and stem wood in sycamore trees growing at four planting densities at the end of the fourth (2013) growing season. The areas of the pie charts are proportional to the biomass production for each planting density (with actual productivity values given in parenthesis)

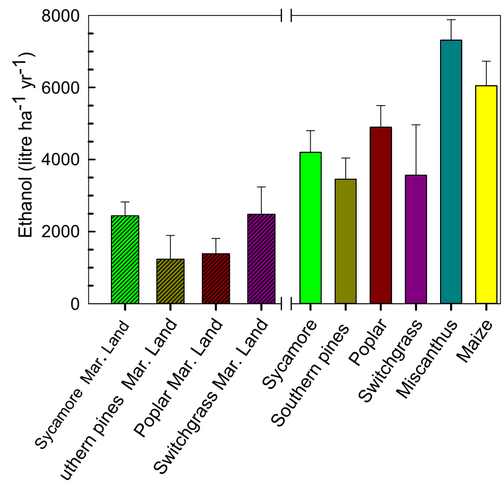

Fig. 7 Mean annual ethanol yields for the 5000 and 10,000 planting densities of American sycamore trees planted on marginal land (*Sycamore Mar. Land*), compared to other woody and non-woody species from marginal and high input lands (data taken from [22, 29] for other American sycamore stands, [48, 49] for southern pines, [32, 33, 45–47] for *Populus* spp., [21, 50] for switchgrass, [51, 52] for giant miscanthus, and [53, 54] for maize)

the throughfall reduction treatment on any of the parameters studied including LAI that is the main parameter driving tree growth, suggesting American sycamore can tolerate moderate water limitation. Even though we did not measure soil water stress during the experiment, an estimation of soil water potential using our measured soil water content data and soil water retention curves, led soil water potentials ranging from −0.2 and −0.8 MPa in the control plots and from −0.4 to −1.7 MPa in droughted plots. Those values indicated that the 20% throughfall reduction treatment likely caused a significant water stress. All of the other studies that investigated effects of water availability on aboveground productivity of American sycamore did so through irrigation [22, 34], even though climatic extremes predicted for the southeast in the coming decades are of increased drought severity [28]. The low inputs and high yields of American sycamore observed here may confer an economic advantage relative to other bioenergy crops when grown under realistic conditions of environmental stress.

Our results and other work in our program [e.g., 28, 29, 32, unpublished data] has shown that sycamore has fairly high tolerance to both biotic and abiotic environmental stresses, facilitating reliable plantation establishment, which will be a prerequisite of any widespread SRWC bioenergy industry. In the current study, sycamore seedlings were able to tolerate (e.g., exhibited high survival) planting in a cold wet winter followed by a severe hot, dry summer on poor soils without any amendments, and the intense herbaceous competition that was present in this converted agricultural field. Even though weed control was applied and seedlings were planted not once, but 2 years in a row, sweetgum, yellow poplar, and a hybrid *Populus* clone (NM6) were unable to establish successfully in what are quite common conditions across central and eastern North Carolina. Even though American sycamore yields were lower than those reported for giant miscanthus, for which we found limited data on productivity on low-input marginal land, ranging from 2 to 32 Mg ha^{-1} year^{-1} [58, 59], the successful establishment of sycamore with very low inputs may make it competitive economically [47, 60, 61]. Moreover, because giant miscanthus is a non-native relative of sugarcane, it may pose risks to native ecosystems [62] and carry diseases that would threaten the US sugarcane industry [63]. Finally, miscanthus planting needs to follow stringent planting, growing, and harvesting protocols to minimize the risk of the plant spreading [64]. Compared to other potential wood-based bioenergy species adapted to the Southeastern USA, American sycamore performed very well with 4–6 Mg ha^{-1} year^{-1} over the entire rotation and 7 Mg ha^{-1} year^{-1} in its final year before coppicing (Fig. 5). At a similar degraded site, with a similar study of biomass being utilized in SRWC, *Populus* spp. produced only 1.2 Mg ha^{-1} before the first coppice and 1.3 Mg ha^{-1} 1 year past the harvest and subsequent coppice [32]. After 3 years of growth, our productivity was also comparable to $ANPP_{wood}$ of native hardwood stands of deciduous forests of the Southeastern USA [30, 65–67], but 20% below productivity from plantations of *Populus* species and their hybrids planted in the rich Mississippi River Valley and in their native western North American region (around 9.5 Mg ha^{-1} year^{-1} [68, 69]). Again, those studies were performed on better soils that are also used for regular agricultural crops. Those $ANPP_{wood}$ values are still half of that from *Eucalyptus* spp. that could potentially produce over 18 Mg ha^{-1} year^{-1} under high-input silviculture [28], but this species is not native to the south and could potentially have unforeseen environmental costs [70]. In addition, large-scale studies are still inconclusive about *Eucalyptus* susceptibility to weed competition, late winter frost tolerance, and nutrient requirements [71, 72]. Loblolly pine, another Southern US indigenous species, could potentially rival the productivity of American sycamore on degraded sites [48]; however, it does not coppice, does best with high inputs, and would have lower ethanol yields due to high lignin content that decreases conversion efficiency [44, 73].

The specific energy value for each treatment was comparable, probably because within a species wood chemical composition is roughly the same regardless of growing conditions [74]. In our study, wood energy value was 19.2 MJ kg^{-1}, which is similar to the 18.7–18.9 MJ kg^{-1} reported for hybrid poplars [75, 76] and sycamore trees [77] and for cellulosic ethanol from corn and soybeans (19.9 MJ kg^{-1}) [77]. Although we only measured energy value of stemwood, earlier studies have found that the energy value between stem and branches is quite similar [75, 77]. Also because leaf and bark energy values of sycamore trees have been showed to be 4–6% higher than either branch or wood energy values [77], our calculations of whole-tree energy values based on trunk wood only were slightly underestimated. Combining biomass production and wood energy values reported here yields GEY ranging between 140 and 47 GJ ha^{-1} year^{-1} (Fig. 5), for the high and low planting density treatments, respectively. GEY for the 10,000 and 5000 planting densities was comparable to highly productive switchgrass [50, 79]. These results demonstrate that American sycamore managed for bioenergy on degraded land could potentially produce 2400 L ethanol ha^{-1} year^{-1} during the first 4-year rotation. This ethanol yield is almost double the calculated poplar or southern pine yields on degraded land and comparable to ethanol yields from low-input switchgrass (Fig. 7). These sycamore yields are, however, around 40–70% lower than that from SRWC grown on fertile arable land with high inputs (Fig. 7). Caution should be made in making direct ethanol yield comparisons with cellulosic sources and corn grain, because corn grain conversion technology is mature, whereas cellulosic conversion efficiency technology is based on an estimated value [80]. Forest biomass has lower hemicellulose content than agricultural biomass, and because of the difficulties in fermenting hemicellulose sugars, ethanol yields from grasses is lower than from woody biomass [78]. Forest biomass also has higher wood density reducing transportation cost, and can be harvested at any time of year, which eliminates long-term storage and allows transport flexibility.

Growing American sycamore at higher planting density resulted in not only smaller individual trees but also higher total above ground biomass production, consistent with other studies [81]. Furthermore, productivity increased together with greater proportional allocation to stem wood and lower allocation to branches (Fig. 6). Planting density had significant impact on wood density but not on growth efficiency and stem energy value. The decrease in wood density with higher planting density is probably the consequence of faster radial growth rates (Fig. 3b), which usually induce an increase in vessel lumen and an increase in cell wall thickness in early-wood and at the same time a higher proportion of latewood composed of vessels with thicker cell walls [74]. Even though the 10,000 trees ha^{-1} plots produced significantly higher GEY (Fig. 5), it may be that 5000 trees ha^{-1} represents the economic optimum, since productivity differences were not statistically significant, yet the cost of planting seedlings at the lower density would be halved. Many studies have quantified the effects of increasing planting density and resulting increase in biomass production [57, 82], and results of the current study are consistent with that body of work. As spacing between trees gets smaller, intraspecific competition increases, resulting in changes in biomass partitioning [82]. While absolute leaf mass increased with increasing stand density (Table 2), the proportion of leaf mass produced as a fraction of the total remained relatively constant (~22%) across planting densities (Fig. 6). However, as density of the stand increased, a larger amount (proportion and absolute mass) of stem wood was produced. In terms of growth efficiency (e.g., stem mass produced per unit leaf area), the higher planting density treatments appeared to exhibit the best performance ([83], Table 2); however, differences were not statistically significant. Taken together, these results suggest there may be a generalizeable relationship between stem production per unit leaf area as function of planting density that should be further investigated in bioenergy SRWC systems.

In conclusion, we determined that American sycamore has a much higher capacity to tolerate conditions of commercial nursery production and handling, transplanting shock, and environmental stresses relative to several other SRWC candidate hardwood species, enabling successful plantation establishment and good early productivity. This is extremely important because as a low marginal value commodity, maximizing bioenergy SRWC plantation establishment success at minimal cost is key to economic viability and adoption by practitioners. The ability to sustain good productivity over the first 4-year rotation using low-input silviculture also speaks to the economically competitive potential of American sycamore as an SRWC species and bodes well for environmental sustainability.

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References

1. International Energy Agency – IEA (2007) World energy outlook world energy outlook. International Energy Agency, Paris
2. Sieminski A (2016) International Energy Outlook 2016. Center for Strategic and International Studies May 11, 2016 Washington, DC
3. Hansen J, Kharecha P, Sato M, Masson-Delmotte V, Ackerman F et al (2013) Assessing “dangerous climate change”: required reduction of carbon emissions to protect young people, future generations and nature. PLoS One 8(12):e81648
4. Princen T, Martin P, Manno J (2015) Ending the fossil fuel era. MIT Press, Cambridge, MA 374p
5. Lee RA, Lavoie JM (2013) From first- to third-generation biofuels: challenges of producing a commodity from a biomass of increasing complexity. Animal Frontiers 3:6–11
6. Balan V (2014) Current challenges in commercially producing biofuels from lignocellulosic biomass. ISRN Biotechnol 2014:1–31
7. Pimentel D (2003) Ethanol fuels: energy balance, economics, and environmental impacts are negative. Nat Resour Res 12:127–133
8. Mohr A, Raman S (2013) Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. Energy Policy 63:114–122
9. Johnson J, Coleman M, Gesch R, Jaradat A, Mitchell R, Reicosky D et al (2007) Biomass-bioenergy crops in the United States: a changing paradigm. Am J Science Biotech 1:1–28
10. Liptow C, Tillman AM, Janssen M, Wallberg O, Taylor GA (2013) Ethylene based on woody biomass-what are environmental key issues of a possible future Swedish production on industrial scale. Int J Life Cycle Assess 18:1071–1081
11. Djomo SN, El Kasmioui O, De Groote T, Broeckx LS, Verlinden MS, Berhongaray G, Fichot R, Zona D, Dillen SY, King JS, Janssens JA, Ceulemans R (2013) Energy and climate benefits of bioelectricity from low-input short rotation woody crops on agricultural land over a two-year rotation. Appl Energy 111:862–870
12. Lemus R, Lal R (2005) Bioenergy crops and carbon sequestration. Critical Rev Plant Sci 24:1–21
13. Ryan MG, Harmon ME, Birdsey RA, Giardina CP, Heath LS, Houghton RA, Jackson RB, McKinley DC, Morrison JF, Murray BC, Pataki DE, Skog KE (2010) A synthesis of the science on forests and carbon for US forests. Issues Ecology 13:1–16
14. Richter DD, Markewitz D (2002) Understanding soil change: soil sustainability over millennia, centuries, and decades. Cambridge University Press, Cambridge, p 255
15. Dale VH, Kline KL, Wright LL, Perlack RD, Downing M, Graham RL (2011) Interactions among bioenergy feedstock choices, landscape dynamics, and land use. Ecol Appl 21:1039–1054
16. Gopalakrishnan G, Cristina NM, Snyder SW (2011) A novel framework to classify marginal land for sustainable biomass feedstock production. J Environ Qual 40:593e1600
17. Wear D, Abt R, Alavalapati J, Comatas G, Countess M, McDow W (2010) The South’s outlook for sustainable forest bioenergy and biofuels production. The Pinchot Institute Report, Washington, DC
18. Costanza J K, Abt RC, McKerrow A J, Collazo JA (2016) Bioenergy production and forest landscape change in the southeastern United States. GCB Bioenergy. In press. Doi 10.1111/gcbb.12386
19. Burke S, Hall BR, Shahbazi G, Tolson EN, Wynne JC (2007) North Carolina’s Strategic Plan for Biofuels Leadership. Environmental Review Commission, North Carolina General Assembly, Raleigh, NC
20. Tenenbaum DJ (2008) Food vs. fuel: diversion of crops could cause more hunger. Environ Health Perspect 116:254–257
21. Gonzalez R, Daystar J, Jett M, Treasure T, Jameel H, Venditti R, Phillips R (2012) Economics of cellulosic ethanol production in a thermochemical pathway for softwood, hardwood, corn stover and switchgrass. Fuel Process Technol 94:113–122
22. Brinks J, Lhotka J, Barton C, Warner R, Agouridis C (2011) Effects of fertilization and irrigation on American sycamore and black locust planted on reclaimed surface mine in Appalachia. For Ecol Manag 261:640–648
23. Wiens J, Fargione J, Hill J (2011) Biofuels and biodiversity. Ecol Appl 21:1085–1095
24. Tarr N, Rubino M, Costanza MJ, McKerrow JK, Collazo AJ, Abt RC (2016) Projected gains and losses of wildlife habitat from bioenergy-induced landscape change. GCB Bioenergy. doi:10.1111/gcbb.12383
25. Tuskan GA (1998) Short-rotation woody crop supply systems in the United States: what do we know and what do we need to know? Biomass Bioenergy 14:307–315
26. Coleman MD, Coyle DR, Blake J, Britton K, Buford M, Campbell RG, Cox J, Cregg B, Daniels D, Jacobson M, Johnson K, McDonald T, McLeod K, Nelson E, Robison D, Rummer R, Sanchez F, Stanturf J, Stokes B, Trettin C, Tuskan J, Wright L, Wullschleger S (2004) Production of short rotation woody crops grown with a range of nutrient and water availability: establishment report and first-year responses. USDA Forest Service, Southern Research Station, Asheville, NC, USA, General Technical Report, SRS- 72, 21 pp
27. Dillen SY, Djomo SN, Al Afas N, Vanbeveren S, Ceulemans R (2013) Biomass yield and energy balance of a short-rotation coppice with multiple clones on degraded land during 16 years. Biomass Bioenergy 56:157–165
28. King JS, Ceulemans R, Albaugh JM, Dillen SY, Domec J-C, Fichot R, Fischer M, Leggett Z, Sucre E, Trnka M, Zenone T (2013) The challenge of lignocellulosic bioenergy in a water-limited world. Bioscience 63:102–117

29. Fischer M, Kelley AM, Ward EJ, Boone JD, Ashley EM, Domec J-C, Williamson JC, King JS (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 Bioenergy 98:214–227
30. Lafleur B, Lalonde O, Labrecque M (2017) First-rotation performance of five short-rotation willow cultivars on different soil types and along a large climate gradient. Bioenerg Res 10:158–166
31. Kline KL, Coleman MD (2010) Woody energy crops in the southeastern United States: two centuries of practitioner experience. Biomass Bioenergy 34:1655–1666
32. Stout AT, Davis AA, Domec J-C, Yang C, Shi R, King JS (2014) Growth under field conditions affects lignin content and productivity in transgenic *Populus trichocarpa* with altered lignin biosynthesis. Biomass Bioenergy 68:228–239
33. Ghezehei SB, Nichols EG, Hazel DW (2016) Early clonal survival and growth of poplars grown on North Carolina Piedmont and mountain marginal lands. Bioenergy Research 2:548–558
34. Coyle D, Coleman M (2005) Forest production response to irrigation and fertilization are not explained by shifts in allocation. For Ecol Manag 208:137–152
35. Davis AA, Trettin CC (2006) Sycamore and sweetgum plantation productivity on former agricultural land in South Carolina. Biomass Bioenergy 30(8–9):769–777
36. Herrick A, Brown C (1967) A new concept in cellulose production-silage sycamore. Agricultural Science Rev 5:8–13
37. Steinbeck K, McApline R, May J (1972) Short rotation of sycamore: a status report. Journal For 70:210–213
38. Ghezehei SB, Shifflett SD, Hazel DW, Nichols EG (2015) SRWC bioenergy productivity and economic feasibility on marginal lands. J Environ Management 160:57–66
39. Dickmann D (2006) Silviculture and biology of short-rotation woody crops in temperate regions: then and now. Biomass Bioenergy 30:696–705
40. Francis J (1984) Biomass accumulation in by single- and multiple-stemmed young sycamore. For Sci 30:372–372
41. Aspinwall M, King J, McKeand S, Bullock B (2011) Genetic effects on stand-level uniformity and above- and belowground dry mass production in juveline loblolly pine. For Ecol Manag 262: 609–619
42. Schneider CA, Rasband WS, Eliceiri KW (2012) NIH image to ImageJ: 25 years of image analysis. Nat Meth 9:671–675
43. Waring RH (1983) Estimating forest growth and efficiency in relation to canopy leaf area. Adv Ecol Res 13:327–354
44. Treasure T, Gonzalez R, Jameel H, Phillips RB, Park S, Kelley S (2014) Integrated conversion, financial, and risk modeling of cellulosic ethanol from woody and non-woody biomass via dilute acid pre-treatment. Biofuels. Bioproducts Biorefining 8:755–769
45. Zalesny RS Jr, Hull RB, Zalesny JA, McMahon BG, Berguson WE, Stanosz GR (2009) Biomass and genotype × environment interactions of *populus* energy crops in the Midwestern United States. Bioenergy Research 2:106–122
46. Zamora D, Wyatt G, Apostol K, Tschirner U (2013) Biomass yield, energy values, and chemical composition of hybrid poplar in short rotation woody crops production and native perennial grasses in Minnesota, USA. Biomass Bioenergy 49:222–230
47. Fischer M, Fichot R, Albaugh JM, Ceulemans R, Domec J-C, Trnka M, King JS (2015) Ecophysiology, above-ground productivity, and stand-level water use efficiency of *Populus* and *Salix* grown in short-rotation coppice for bioenergy. Chapter 7 (157-194p). In: Bhardwaj AK, Zenone T, Chen J (eds) Sustainable biofuels: an ecological assessment of the future energy. HEP deGruyter, Berlin 366p
48. Zhao D, Kane M, Borders BE (2011) Growth responses to planting density and management intensity in loblolly pine plantations in the Southern USA Lower Coastal Plain. Annals For Sci 68:625–635
49. Samuelson LJ, Johnsen K, Stokes T (2004) Production, allocation, stemwood growth efficiency of *Pinus taeda* L. stands in response to 6 years of intensive management. For Ecol Manag 192:59e70
50. Schmer MR, Vogel KP, Mitchell RB, Perrin RK (2008) Net energy of cellulosic ethanol from switchgrass. PNAS 105(2):464–469
51. Heaton EA, Dohleman FG, Long SP (2008) Meeting US biofuel goals with less land: the potential of *Miscanthus*. Glob Chang Biol 14:2000–2014
52. Christian DG, Riche AB, Yates NE (2008) Growth, yield and mineral content of *Miscanthus* × *giganteus* grown as a biofuel for 14 successive harvests. Industrial Crops Prod 28:320–327
53. Wallington TJ, Anderson JE, Mueller SA, Kolinski Morris E, Winkler SL, Ginder JM, Nielsen OJ (2012) Corn ethanol production, food exports, and indirect land use change. Environ Sci Technol 46:6379–6384
54. Mumm RH, Goldtsmith PD, Raush KD, Stein HH (2014) Land usage attributed to corn ethanol production in the United States: sensitivity to technological advances in corn grain yield, ethanol conversion, and coproduct utilization. Biotechnology for Biofuels 7:61
55. Kopp RF, Abrahamson LP, White EH, Volk TA, Nowak CA, Fillhart RC (2001) Willow biomass production during ten successive annual harvests. Biomass Bioenergy 20:1–7
56. English B, La Torre D, Ugarte DG, 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. University of Tennessee Agricultural Economics
57. Wittwer R, King R, Clayton J, Hinton O (1978) Biomass yield of short rotation American sycamore as influenced by site, fertilizers, spacing, and rotation age. Southern J Applied For 2:15–19
58. Montgomery AK (2014) Water quality and production potential effects of cellulosic biofuel crops grown on marginal land (Ph.D. Thesis), Environmental engineering, Purdue University, USA, 126p
59. Xue S, Lewandowski I, Wang X, Yi Z (2016) Assessment of the production potentials of Miscanthus on marginal land in China. Renew Sustainable Energy Rev 54:932–943
60. Anderson EK, Voigut TB, Bollero GA, Hager AG (2010) *Miscanthus* x *giganteus* response to preemergence and postemergence herbicides. Weed Tech 24:453–460
61. Jørgensen U (2011) Benefits versus risks of growing biofuel crops: the case of miscanthus. Curr Opin Environ Sustain 3:324–330
62. Tilman D, Hill J, Lehman C (2006) Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 314:1598–1600
63. Quinn LD, Barney JN, McCubbins JSN, Endres AB (2013) Navigating the “noxious” and “invasive” regulatory landscape: suggestions for improved regulation. Bioscience 63:124–131
64. USDA Farm Service Agency. 2012. Mitigated finding of no significant impact: environmental assessment proposed BCAP giant miscanthus (*Miscanthus* x *giganteus*) establishment and production in Georgia, North Carolina, and South Carolina. USDA Farm Service Agency Biomass Crop Assistance Program
65. Bolstad P, Vose JM, McNulty SG (2001) Forest productivity leaf area, and terrain in southern Appalachian deciduous forests. For Sci 47(3):419–427
66. Coyle D, Coleman M, Durant J, Newman L (2006) Survival and growth of 31 *Populus* clones in South Carolina. Biomass Bioenergy 30(8–9):750–758
67. Kaczmarek DJ, Coyle DR, Coleman MD (2013) Survival and growth of a range of *Populus* clones in central South Carolina USA through age ten: do early assessments reflect longer-term survival and growth trends? Biomass Bioenergy 49:260–272
68. Heilman PE, Xie F (1993) Influence of nitrogen on growth and productivity of short-rotation *Populus trichocarpa* x *Populus deltoides* hybrids. Canadian J For Res 23:1863–1869
69. Zalesny RS, Cunningham MW, Hall RB, Mirck J, Rockwood DL, Stanturf JA, Volk TA (2011) Woody biomass from short rotation energy crops. In Sustainable production of fuels, chemicals, and

fibers from forest biomass; Zhu, J., Zhang, X., Pan, X., Eds.; ACS Symposium Series: Washington, DC, USA, 2011; pp. 27–63

70. Lorentz KA, Minogue PJ (2015) Exotic Eucalyptus plantations in the southeastern US: risk assessment, management and policy approaches. Biol Invasions 17:1581–1593
71. Davidson J (1985) Setting aside the idea that eucalypts are always bad. FAO-UNDP/FAO Project BED/79/017, Working paper no 10, Ecological issues raised against eucalypts are answered
72. Laclau J-P, Almeida JCR, Gonçalves JLM, Saint-André L, Ventura M, Ranger J, Moreira RM, Nouvellon Y (2009) Influence of nitrogen and potassium fertilization on leaf life span and allocation of above-ground growth in Eucalyptus plantations. Tree Physiol 21: 111–124
73. Frederick WJ Jr, Lien SJ, Courchene CE, DeMartini NA, Ragauskas AJ, Iisa K (2008) Production of ethanol from carbohydrates from loblolly pine: a technical and economic assessment. Bioresour Technol 99:5051–5057
74. Panshin AJ, de Zeeuw C (1980) Textbook of wood technology, 4th edn. McGraw-Hill, New York 722 p
75. Benetka V, Bartáková I, Mottl J (2002) Productivity of *Populus nigra* L. ssp. *nigra* under short-rotation culture in marginal areas. Biomass Bioenergy 23(5):327–336
76. Nassi o Di Nasso N, Guidi W, Ragaglini G, Tozzini C, Bonari E (2010) Biomass production and energy balance of a twelve-year-old short-rotation coppice poplar stand under different cutting cycles. Global Chan Biol Bio 2:89–97
77. Tuskan G, De La Cruz A (1982) Solar input and energy storage in a five-year-old American sycamore plantation. Forest Ecol Management 4:191–198
78. Hammerschlag R (2006) Ethanol's energy return on investment: a survey of the literature 1990–present. Environ Sci Technol 40: 1744–1750
79. Albaugh JM, Domec J-C, Maier CA, Sucre EB, Leggett ZH, King JS (2014) Gas exchange and stand-level estimates of water use and gross primary productivity in an experimental pine and switch grass intercrop forestry system on the Lower Coastal Plain of North Carolina, USA. Agricultural Forest Met 192-193:27–40
80. Renewable and Applicable Energy Laboratory (2007) Energy and resources group biofuel analysis meta-model. Univ of California, Berkeley, CA
81. DeBell DS, Clendenen GW, Harrington CA, Zasada JC (1996) Tree growth and stand development in short-rotation *Populus* plantings: 7-year results for two clones at three spacings. Biomass Bioenergy 11:253–269
82. 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. For Sci 49(2):224–234
83. McDowell NG, Adams HD, Bailey JD, Kolb TE (2007) The role of stand density on growth efficiency, leaf area index, and resin flow in southwestern ponderosa pine forests. Can J For Res 37:343–355