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Sycamore and sweetgum plantation productivity on former agricultural land in South Carolina ☆

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Abstract

Former agricultural lands in the southern US comprise a significant land base to support short rotation woody crop (SRWC) plantations. This study presents the seven-year response of productivity and biomass allocation in operational-scale, first rotation sycamore (*Plantanus occidentalis* L.) and sweetgum (*Liquidambar styraciflua* L.) plantations that were established on drained Ultisols which were historically planted in cotton and soybeans. Three plantation systems, sycamore open drainage, sycamore plus water management, and sweetgum open drainage were established on replicate 3.5–5.5 ha catchments. Height, diameter, and mortality were measured annually. Allometric equations, based on three, five, and seven year-old trees, were used to estimate aboveground biomass. Below-ground biomass was measured in year-five. Water management did not affect sycamore productivity, probably a result of a 5 year drought. The sycamore plantations were more productive after seven growing seasons than the sweetgum. Sycamore were twice the height (11.6 vs. 5.5 m); fifty percent larger in diameter (10.9 vs. 7.0 cm); and accrued more than twice the biomass (38–42 vs. 17 Mg ha^{-1}) of the sweetgum. Sweetgum plantation productivity was constrained by localized areas of high mortality (up to 88%) and vegetative competition. Mean annual height increment has not culminated for either species. Diameter growth slowed in the sycamore during growing seasons five through seven, but was still increasing in the sweetgum. Both species had similar partitioning of above-ground (60% of total) and below-ground biomass (40% of total).

Keywords: *Platanus occidentalis*; *Liquidambar styraciflua*; Short rotation woody crop; Productivity; Hardwood plantation

1. Introduction

The southern United States is the largest producer of timber products worldwide and production in this region is expected to increase in the future [1]. Timberland in this region is also projected to decrease with losses due to urbanization offset by conversion of agricultural land to plantations [1]. Softwood production dominates the timber market in the southern US, however demand for hardwoods is expected to increase over time [2] and exceed supply within the next 30 years [1]. In addition, it is anticipated that the region could supply approximately one-fourth of the nation's bioenergy crops in the future, with sweetgum and sycamore plantations accounting for roughly a third of the region's supply [3]. A shift from extensive management of natural forests to intensively managed plantations could help reduce the land area required to meet future forest products and bioenergy needs, thereby easing the burden placed on natural forests [2,4].

Currently there are approximately 800 km^2 of hardwood plantations in the southern US; 30% of which are owned by the forest industry [5]. An additional 4000 ha have been planted in intensively managed short rotation woody crop (SRWC) plantations [5]. Previous research has made significant progress in determining species-specific best management practices for site preparation and establishment, optimal spacing, herbicide and fertilizer regimes [6,7], but a better understanding is needed on the growth response to soil quality and water availability [7,8] and the

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need to control weeds and augment soil nutrients, which can often work against each other [9–11]. Integrating these factors through site-specific management prescriptions is necessary to sustain the productivity potential of the land [12,4].

In order for SRWC plantations to be successful over the long term, they need to be sustainable, providing high yields over multiple rotations. In the southern US, idle or poor-producing agricultural land presents a significant land base to support sustainable SRWC plantations while providing an opportunity to improve soil tilth, water quality and wildlife habitat [3,13–15].

1.1. Objective

In 1996, we initiated a study to assess the sustainability of SRWC hardwood plantation management in the upper coastal plain of South Carolina. The study was an operational scale assessment of short-rotation sycamore (*P. occidentalis* L.) and sweetgum (*L. styraciflua* L.) plantation productivity on prior agricultural land. The prescriptions were based on established industry practices regarding growing stock, cultivation, and management. In this paper we present above-ground productivity, and above- and below-ground biomass allocation in the 7-year old plantations.

2. Methods

2.1. Site description

The site is located approximately 1 km southwest of Mayesville (33° 59′ N, 80° 12′ W), in Sumter County, South Carolina on land owned by International Paper. Until its conversion to SRWC in 1996, the tract (approximately 1100 ha) was owned by a single family for generations and planted with cotton, soybeans and wheat, with a small portion of the acreage in pasture and pine/hardwood forest. Much of the agricultural land had been drained. The tract (approx. 35 ha) encompassing the study area was on land that had been cultivated for many decades.

The soils within the study area are Ultisols with predominantly loamy sand or sandy loam epipedons overlaying a clayey subsoil. Based on a detailed survey in 1999, the soils on the study site are comprised mainly of Aquic Paleudults (36%), Typic Paleaquults (31%), and Typic Kandiudults (30%). The soil temperature regime is thermic. A plow-pan at 28 cm was common throughout the site. As is common in plantations with an agricultural history [16,8], weedy species were prevalent in the first few growing seasons. The most common species included: *Eupatorium capillifolium* (dog fennel), *Ipomoea coccinea* (scarlet morning-glory), *Xanthium pennsylvanicum* (cocklebur), *Amaranthus retroflexus* (redroot amaranth), and *Cassia obtusifolia* (sicklepod).

2.2. Climate

The climate of Sumter County is mild and temperate. Mean annual temperature is 17 °C (63 °F) and mean annual precipitation is 122 cm (48 in.) with 70% of the precipitation occurring during the March–October growing (frost-free) season (Fig. 1) [17]. Throughout the study period, total annual precipitation ranged from a minimum 93 cm to a maximum of 152 cm. The area received unusually high amounts of precipitation in 1997 and the spring of 1998. Following that wet period, an extended drought began in June 1998 and continued through August of 2002 (Fig. 1) reducing the water supply in shallow and deep aquifers across the state [18]. Severe to extreme drought conditions were reported for the winter of 2001 and for most of the 2002 growing season. The Sumter area suffered an average precipitation deficit of 17 cm yr^{-1} during the drought period of 1998–2002. Drought conditions reversed in late 2002, due to above average rainfall which continued throughout 2003. Normal to above average rainfall was recorded only for the 1997 and 2003 growing seasons

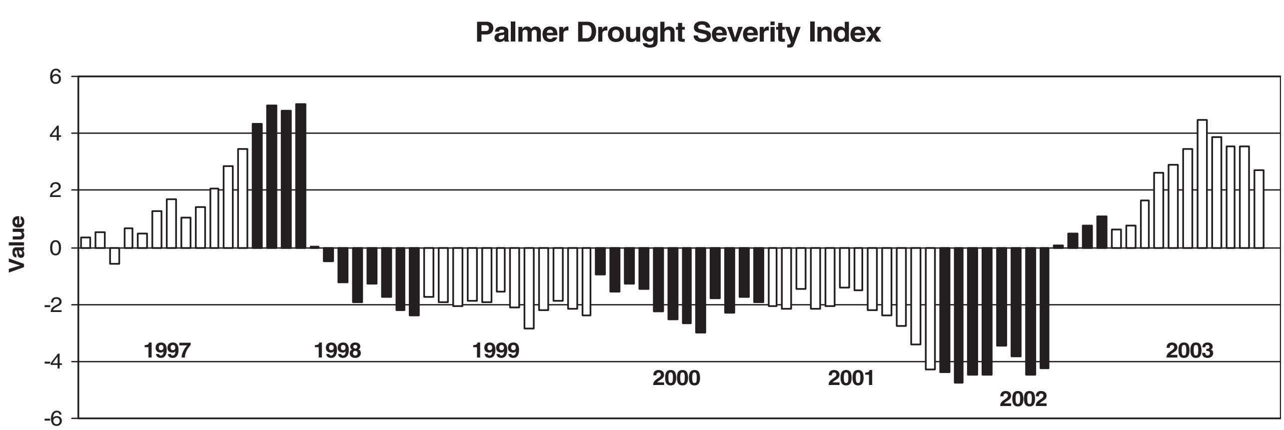

Fig. 1. Palmer drought severity index for South Carolina, division 6. Each bar represents the indices for a particular month. Light and dark-colored bars indicate changes in year. Positive values indicate moist spells, negative values indicate drought. Absolute values of 0–1 indicate near normal conditions, 1–3 mild or moderate spells, 3–4 extreme, and 4+ severe conditions.

(Fig. 1). There was a total precipitation deficit of 60 cm during the first seven growing seasons [19,20].

2.3. Experimental approach

The study was designed at a catchment scale because some processes are manifest differently at the small-plot level (e.g., 0.1–0.5 ha) as compared to the stand level (e.g. 5–10 ha). The catchment provides the scale that is needed to assess the cumulative effects of management prescriptions on productivity, soil tilth and environmental attributes such as water quality. Six hydrologically distinct catchments, 3.5–5.5 ha, were used as the experimental units for this study (Fig. 2). Each catchment had a pre-existing, centrally located ditch that was used for the hydrologic monitoring. The catchments were randomly assigned to one of three treatments, providing two replicates per treatment.

2.4. Treatments

This study comprised three treatments, which are defined on the basis of the species and drainage system. The three treatments were:

- Sweetgum, open drainage (SWO).
- Sycamore, open drainage (SYO).
- Sycamore, controlled drainage (SYC).

The treatments SWO and SYO represent operational plantation management practices, with free-to-flow drainage from the plantation, defined by the pre-existing agricultural drainage ditch. In the SYC treatment, a drainage control structure was installed during the third growing season, July 1999, which effectively eliminated drainage via the ditches. SWO and SYO treatments were installed to examine species response to site conditions and operational prescriptions. The SYC was implemented to test the likelihood of improving productivity and water quality through changes in water management (SYO vs. SYC).

The plantations were established in February, 1997. Soils were ripped prior to planting to disrupt the plow-pan. Sycamore was hand planted on a 2.4 m × 3.0 m spacing using 1-year-old, nursery bed-grown, bare root seedlings. Sweetgum was hand planted on a 1.8 m × 3.0 m spacing using 1-year-old bare root stock.

The sycamore and sweetgum plantations were managed according to standard operational prescriptions for herbicide and fertilizer application. A pre-emergent herbicide (Oust) was applied aerially at a rate of 0.07 kg ha^{-1} to the catchments in early spring of the first three years. A ground application of foliar herbicide (Accord) at 0.07 kg ha^{-1} was also applied in May and July of the first two growing seasons. The sweetgum catchments experience heavy competition from weedy species, particularly vines, through the fourth growing season, so an additional

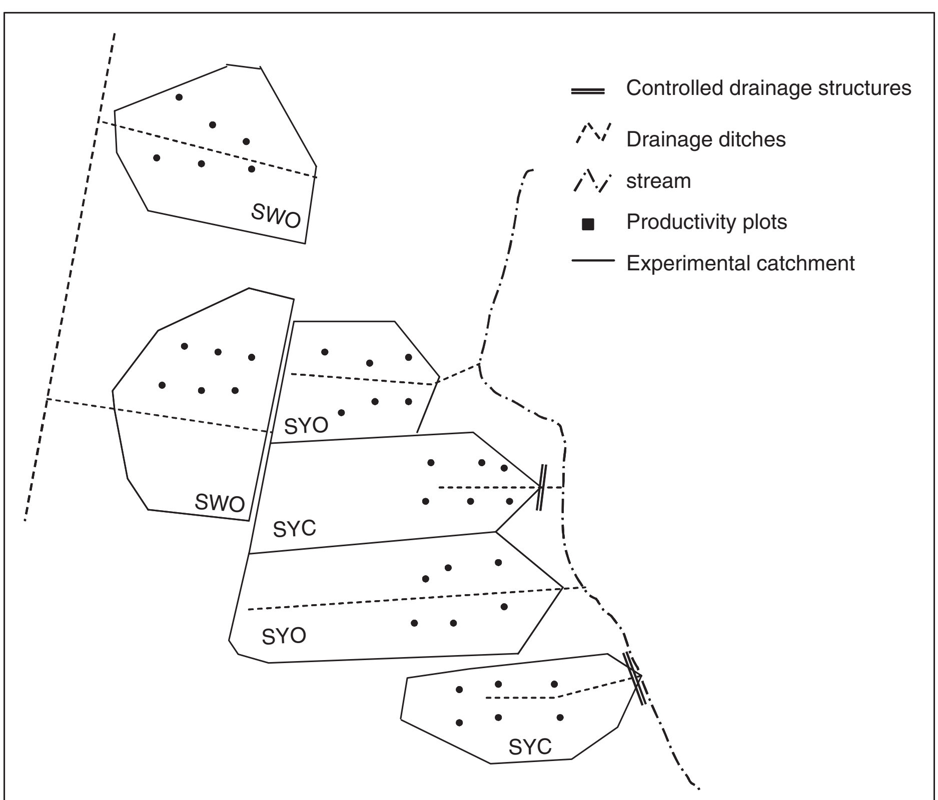

Fig. 2. Physical relationship of catchments. Each catchment has a central drainage ditch and six permanent 12 × 12 m plots for monitoring productivity.

application of Oust (0.07 kg ha^{-1}) was applied prior to the beginning of the fifth growing season in March 2001. At planting, the plantations received 224 kg ha^{-1} di-ammonium phosphate (DAP) fertilizer. Subsequently, the plantations were fertilized with urea (224 kg ha^{-1}) each spring through the third year, then every second year. The fertilizers were applied aerially in granular form during the month of February.

2.5. Sample design

Six, 12 × 12 m permanent sampling plots were installed in each catchment to measure productivity (Fig. 2). Each plot encompassed 20–25 trees, which were tagged to allow for consistent re-measurement. Heights of seedlings were measured in February 1997 at the time of planting. Heights and diameters of trees were measured each subsequent year during the dormant season. Diameter measurements were taken at 15 cm above the soil surface until the trees reached an appropriate size for measuring diameter at breast height (1.4 m). Data are reported for the first seven growing seasons.

In addition to the productivity monitoring within plots, representative trees outside the plots were identified and destructively sampled for biomass determination in 2000, 2002, and 2004 (third, fifth, and seventh growing seasons). Trees were selected to span the range of height and diameter measurements that existed within the plantations at the time of each sampling period. In 2000 and 2004, six–eight trees from each species were sampled to determine above-ground biomass. In 2002, both above- and below-ground biomass were measured for five sweetgum and eight sycamore trees.

Sampling methods were adapted from Whittaker et al. [21]. Individual trees were separated into five components: bole, branch, root ball, coarse roots and fine roots. The fresh weights of all fractions were measured in the field. To determine dry mass, a single, 5 cm long subsample was collected from the bole sections and rootball; five, 10 cm long subsamples were collected from the branches and coarse roots. A tree spade was used to remove the belowground portion, creating a hole approximately 85 cm in depth with a diameter of 1 m at the soil surface. The area around the hole was excavated further to collect any coarse roots within 1 m of the base of the tree. Fine root biomass, collected by hand-sieving the soil removed by the spade, was determined for all of the sweetgum trees and two of the sycamore.

Litterfall collection began in 1997. To accommodate the small stature of the seedlings in the first growing season, three trees per catchment were netted to collect the entire litter fall. The litter was collected in December. Subsequently, 21 baskets (1.25 m^2) were randomly located within each permanent growth plot, providing a total of 12 baskets/catchment. Litterfall samples were collected monthly, year-round through the fifth growing season.

2.6. Statistical analysis

Treatment means and standard errors are reported for the height, diameter, mortality and aboveground biomass data. Allometric regression equations were developed to predict aboveground biomass for each species using diameter as the independent variable. One-way repeated measures ANOVAs were performed on the catchment means to test for water management (SYO vs. SYC), and tree species (SYO vs. SWO) effects on plantation productivity; specifically tree height, diameter, mortality and aboveground biomass. Analysis of variance tests were performed in SYSTAT version 10, significance was determined at an alpha $\leqslant$0.05 level. Results are reported for the interaction between time and treatment.

3. Results & discussion

Based on the site evaluation guidelines developed by Baker and Broadfoot [22], the cumulative effects of long-term agriculture, specifically upland soils high in bulk density and low in organic matter with evidence of a plow-pan, result in a low site index for sweetgum and sycamore. From those guidelines, this tract would be considered marginal, suggesting that the measured yields from these plantations represent the low-end of biomass that could be expected from southern agricultural lands which are converted to hardwood SRWC plantations.

3.1. Height, diameter, and mortality

There were no significant differences in height, diameter, or mortality between the two sycamore water management treatments (SYO, SYC) over the first seven growing seasons. The SYO treatment reflects current management practices where drainage ditches were maintained and kept open. The SYC treatment had controlled drainage structures installed in July 1999 (third growing season), effectively eliminating drainage via the ditches. Treatment means varied by less than one percent, or 0.1 m in height and 0.1 cm in diameter. The average seven-year-old sycamore tree was 11.6 m tall with a diameter of 10.8 cm (Table 1). Both sycamore treatments outperformed sweetgum from the beginning of the rotation (Table 1). Species did not differ ($P = 0.99$) in mortality. However, sycamore grew more in height ($P \leqslant 0.001$) and diameter ($P \leqslant 0.03$) than sweetgum.

Though not statistically significant, mortality did vary between the two treatments with the SYC treatment having 13% and the SYO treatment 22% mortality (Fig. 3). Most of the mortality occurred prior to implementing the controlled drainage in the SYC treatment, thus the lower mortality could not be attributed to water management. Most of the mortality in both species occurred during the first two growing seasons; at the end of the seventh season sweetgum had somewhat higher mortality (30% ± 12) than the SYO treatment with similar drainage practices (22% ±

Table 1
Annual productivity metrics, standard errors are reported in parentheses

		Planting	Growing season						
			1st	2nd	3rd	4th	5th	6th	7th
Height (m)	SYO	1.0 (0.0)	1.8 (0.0)	3.8 (0.1)	5.4 (0.0)	6.7 (0.1)	7.9 (0.0)	9.3 (0.2)	11.6 (0.0)
	SYC	1.0 (0.1)	1.7 (0.0)	3.8 (0.1)	5.5 (0.3)	6.8 (0.3)	8.0 (0.2)	9.5 (0.1)	11.7 (0.2)
	SWO	0.8 (0.0)	0.8 (0.0)	1.1 (0.1)	1.7 (0.1)	2.3 (0.1)	2.9 (0.1)	4.1 (0.2)	5.5 (0.3)
Diameter (cm)[a]	SYO	—	—	3.4 (0.1)	5.9 (0.1)	7.4 (0.1)	8.8 (0.1)	10.0 (0.2)	10.9 (0.2)
	SYC	—	—	3.4 (0.1)	5.9 (0.2)	7.3 (0.3)	8.7 (0.4)	9.9 (0.3)	10.8 (0.3)
	SWO	—	—	2.1 (0.1)	3.3 (0.3)	4.3 (0.2)	3.6 (0.1)	5.0 (0.5)	7.0 (0.5)
Cum. mort (%)	SYO	—	16 (1)	21 (6)	21 (6)	21 (6)	21 (6)	21 (6)	22 (5)
	SYC	—	8 (2)	10 (3)	10 (3)	10 (3)	10 (3)	12 (2)	13 (3)
	SWO	—	21 (3)	27 (13)	28 (12)	29 (12)	29 (12)	29 (11)	30 (12)
Aboveground biomass (Mg/ha)	SYO	—	—	4.48 (0.46)	12.07 (0.89)	18.48 (0.85)	25.61 (0.97)	32.61 (0.62)	38.44 (0.35)
	SYC	—	—	5.09 (0.16)	13.79 (0.28)	20.71 (0.54)	28.73 (0.90)	36.27 (0.74)	41.60 (0.49)
	SWO	—	—	0.50 (0.13)	1.46 (0.35)	3.04 (0.56)	6.24 (1.36)	10.86 (2.41)	17.52 (3.37)
Litterfall (Mg/ha)	SYO	—	0.28	1.19	5.28	3.86	6.11	—	—
	SYC	—	0.4	0.85	4.74	3.39	7.77	—	—
	SWO	—	0.06	0.03	0.57	0.33	1.85	—	—

[a]Diameter refers to diameter at breast height (1.4 m) with one exception. Basal diameters (15 cm) are reported for sweetgum until season five.

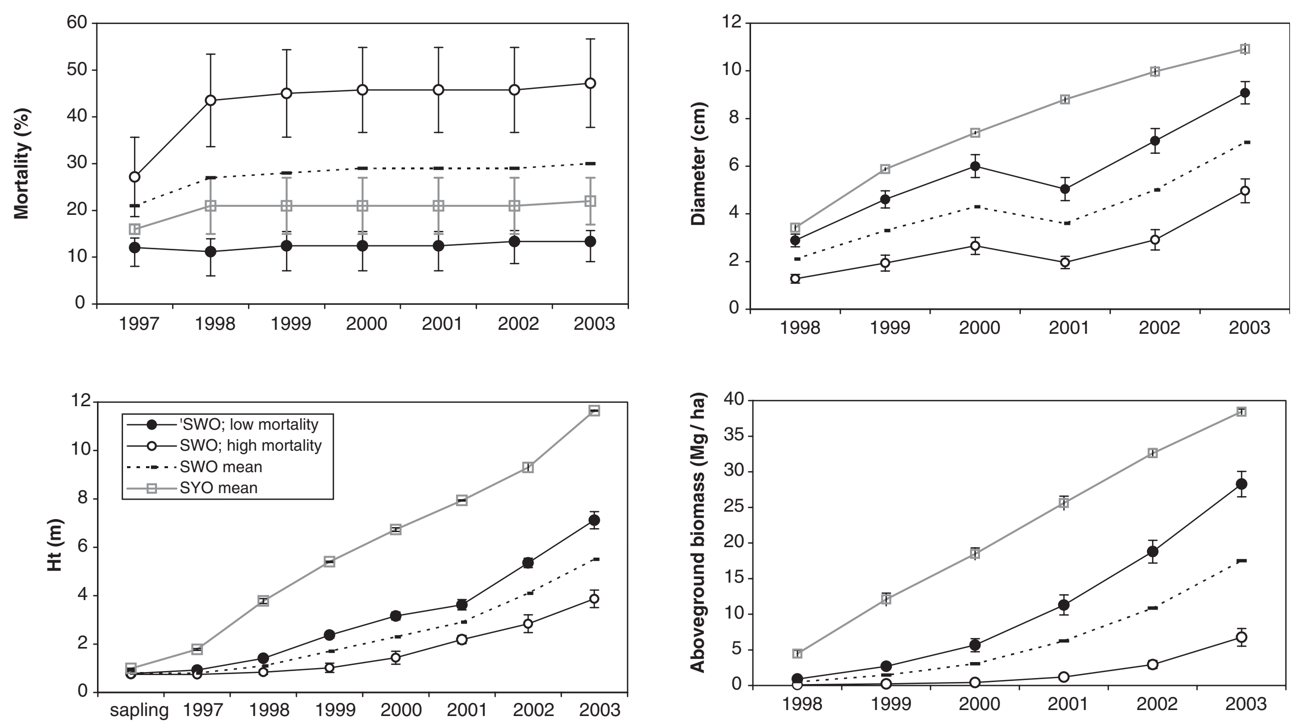

Fig. 3. (a–d) (t–b, l–r). Mortality, height, diameter, and aboveground biomass of SYO treatment compared to the two groups of sweetgum: low mortality, high mortality. The mean for SWO treatments are also given for reference.

5) (Fig. 3). Much of the sweetgum mortality was localized in areas near the drainage ditch. These areas experienced intense, prolonged competition from weedy species, particularly vines.

Weedy species were virtually eliminated in the sycamore plantations by the fourth year through a combination of chemical weed control and canopy closure. However, in areas of high mortality within the sweetgum catchments, *I. coccinea* (scarlet morning-glory) vines continued to completely cover the sweetgum trees through the sixth growing season. By the end of the fourth growing season, the sweetgum, at 2.3 m, were only one-third the height of the sycamore (Table 1). A previous study of sweetgum and sycamore plantations on former pine forest in Georgia produced similar results. Four-year-old sweetgum were slightly less than half the height of the sycamore, 2.1 vs. 4.6 m, respectively [23].

At the end of the seventh growing season, the sweetgum were half the height and roughly two thirds of the diameter of the sycamore (Table 1). Annual height increment has not culminated for either of these species, rather it has increased for both during the sixth and seventh growing seasons (Table 1). Sweetgum, in particular, has shown a marked increase in height and diameter growth over the last three growing seasons, with its annual height increment doubling in the sixth year. These increases may be partially attributed to above-normal precipitation which occurred in 2003 (Fig. 1) and decreased competition from weedy species in the sweetgum plantations.

Intense competition from weedy species is not uncommon [23–25]. Sweetgum, with its slower initial growth, tends to suffer greater effects of weed competition [26,27]. Weedy species, especially vines, compete for resources both above and belowground [28,29]. Several studies have examined the effectiveness of different forms of weed control, mechanical and chemical, but results have been inconsistent, and further research is needed to determine site or species-specific remedies [26,30–32].

Applying nitrogen at the start of the rotation can serve to stimulate weed growth exacerbating the negative effect weedy species have on productivity [10,23]. Nelson [27] found that early sweetgum productivity improved more from weed control (hoeing) than weed control plus fertilization; after six years the hoed treatments were 47% taller and had greater survival rates than the unhoed treatment, 88% vs. 67% survival, respectively. The hoed plus fertilized treatment had trees of similar size but slightly higher mortality than the hoed only treatment. Nelson and others [33] suggested that fertilizers should be applied later in the rotation, once the trees have occupied the site and can more efficiently utilize the added nutrients.

Soil moisture conditions may also play a role in a particular species response to weed control and fertilization. Sweetgum growing on a former pastureland in Tennessee had twice the survival on wetter locations (56% vs. 28%), despite facing heavier competition from weeds in those areas [24]. The sweetgum also showed improved growth with weed control, up to 15%, at the end of the fourth growing season. Given the high cost of fertilizer prescriptions, further studies examining the interactions between weed control and nutrition management under a variety of site conditions are required.

3.2. Allometric relationships

Both height and diameter were found to be good predictors of total (leafless) aboveground biomass in the sycamore and the sweetgum with r^2 values ranging from 0.88 to 0.97. However, the winter 2004 (after 7th growing season) sampling showed that the height/biomass relationship in sycamore had diverged from allometric equations based on the two prior sampling periods and we found that height was no longer as good a predictor of biomass over time ($r^2 = 0.81$) as diameter ($r^2 = 0.97$). Field observations indicated that sycamore trees within the interior of the plantations lost a significant portion of their lower branches between the fifth and seventh growing season (2002–2004) and very few branches remained below 4 m. Height and bole biomass data for the three sampling periods were regressed and the r^2 value improved to 0.88; indicating that branch loss only partially explained the changes in allometry. The relationship between height and diameter also changed between 2000 and 2004 (a ratio of 0.91 vs. 1.06) with sycamore trees of similar diameter having greater height in later years. The loss of lower branches and the changing allometric relationships are indications that the sycamore have fully occupied the site and stand density may begin to affect sycamore diameter growth [34,35].

Diameter had a consistent relationship with biomass over time in both species and was selected as the independent variable to use in the allometric equations. Two equations were used for the sweetgum catchments, the basal diameter (db; 15 cm above soil surface) was used for the first four years until the trees reached a size at which diameter could be measured at breast height (1.4 m) then dbh measurements were used in later years. A single equation, based on dbh, was used for the sycamore. Sycamore trees ranged from 1.3 to 13.5 m in height with diameters ranging from 2 to 13 cm. The young sweetgum trees used for Eq. (1) had basal diameters ranging from 3.1 to 7.8 cm. The older sweetgum trees used for Eq. (2) had dbh measurements of 1.8–13.5 cm.

In the following equations, y represents above ground biomass (kg tree^{-1}):

$$y = 0.436(\text{db})^{2.4}, \quad r^2 = 0.88, \quad n = 11 \text{ (sweetgum)}, \qquad (1)$$

$$y = 0.5256(\text{dbh})^{1.6}, \quad r^2 = 0.97, \quad n = 13 \text{ (sweetgum)}, \qquad (2)$$

$$y = 0.3371(\text{dbh})^{1.9}, \quad r^2 = 0.97, \quad n = 22 \text{ (sycamore)}. \qquad (3)$$

3.3. Aboveground biomass

The aboveground biomass was different among the two sycamore treatments ($P \leqslant 0.001$), with the SYC having a slightly greater biomass after seven growing seasons, 42 vs. 38 Mg ha^{-1} (Table 1). The difference among the sycamore treatments is principally attributed to difference in stocking as a result of mortality. In contrast, the SWO had accrued less than half aboveground biomass of the open-drainage sycamore treatment by year seven (Table 1).

At four-years-old, the sweetgum and sycamore had accrued less biomass (3 Mg ha^{-1} and 18–21 Mg ha^{-1}, respectively) than similarly aged plantations growing on an old field site in Alabama, which were planted at 1.8 × 3.1 m spacing, and had aboveground biomass estimates of 17.6 Mg ha^{-1} and 24.8 Mg ha^{-1}, respectively [36]. Torreano and Frederick [36] found their old field sites were nearly three times more productive than nearby cleared and fertilized forest sites. Studies such as theirs, specifically designed to examine the effects of prior land use on productivity, are rare. Our sweetgum yields were half those reported for the formerly forested sites in Alabama. The fourth season yields in the sycamore were 20–30% lower than those from the old field site in Alabama but similar to yields (18 Mg ha^{-1}) from a former pine/hardwood forest site in Georgia [37]. Land use history, as it affects initial site conditions, is clearly important. However the confounding effects of different management practices, and environmental factors, complicate attempts to make direct comparisons in the literature; more paired studies are needed to determine if prior land use could be used as an indicator of plantation productivity.

3.4. Variability within sweetgum plantations

There were localized areas of high mortality (up to 88%) within the sweetgum catchments that reduced overall plantation productivity. The differences in mortality and aboveground biomass in these areas were significant enough to cause us to differentiate these areas from the more successful areas of the sweetgum catchments for further comparison. The 12 measurement plots from the two catchments were split into two groups ($n = 6$); those located in areas of high mortality, HM, versus low mortality, LM.

The HM plots had nearly four times the mortality of the LM plots. The LM sweetgum plots had mortality rates (14%) similar that of the two sycamore treatments (Fig. 3a). Height and diameter growth in the HM sweetgum plots were roughly half of what was observed in the LM sweetgum plots (Figs. 3b, c). Total aboveground biomass after seven years was only a quarter of the biomass yield in the more successful LM sweetgum (28 Mg ha^{-1}).

Productivity (height, diameter, biomass) in the LM sweetgum plots was still not equivalent to sycamore productivity (Figs. 3b–d). The average sweetgum tree from these plots, after seven growing seasons, had a height of 7.1 m and a diameter of 9.0 cm. The LM sweetgum produced 30% less aboveground biomass than the sycamore plantations during the first seven growing seasons.

Steinbeck [6] found that while sycamore had greater initial growth, after the first several years, sycamore growth slowed while sweetgum growth rates increased such that at the end of 10–15 year rotations sweetgum plantations had higher yields (4.7 vs. 3.5 Mg ha^{-1} yr^{-1}) under lower intensity management (fertilization at planting). Looking at growth over time, the LM sweetgum could achieve yields similar to that of the sycamore by the end of a 16-year rotation. Diameter growth in sycamore slowed while in sweetgum it increased rapidly from year 5 to 7 (Fig. 3c). In addition, aboveground biomass in the LM sweetgum increased at a faster rate than in the sycamore plantations (6.6 vs. 5.8 Mg ha^{-1} in year seven) (Fig. 3d).

3.5. Biomass allocation patterns

Total biomass (above and belowground) was measured once, after the fifth growing season, to determine allocation patterns for sycamore and sweetgum. Sycamore trees ranged from 5 to 8 m in height; sweetgum ranged from 2 to 4 m. Similar allocation patterns were found to occur in both species with 60–65% of total biomass allocated in aboveground components (Table 2). Sycamore allocated slightly more aboveground while sweetgum had a higher percentage of root biomass, particularly fine roots. These patterns are similar to those reported for other short-rotation hardwood species. Grigal and Berguson [38] reported that belowground biomass in these systems commonly account for 25–50% of total tree biomass depending upon the tree species and age. Kuers et al. [39] findings were also within that range, reporting that the root ball was roughly 30% of total harvested biomass in 12 yr old. sweetgum and sycamore. They also found no significant difference in allocation between the two species, and suggested that site factors and management practices may affect allocation patterns more than species differences.

3.6. Annual productivity rates

In more traditional plantation forestry, high yield generally infers productivity rates of 5 Mg ha^{-1} yr^{-1} [40]. However these yields are considered low for SRWC; the range reported for *Populus* and *Salix* spp. is 9–22 Mg ha^{-1} yr^{-1} [7,41–43]. Graham [44] defined 'suitable' productivity for bioenergy crops to be a minimum of

Table 2
Above- and below-ground biomass allocation, and the proportion of individual components to total tree biomass after five growing seasons

	Sycamore (%)	Sweetgum (%)
Above-ground (total)	65	60
Bole	38	36
Branch	27	25
Below-ground (total)	35	40
Fine roots	1	4
Coarse roots	23	22
Rootball	11	14

Note: Data are based on whole-tree sample; sycamore $n = 8$, sweetgum $n = 5$. The allometric equations for total belowground biomass are: sycamore (kg tree^{-1}) $= 0.29 * \text{dbh(cm)} ** 1.6396$ [$r^2 = 0.80$], sweetgum (kg tree^{-1}) $= 0.022 * \text{diameter(cm)}$ at $15\,\text{cm} ** 2.6987$ [$r^2 = 0.99$]. The allometric equations for total above-ground biomass are: sycamore (kg tree^{-1}) $= 0.3355 * \text{dbh(cm)} ** 1.9275$ [$r^2 = 0.96$], sweetgum (kg tree^{-1}) $= 0.0436 * \text{diameter(cm)}$ at $15\,\text{cm} ** 2.3851$ [$r^2 = 0.98$].

$11.2\,Mg\,ha^{-1}\,yr^{-1}$ over the course of the rotation at current technology.

The sycamore and the LM sweetgum in this study produced an average of $4–6\,Mg\,ha^{-1}\,yr^{-1}$ over the first seven growing seasons. The four-year drought likely had an impact on productivity in these plantations. However, other studies in the southeast have found similar productivity rates for these two species early in the rotation; $4.4–6.2\,Mg\,ha^{-1}\,yr^{-1}$ for 4-year-old sycamore and sweetgum in Alabama [36] and $4.5\,Mg\,ha^{-1}\,yr^{-1}$ for 4-year-old sycamore in Georgia [37]. Few studies report productivity throughout the entire rotation for these species. We would expect that mean annual biomass increment would be somewhat higher when averaged across the entire rotation length, rather than just the first 4–7 growing seasons.

Steinbeck [6] found that when conditions were improved through more intensive management, such as irrigation and additional fertilizer applications, sycamore produced an average of $12.5\,Mg\,ha^{-1}\,yr^{-1}$ of woody biomass and sweetgum produced $9.9\,Mg\,ha^{-1}\,yr^{-1}$ during the first five growing seasons. This suggests there is potential for these two species to produce higher yields with more intensive management. Longer term research, as well as economic analysis, is needed to determine if these two species can be economically viable bioenergy crops in the southeastern United States.

4. Conclusions

Sycamore out-performed sweetgum on these former agricultural soils accumulating greater above-ground biomass during the first seven growing seasons (38 vs. $17\,Mg\,ha^{-1}$, respectively). Mean annual biomass increment has not tapered off for either species. Currently, sweetgum is accruing biomass more rapidly than sycamore (6.6 vs. $5.8\,Mg\,ha^{-1}$ in year seven) and the sweetgum plantations may have overall yields similar to that of the sycamore plantations. Growth and yield models are needed to facilitate the comparison of SRWC productivity rates among different stages of plantation development and management presecriptions. While the average productivity of the sycamore and sweetgum stands in this in this study ($4–6\,Mg\,ha^{-1}\,yr^{-1}$ through the seventh growing season) is below the range reported for *Populus* and *Salix* spp. plantations ($9–22\,Mg\,ha^{-1}\,yr^{-1}$), its quite likely that the final yield of the plantations in this study will be within that range.

Weedy species greatly reduced the productivity of sweetgum in certain areas of the plantation, demonstrating the importance of weed control during the early growing seasons (e.g., years 1–4). Sweetgum, and other species exhibiting slow early growth, may require different management practices including foregoing fertilizer for the first couple of growing seasons and more frequent, or prolonged herbicide applications. The sweetgum findings also illustrate the need for consistency and precision in applying treatments similar to "precision agriculture". Agricultural lands provide a valuable resource for the development of operational SRWC plantations. However, additional work on developing fertilization and weed control prescriptions is warranted in order to provide a better basis for managing productivity, ensuring environmental quality, and minimizing costs.

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References

[1] Prestemon JP, Abt RC. Timber products supply and demand. In: Wear DN, Greis JG, editors. Southern forest resource assessment. Asheville: Southern Research Station; 2002. p. 299–326.

[2] Alig RJ, Adams DM, McCarl BA, Ince PJ. Economic potential of short-rotation woody crops on agricultural land for pulp fiber production in the United States. Forest Products Journal 2000;50:67–74.

[3] Ranney JW, Mann LK. Environmental considerations in energy crop production. Biomass and Bioenergy 1994;6:211–28.

[4] Fox TR. Sustained productivity in intensively managed forest plantations. Forest Ecology and Management 2000;138:187–202.

[5] Siry JP. Intensive timber management practices. In: Wear DN, Greis JG, editors. Southern forest resource assessment. Asheville: Southern Research Station; 2002. p. 299–326.

[6] Steinbeck K. Thirty years of short-rotation hardwoods research. In: Haywood JD, editor. Proceedings of the tenth biennial southern silvicultural research conference. 16–18 February; Asheville, NC; 1999. p. 63–5.

[7] Tuskan GA. Short-rotation woody crop supply systems in the United States: what do we know and what do we need to know? Biomass and Bioenergy 1998;14:307–15.

[8] Scott DA, Burger JA, Kaczmarek DJ, Kane MB. Nitrogen supply and demand in short-rotation sweetgum plantations. Forest Ecology and Management 2004;189:331–43.

[9] Buhler DD, Netzer DA, Riemenschneider DE, Hartzler RG. Weed management in short rotation poplar and herbaceous perennial crops grown for biofuel production. Biomass and Bioenergy 1998;14:385–94.

[10] Woods PV, Nambiar EKS, Smethurst PJ. Effect of annual weeds on water and nitrogen availability to Pinus radiate trees in a young plantation. Forest Ecology and Management 1992;48:145–63.

[11] Williams TM. Nitrate leaching from intensive fiber production on abandoned agricultural land. Forest Ecology and Management 1999;122:41–9.

[12] Jug A, Makeschin F, Rehfuess KE, Hofmann-Schielle C. Short-rotation plantations of balsam poplars, aspen and willows on former arable land in the Federal Republic of Germany. III. Soil ecological effects. Forest Ecology and Management 1999;121:85–99.

[13] Garten Jr CT. Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA. Biomass and Bioenergy 2002;23:93–102.

[14] Tolbert Vr, Todd DE, Mann LK, Jawdy CM, Mays DA, Malik R, et al. Changes in soil quality and below-ground carbon storage with conversion of traditional agricultural crop lands to bioenergy crop production. Environmental Pollution 2002; 116:S97–106.

[15] Thornton FC, Joslin JD, Bock BR, Houston A, Green TH, Schoenholtz S, et al. Environmental effects of growing woody crops on agricultural land: first year effects on erosion, and water quality. Biomass and Bioenergy 1998;15:57–69.

[16] Steinbeck K. Increasing the biomass production of short rotation coppice forests. In: Proceedings of the third annual biomass energy systems conference, 5–7 June, Golden CO, 1979. p. 47–51.

[17] United States Department of Agriculture, Soil Conservation Service. 1974. Soil survey of Florence and Sumter counties, South Carolina.

[18] Kiuchi M. Multiyear-drought impact on hydrologic conditions in South Carolina, water years 1998-2001. South Carolina Department of Natural Resources. Land, Water, and Conservation Division 2002, p. 1–3.

[19] National Oceanic and Atmospheric Administration. 2004. Annual climatological summaries for the 1997–2004 period from weather station 388440 in Sumter, South Carolina, USA. http://www.ncdc.noaa.gov/oa/climate/climateinventories.html.

[20] National Oceanic and Atmospheric Administration. 2004. Cimate Division: precipitation temperature and drought information for the 1997–2004 period for South Carolina Division 6. http://lwf.ncdc.noaa.gov/oa/climate/onlineprod/drought/xmgr.html.

[21] Whittaker RH, Bormann FH, Likens GE, Siccama TG. The Hubbard Brook ecosystem study: forest biomass and production. Ecological Monographs 1974;44:233–52.

[22] Baker JB, Broadfoot WM. A practical field method of site evaluation for commercially important southern hardwoods. General Technical Report SO-26; Southern Research Station, 1979, p. 1–51.

[23] Steinbeck K, Skinner TM. Growing short-rotation forests in the southeastern USA. Bioenergy 1984;2:63–9.

[24] Hopper GM, Buckner ER, Mullins JA. Effects of weed control and fertilization on plantation establishment and growth of green ash, sweet gum, and loblolly pine: four year results. In: Proceedings of the seventh biennial southern silvicultural research conference, 17–19 November; Mobile, AL, 1992. p. 357–60.

[25] Ezell AW, Hodges JD. Herbaceous weed control improves survival of planted shumard oak seedlings. In: Outcalt KW, editor. Proceedings of the 11th biennial silvicultural research conference. General technical report SRS-48. Asheville: USDA Forest Service Southern Research Station, 2002. p. 273–5.

[26] Krinard RM, Kennedy Jr HE. Growth and yields of 5-year-old planted hardwoods on sharkley clay soil. Southern Forest Experiment Station Research Note 1981; SO-271;1–3.

[27] Nelson EA. Weed control and fertilization aid sweetgum plantation establishment. In: Dawson JO, Majerus KA, editors. Proceedings of the 5th central hardwood forest conference, 15–18 April, Champange, IL, 1985. p. 68–70.

[28] Dillenburg LR, Whigham DF, Teramura AH, Forseth IN. Effects of vine competition on availability of light, water, and nitrogen to a tree host (*Liquidambar styraciflua*). American Journal of Botany 1993;80:244–52.

[29] Dillenburg LR, Teramura AH, Forseth IN, Whigham DF. Photosynthetic and biomass allocation of *Liquidambar styraciflua* (*Hamamelidaceae*) to vine competition. American Journal of Botany 1995;82:454–61.

[30] Zutter BR, Nelson LR, Minogue PJ, Gjerstad DH. Hardwood plantation growth following weed control using herbicides and cultivation. Southern Journal of Applied Forestry 1987;11:134–8.

[31] Malik RK, Green TH, Brown GF, Beyl CA, Sistani KR, Mays DA. Biomass production of short-rotation bioenergy hardwood plantations affected by cover crops. Biomass and Bioenergy 2001;21:21–33.

[32] Groniger JW, Babassana DA. Accelerating planted green ash establishment on an abandoned soybean field. In: Outcalt KW, editor. Proceedings of the 11th biennial silvicultural research conference. General technical report SRS-48. Asheville: USDA Forest Service Southern Research Station; 2002. p. 270–2.

[33] Nelson LE, Shelton MG, Switzer GL. Aboveground net primary productivity and nutrient content of fertilized plantation sweetgum. Soil Science Society of America Journal 1995;59:925–32.

[34] Oliver CD, Larson BC. Forest stand dynamics, 1st ed. New York: McGraw-Hill; 1990.

[35] Zeide B, Vanderschaal C. The effect of density on the height–diameter relationship. In: Outcalt KW, editor. Proceedings of the 11th biennial silvicultural research conference. General technical report SRS-48. Asheville: USDA Forest Service Southern Research Station; 2002. p. 463–6.

[36] Torreano SJ, Frederick DJ. Influence of site conditions, fertilization and spacing on short rotation hardwood coppice and seedling yields. Biomass 1988;16:183–98.

[37] Dickmann DI, Steinbeck K, Skinner T. Leaf area and biomass in mixed and pure plantations of sycamore and black locust in the Georgia piedmont. Forest Science 1985;31:509–17.

[38] Grigal DF, Berguson WF. Soil carbon changes associated with short-rotation systems. Biomass and Bioenergy 1998;14:371–7.

[39] Kuers K, Steinbeck K, Morris LA. Root-shoot relationships of coppiced sycamore and sweetgum. In: Proceedings of the seventh biennial southern silvicultural research conference, 17–19 Mobile, AL; 1992. p. 279–85.

[40] Evans J. Worldwide experience with high yield forest plantations. Biomass and Bioenergy 1997;13:189–91.

[41] Debell DS, Clendenen GW, Harrington CA, Zasada JC. Tree growth and stand development in short-rotation populus plantings: 7-year results for two clones at three spacings. Biomass and Bioenergy 1996;11:253–69.

[42] Fang S, Xu D, Lu S, Tang L. Growth dynamics and biomass production in short-rotation poplar plantations: 6-year results for three clones at four spacings. Biomass and Bioenergy 1999;17:415–25.

[43] Adegbidi HG, Volk TA, White EH, Abrahamson LP, Briggs RD, Bickelhaupt DH. Biomass and nutrient removal by willow clones in experimental bioenergy plantations in New York state. Biomass and Bioenergy 2001;20:399–411.

[44] Graham RL. An analysis of the potential land base for energy crops in the conterminous United States. Biomass and Bioenergy 1994;6:175–89.