



Productivity of hybrid sweetgum (*Liquidambar formosana* x *styraciflua*) plantations compared to native sweetgum (*L. Styraciflua*) in the Western Gulf Region of south-central U.S.

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Abstract

Sweetgum (*Liquidambar styraciflua*) is an excellent short-rotation woody crop species for producing hardwood pulp and biofuel feedstock on marginal sites. A recent development which may improve growth is the production of hybrid sweetgum (*L. formosana* x *styraciflua*) clones. We compared the productivity and attributes, e.g., wood specific gravity and stand growth, of operational plantations of hybrid sweetgum clones to improved native sweetgum half-sib families in 36 stands in Oklahoma, Texas, and Louisiana, U.S. The least square means (LSMean) of wood specific gravity was significantly greater for hybrids clones than the half-sibs (0.49 vs. 0.46 g/cm³), and the hybrid clones had less taper which necessitated developing genotype-specific volume and biomass equations. Despite having less fertilizer inputs on average, the hybrids had greater standing green stem biomass than the half-sibs at an age of 8.5 years (LSMean of 73.3 vs. 51.9 Mg/ha). The hybrids as a group also exhibited greater green biomass growth during the 2022 growing season when compared to the half-sibs at 8.5 years (LSMean of 15.8 vs. 11.4 Mg/ha/y). Therefore, the hybrids provide growth and wood quality advantages that may provide an opportunity to increase productivity and profitability of hardwood SRWC plantings.

Keywords Sweetgum · SRWC · Current annual increment · Allometric equation · Hybrid · Specific gravity

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Introduction

Hardwood forests of the southeastern U.S. serve as feedstock for pulp and paper mills across the region. However, the harvest of these forests can have issues, including wet soils and regulatory challenges (Aust et al. 2020). While the amount of hardwood biomass in the southeastern U.S. has increased somewhat in recent years, the growth-to-drain ratio for these forests varies by location (Southern Timber Supply Analysis 2021). For example, there have been some years where more hardwood biomass was harvested than grown in eastern Texas (Edgar and Zehnder 2018). In Oklahoma, hardwood pulpwood is being harvested 50% more quickly than it is currently growing (Southern Timber Supply Analysis 2021). Natural, unmanaged forests in some areas may no longer be sufficient to meet demand, suggesting the need for dedicated hardwood pulp plantations. In addition to the existing demand for pulp and paper, there is an increasing demand for renewable energy (U.S. Department of Energy 2016) to help reduce CO₂ emissions from fossil fuels. As such, renewable energy provides an additional potential market for plantation-grown hardwoods in the southern U.S. (U.S. Department of Energy 2016).

Short-rotation woody crops (SRWC) are highly managed, planted stands that are dedicated for producing wood and fiber quickly and will likely become more important as feedstocks for traditional forestry objectives as well as biofuels. Among the benefits SRWC offer are reduced transportation costs, self-sufficiency, the ability to quickly incorporate new technologies, constancy of wood supply, reduced carbon footprint, and reduced impact on natural stands (Self and Rousseau 2021). The ideal SRWC species are fast-growing, responsive to resource inputs, disease and insect resistant, and amenable to a wide range of soils and sites.

In the southeastern U.S. a number of species have been evaluated in SRWC systems, including *Populus* spp., *Salix* spp., *Platanus occidentalis*, *Liriodendron tulipifera*, and *Liquidambar styraciflua* (Self and Rousseau 2021). Overall, Kline and Coleman (2010) found that *Liquidambar styraciflua* (sweetgum) is often the best-suited hardwood species for biomass production in the southeastern U.S. The species is relatively tolerant of drier conditions on upland soils, which gives it an advantage over the faster growing cottonwood (*Populus deltoides*) and eucalypts (*Eucalyptus* spp.) that require specific site conditions and are more susceptible to pests and pathogens. Also, sweetgum is more efficient than many other species for conversion to ethanol and similar liquid biofuels (McConnell and Shi 2011). While plantation-grown loblolly pine (*Pinus taeda*) typically grows more quickly than sweetgum and has lower management costs (Cobb et al. 2008; Coyle et al. 2008; Kline and Coleman 2010), sweetgum offers an excellent opportunity on marginal sites for uses that need or prefer hardwoods.

A recent development which may improve the productivity of SRWC is the production of hybrid sweetgum (*Liquidambar formosana* $\times$ *styraciflua*) clones. *Liquidambar formosana*, found in subtropical broad-leaved evergreen forests of southeast Asia, is a common pioneer tree known for its fast growth and ability to grow under various conditions (Chen et al. 2023). Studies suggested that hybrid sweetgums grow faster (Adams et al. 2022) and possess greater wood specific gravity than their native counterpart (McConnell et al. 2020). Given the advantages that sweetgum already possesses as a SRWC, deployment of hybrid sweetgums may further push the potential productivity of hardwood plantations across the southeastern U.S. and increase their biological and economic viability. To address this

issue, we compared the productivity and attributes of operationally-planted hybrid sweetgum clones to improved native sweetgum half-sib families in the Western Gulf region of the south-central U.S. (Oklahoma, Texas, and Louisiana). More specifically, we compared specific gravity, developed tree volume and biomass equations, and determined the stand-level mean stem biomass and current annual increment (CAI) for each genotype. We expected that hybrid sweetgum would exhibit increased biomass growth and greater wood specific gravity when compared to native sweetgum.

Methods and materials

The majority of the operationally-planted sweetgum stands in our study were located in southeastern Oklahoma with a additional sites in northeastern Texas (Fig. 1; Table 1). A highly controlled, experimental planting was located at the Louisiana State University Agricultural Center’s Hill Farm Research Station outside of Homer, Louisiana. Soil conditions for the operational plantings varied greatly and ranged from sandier soils on upland sites to finer soils on bottomland sites (Online Resource 1). Across the study area, annual precipitation ranged from approximately 1410 to 1143 mm/y (east to west gradient of decreasing precipitation), average temperatures ranged from 15.8 to 18.9 °C (north to south gradient of increasing temperature), and the typical frost-free period ranged from 210 to 248 days long (north to south gradient) (Online Resource 2).

A total of 36 stands located on 16 sites were selected for this study to broadly characterize the growth potential of sweetgum across the region. Twelve of these stands were planted with half-sib families of sweetgum, and 24 of the stands were planted with hybrid clones (Table 1). Four hybrid clones (AGHS-1, AGHS-2, AGHS-3, AGHS-4) developed by ArborGen Inc (Ridgeville, SC) were measured. These were created by crossing improved native

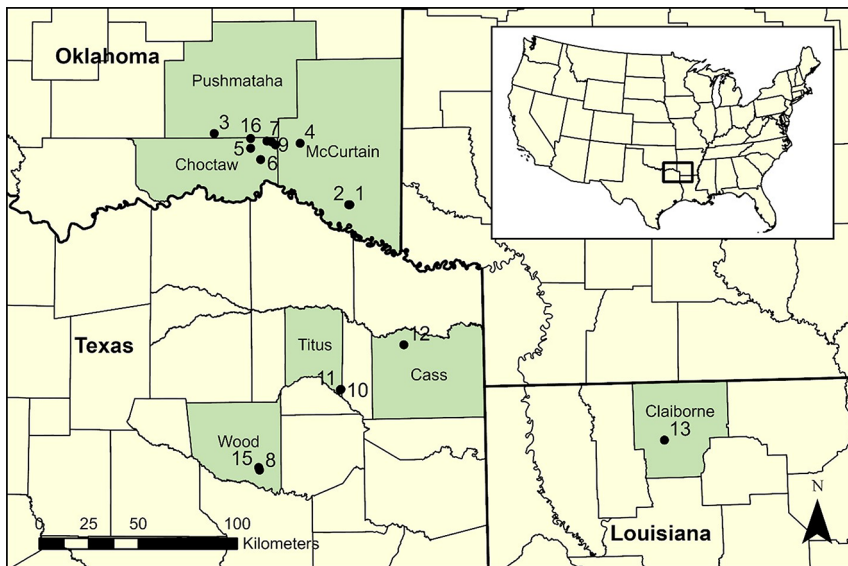


Fig. 1 The 16 sites were distributed across seven counties in three U.S. states (U.S. Bureau of the Census 2023). Site numbers shown here correspond to those found in Table 1

Table 1 List of site locations, establishment years, planting densities, genotypes and whether it was fertilized

Site	State	County/ Parish	Latitude	Longitude	Planting Year	Density TPH	Spacing (m)	Genotypes*	Fert
1	OK	McCurtain	33°51'0.96"N	94°45'44.05"W	2011	1282	2×4	8	Y
2	OK	McCurtain	33°51'0.87"N	94°46'4.85"W	2012	1035	2.4×4	9	Y
3	OK	Pushmataha	34°10'37.64"N	95°30'20.83"W	2012	1077	3×3	10	Y
4	OK	Choctaw	34°7'48.62"N	95°12'55.93"W	2013	1273	2.6×3	5	Y
5	OK	Choctaw	34°6'32.73"N	95°18'17.64"W	2013	1273	2.6×3	5	Y
6	OK	Choctaw	34°3'30.94"N	95°15'0.88"W	2013	1196	2.7×3	5	Y
7	OK	Choctaw	34°8'28.10"N	95°12'56.25"W	2014	1347	2.4×3	5	Y
8	TX	Wood	32°39'18.65"N	95°16'10.18"W	2014	1347	2.4×3	5	Y
9	OK	Choctaw	34°8'15.68"N	95°11'24.59"W	2014	1347	2.4×3	1, 2, 3, 5	Y
10	TX	Titus	33°0'49.52"N	94°49'41.31"W	2015	1347	2.4×3	1, 2, 3, 4	N
11	TX	Titus	33°1'0.32"N	94°49'27.30"W	2015	1347	2.4×3	5	N
12	TX	Cass	33°12'48.91"N	94°28'40.61"W	2015	1347	2.4×3	1, 2, 3, 4	N
13	LA	Claiborne	32°45'18.16"N	93°4'25.52"W	2015	2152	1.5×3	1, 2, 3, 4, 6	Y
14	OK	Choctaw	34°7'28.17"N	95°10'6.92"W	2016	1347	2.4×3	7	Y
15	TX	Wood	32°40'1.54"N	95°16'29.04"W	2016	1347	2.4×3	4	Y
16	OK	Choctaw	34°9'12.13"N	95°18'19.53"W	2017	1282	2.1×3.7	1, 2, 3, 4	Y

* Genotypes are 1=AGHS-1, 2=AGHS-2, 3=AGHS-3, 4=AGHS-4, 5=AGH-21, 6=AGH-25, 7=AGH-26, 8=AGH-9, 9=Family 148, 10=AGH-22. Genotypes beginning with AGHS were hybrid clones and the remainder were native half-sib families

sweetgum (*L. styraciflua*) with Formosan gum (*L. formosana*). In addition, we examined six native half-sib families produced by ArborGen. Often, there were block plantings (stands) of multiple clones at given sites, and at two of the sites, there were two replications of each clone. We considered sites 10 (hybrid plantings) and site 11 (native planting) as separate, but they were adjacent, and their soil and environmental conditions were similar.

The ages of these stands varied, with some sites planted as early as 2011 and others as recently as 2017 (Table 1). At the beginning of this study in 2021, stand ages ranged from 6 to 11 years for the native half-sibs and 5–8 years for the hybrid clones. This range of stand ages, and therefore tree sizes, was beneficial for developing growth and yield equations. The spatial distribution of these stands also allowed the study to encompass variation in climate and a wide range of topographic conditions and soil types so that the results could be generalized to the region.

Site preparation for each stand typically involved mechanical ripping to a depth of 0.5 to 1.0 m and removal of debris from the rows. To control herbaceous competition, a solution containing 15 g/L of Oust XP® and 0.25% surfactant was then broadcast at a rate of about 94 L/ha using a helicopter. The following January, commercially available seedlings were purchased from ArborGen and were hand-planted. Half-sib seedlings were typically bare-root, while the hybrid seedlings were containerized. Planting densities for the operational plantings ranged from 1,035 to 1,347 trees/ha with an average of 1,305, while the planting density for the LSU site was about 2,150 trees/ha. The typical tree spacing was approximately 2.5 × 3 m, with only a handful of stands deviating from this pattern (Table 1). Post-planting competition control began as early as the year of stand establishment. For this, ATVs equipped with sprayers applied a banded application of a solution containing 1.5% glyphosate and 0.5% surfactant. This solution was applied in 1 m bands at a rate of about 234 L/ha. In general, the half-sib stands received two to four herbicide applications following planting, whereas the hybrid stands typically received just two.

Beginning 3 to 6 years after establishment, 10 of the 12 sites (10 of 12 stands) containing half-sib families were fertilized (Table 1) either one (seven stands) or two times (three stands). In contrast, only three of six sites (12 of 24 stands) containing hybrids were fertilized. Between 319 and 392 kg/ha of coated urea fertilizer (110–135 kg/ha of nitrogen) was used for the first application, whereas a mixture of 336 kg/ha of urea (155 kg/ha of nitrogen) and 140 kg/ha of Di-ammonium phosphate (25 kg/ha of nitrogen and 64 kg/ha of phosphorus) was used any successive applications. Each fertilizer application was broadcast using a helicopter.

Except for seven stands, three to six permanent sample plots were installed within each stand, with a target of 40 individual stems per plot. The other seven stands were smaller clonal trials and were fully censused. Plot size varied based on stand configuration, topography, and local conditions. Overall, the plots ranged from 0.02 to 0.05 hectares and contained between 20 and 71 stems. Each of the sample plots was a quadrilateral with the two longer boundaries being equidistant between planting rows. The dimensions of each plot were measured using the sonar-based Vertex III hypsometer (Haglöf, Sweden). To calculate area, measurements were taken along each of the four boundaries of a given plot, as well as the two diagonals.

The first year of data collection went from October 2021 until April 2022. Similarly, the second year of data collection lasted from October 2022 through March 2023. During data collection, total height and the diameter at breast height (DBH) were measured for each tree

within a given plot. Height poles were the preferred method for measuring the heights of the younger, shorter trees. The older, taller trees were measured to the nearest 0.1 m with either a TruPulse 200 hypsometers (Laser Tech, USA) or Vertex III hypsometer. Diameter tapes were used to measure DBH to the nearest millimeter. When a fork occurred below breast height, the height and DBH of each viable stem were documented.

Over the course of the 2022 growing season, additional data regarding stem taper and biomass were collected from 20 of the stands. Sixteen of these stands had hybrid clones (four stands for each of the four clones; AGHS-1, AGHS-2, AGHS-3, and AGHS-4), while the remaining four stands had an improved half-sib family (AGH-21) of native sweetgum. For each stand, five to six trees were harvested, totaling 103 trees. Once each tree was felled, the total height was measured to the nearest centimeter. Following this, diameter tapes were used to measure the diameter outside the bark (DOB) at ground level, 1 m, 1.37 m, 2 m, and in 2 m intervals thereafter.

Once a given tree was delimbed and cut into manageable sections, the green biomass of the stem was determined to the nearest 0.1 kg using a digital scale. At each of the locations measured for DOB, ~2 cm thick disks were collected, sealed in plastic bags, and stored on ice until the completion of fieldwork for the day. Each afternoon/evening of collection, measurements were conducted on each disk for bark green mass, wood green mass, diameter inside the bark (DIB), and bark thickness. The first step was to remove the bark from a given sample using a wood chisel. The bark and wood components were then weighed separately to the nearest 0.1 g. The bark thickness was measured five times per sample to the nearest 0.1 mm using digital calipers and averaged. Finally, the DIB for each disk was measured to the nearest millimeter using a diameter tape.

Once the green measurements were collected, bark samples were dried at 60 °C until they achieved a constant weight and then weighed to the nearest 0.1 g. The wood disk samples were placed in water-filled plastic bags for at least 12 h to fully hydrate. The volume of each wood sample was then determined using the water displacement method. Following the collection of the volume measurements, the wood samples were transferred to a paper bag, dried at 60 °C until they achieved a constant weight, and weighed to the nearest 0.1 g. Specific gravity, i.e., dry weight/volume, of each disk was calculated from these measurements. Specific gravities of individual disks were used to calculate biomass of associated tree segments (see below).

Volume outside bark (VOB) was calculated by dividing each given tree into frustums based on harvest intervals. The volume of each frustum was then calculated using the top and bottom diameters of each segment. The volume of the top section of each tree was calculated as a cone. Tree VOB was determined by summing the volume of all frustums and the terminal cone. Volume inside bark (VIB) was calculated similarly using the diameters with the bark removed.

Once VIB was calculated for each stem, stem wood dry biomass was determined by applying the corresponding specific gravity data. For this, the volume of each frustum was converted to wood dry biomass by multiplying volume by the average specific gravity of the top and bottom disk. The top portion of each tree (cone) was multiplied by the specific gravity of the disk at the base of that section. The total stem wood dry biomass of each given tree was found by summing the dry mass of each frustum and the terminal section. After the total dry weight and total volumes were calculated, the average wood specific gravity of each tree

was calculated by dividing the total dry mass by the total VIB. Likewise, the average bulk density (wood and bark) was calculated by dividing total green weight by total VOB.

For total green mass, stem wood dry mass, VOB, VIB, and average specific gravity, linear relationships with D^2H were developed, where D was the DBH of a given stem and H was height. Differences among the linear relationships for the various genotypes were compared by testing for differences in the slope and intercept (SAS 9.4, Carey, NC). As part of this process, the least square mean (LSMean) of each genotype was calculated (SAS 9.4, Carey, NC). Here and in other analyses when appropriate, the PDIFF function was used to calculate differences among means.

The genotype-specific volume and biomass equations developed from the harvest data were used to calculate the volume and biomass of each tree measured during plot-level dormant season data collection. Then, the plot-level biomass was calculated by summing all trees within a plot. These values were then scaled to the per-hectare basis using the plot area. Additional plot-level variables included mean DBH and height as well as basal area and trees per hectare. Data from plots within stands were then averaged to calculate stand-level variables.

The difference between the two dormant-season data collections was used to determine growth during 2022. The linear relationship between growth during 2022 and stand age was calculated for each hybrid clone individually and for the half-sib families as a group. A regression was also calculated for all hybrids as a group. The slopes of these relationships served as an estimate of the current annual increment (CAI) across the range of stand ages measured and allowed for comparison between the typically older half-sib families and younger hybrid clones. Slopes were tested using age as a covariate and examining the interaction between age and CAI (SAS 9.4, Carey, NC).

To specifically test for differences among clones, sites were included based upon two criteria: each of the four clones had to be present at a given site, and the stands within the site had to be the same age. Based on these criteria, there were two blocks at site 10, one at site 12, and two at site 16. Data for clonal comparisons were tested using a randomized complete block design where block included variation due to site and/or age.

During the spring of 2023, trees were harvested from the LSU location and measured for branch and stem biomass. This was done to supplement the stem biomass data collected from Oklahoma and Texas the previous year. At the time of measurement, the trees were eight years old. A total of 18 trees were harvested from the LSU location, three to four stems for each of the four hybrid clones and four stems for a half-sib family of native sweetgum (AGH-25). As before, the green mass of the stem was measured. The total mass of the live branches was also measured for each stem. From these data, branch/stem biomass ratios were developed for each genotype, and their means were compared statistically.

Results

Tree harvest and allometric equations

The average age of the half-sib native sweetgum trees that were harvested to develop equations was 8 years, while the average age of the hybrid clones was 6.5 years. Despite this difference in age, the younger hybrids were similar in size to the half-sib trees. DBH of har-

vested trees ranged from 3.6 to 18.8 cm and did not differ among genotypes ($p=0.59$), with genotype means ranging from 10.1 to 11.4 cm (Fig. 2). While the average height of hybrid AGHS-3 (9.0 m) was significantly shorter ($p<0.05$) than hybrid AGHS-1 (11.2 m), the half-sib trees (AGH-21) were not statistically different from any of the hybrid clones (Fig. 2). For specific gravity (wood dry biomass/VIB), hybrid clones AGHS-1 and AGHS-2 (both 0.52 g/cm³) were greater ($p<0.05$) than the other two clones (0.47 and 0.46 g/cm³) and the half-sib genotype trees AGH-21 (0.46 g/cm³). A similar pattern occurred for bulk density (stem green biomass/VOB), but AGHS-1 was statistically similar to AGHS-3 (Fig. 2).

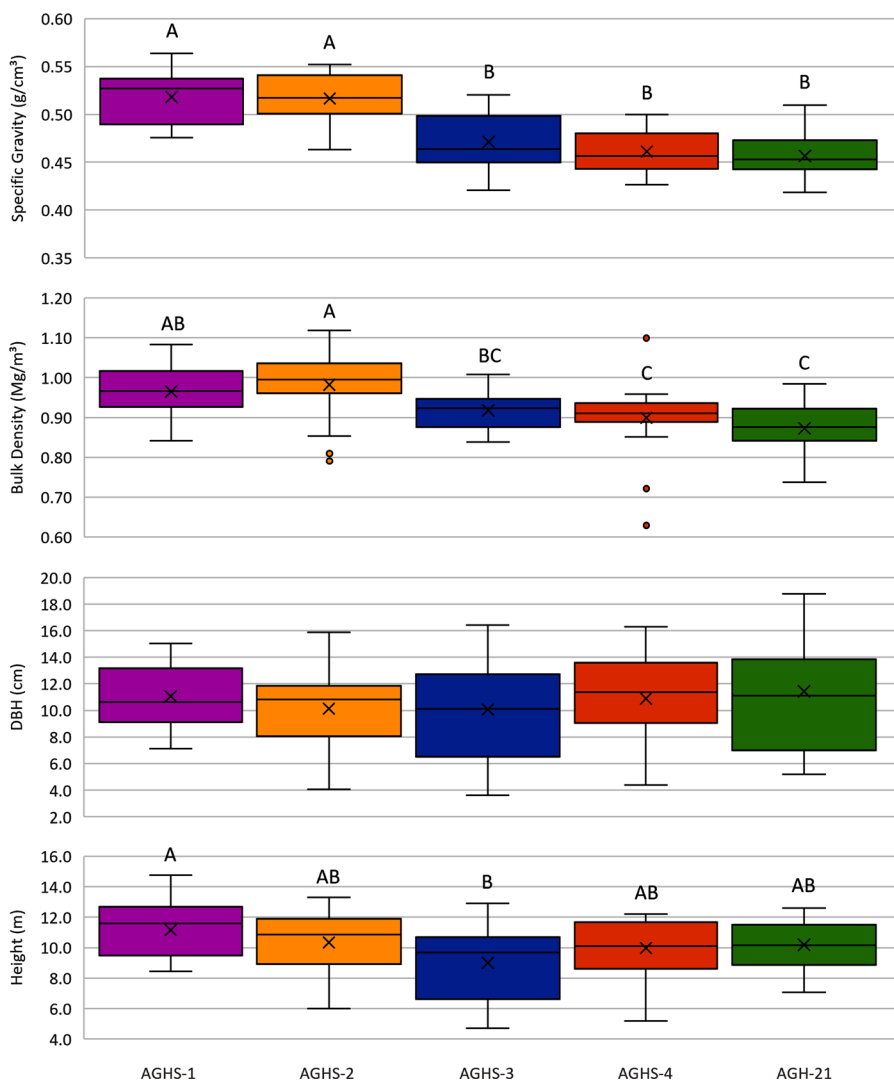


Fig. 2 Box-whisker plots comparing wood specific gravity, stem bulk density, DBH, and height of the harvested trees for each genotype. The average age for the hybrid clones (AGHS-1, AGHS-2, AGHS-3, and AGHS-4) was 6.5 years, and average age for the half-sib native sweetgum (AGH-21) was 8 years. Genotypes with the same letter were not significantly different

The genotype-specific volume and biomass equations developed from the harvest indicated a very strong relationship between D^2H and tree size with a minimum R^2 of 0.96 (Table 2). Analyses of slopes for the relationship between tree size and VOB indicated no significant differences among genotypes ($p=0.35$). Likewise, slopes for VIB did not differ ($p=0.30$). In terms of biomass, there were some differences among slopes. For example, hybrids AGHS-2 and AGHS-3 had significantly greater slopes for the relationship between tree size and green biomass than half-sib AGH-21 ($p=0.03$). For dry biomass, the slopes were highly significant ($p=0.0008$) with hybrids AGHS-1 and AGHS-2 having greater slopes than the remainder of the genotypes. When comparing the LSMeans from the harvest data, i.e., size at the mean tree size for all data combined, there were significant differences among genotypes ($p<0.0001$). For VOB, the four hybrid clones were all greater than the half-sib native sweetgum and AGHS-4 was greater than AGHS-3. For VIB, the four hybrid clones were statistically similar and greater than the half-sib native sweetgum (Table 3). For green and dry biomass, AGHS-1 and AGHS-2 were greater than the other genotypes with AGHS-3 and AGHS-4 also greater than the native half-sib trees (Table 3). These differences among genotypes necessitated the use of genotype-specific equations for calculating plot-level biomass.

Based on the data from the LSU site, the hybrid clones had a significantly lower branch: stem ratio than the half-sib native sweetgum (0.18 vs. 0.32, $p=0.0018$). When genotypes were considered separately, hybrid genotypes AGHS-1 (0.17), AGHS-2 (0.17), and AGHS-4 (0.16) had significantly lower branch: stem ratios ($p<0.05$) from the half-sib (0.32). However, AGHS-3 (0.24) was not significantly different from half-sib AGH-25 or from the other hybrid genotypes.

Stand-level results

Following the 2021 growing season, stand-level means of DBH ranged from 4.4 to 14.4 cm (Online Resource 3). Following the 2022 growing season, these means increased to a range of 5.5 to 14.9 cm (Table 4). The stand-level means of height also increased during that time (Supplemental Table 4) and ranged from 5.5 to 14.7 m following the 2022 growing season (Table 4). Basal area increased from a range of 1.9 to 23.7 m^2/ha in 2021 (Online Resource 3) to a range of 2.9 to 25.6 m^2/ha in 2022 (Table 4). Means for green biomass ranged from about 11 to 132 Mg/ha following the 2021 growing season (Online Resource 4), and these means increased to a range of about 15 to 150 Mg/ha following the 2022 growing season (Table 5). VOB, VIB, and dry biomass followed similar trends as green biomass (Table 5; Online Resource 5; Online Resource 6).

During the 2022 growing season, growth was largely proportional to standing biomass and ranged from 12.1 to 104.6 m^3/ha for VOB, 10.0 to 91.5 m^3/ha for VIB, 1.6 to 13.1 Mg/ha dry mass, and 3.4 to 28.3 Mg/ha green biomass (Supplemental 6). Because of the relationship between productivity and age, standing green biomass and annual production of green biomass were analyzed using stand age as a covariate. The hybrids as a group exhibited greater standing green biomass than the half-sibs at an age of 8.5 years (LSMeans of 73.3 vs. 51.9 Mg/ha , $p<0.0001$) (Fig. 3). These values convert to 8.6 vs. 6.1 $Mg/ha/y$ mean annual increment (MAI). The hybrids as a group also exhibited greater green biomass growth during 2022 (CAI) when compared to the half-sibs at 8.5 years (LSMeans of 15.8 vs. 11.4 $Mg/ha/y$, $p<0.0001$) (Fig. 3).

Table 2 Individual-stem volume and biomass equations based on D^2H , with D representing the DBH in m and H representing the height in m. VOB (m^3) is the volume of a stem outside the bark, VIB (m^3) is the volume inside the bark, stem green biomass (Mg) with the bark included represents the dry wood component. Dry biomass is wood only

Genotype	VOB		Green Biomass		VIB		Dry Biomass	
	Equation	R^2	Equation	R^2	Equation	R^2	Equation	R^2
AGH-21	$y = 0.35x + 0.0041$	0.99	$y = 0.31x + 0.0032$	0.99	$y = 0.30x + 0.0022$	0.99	$y = 0.14 + 0.0007$	0.99
AGHS-1	$y = 0.34x + 0.0087$	0.98	$y = 0.33x + 0.0081$	0.96	$y = 0.30x + 0.0073$	0.97	$y = 0.17 + 0.0027$	0.98
AGHS-2	$y = 0.34x + 0.0069$	0.99	$y = 0.35x + 0.0062$	0.99	$y = 0.30x + 0.0057$	0.99	$y = 0.16 + 0.0027$	0.99
AGHS-3	$y = 0.34x + 0.0061$	0.99	$y = 0.33x + 0.0039$	0.99	$y = 0.30x + 0.0049$	0.99	$y = 0.15 + 0.0019$	0.99
AGHS-4	$y = 0.37x + 0.0056$	0.99	$y = 0.33x + 0.0042$	0.97	$y = 0.33x + 0.0040$	0.98	$y = 0.15 + 0.0018$	0.98

Clonal differences

For testing clonal differences using sites where all clones were included, height ($p=0.0004$), DBH ($p=0.009$), and standing green biomass ($p=0.05$) after the 2022 growing season, and green biomass growth during the 2022 growing season ($p=0.004$) were all influenced by clone. In general, clone AGHS-3 was the smallest, and clone AGHS-4 was the largest. Specifically, the height of AGHS-3 was significantly shorter than the other three clones (Table 6). Hybrid clone AGHS-3 had significantly smaller DBH and less standing green biomass than AGHS-4 (other clones intermediate) (Table 6). Hybrid clone AGHS-4 had significantly greater green biomass growth than the other clones (Table 6).

Discussion

As expected, hybrid clones grew faster and had greater wood specific gravity than the native half-sibs. While we could not experimentally control for stand age or site characteristics, the strength of our study is that it was operationally installed at multiple locations across a large geographical area, and as such represents expected results of landowners willing to adopt management for SRWC hardwood systems. The better performance of the hybrid clones demonstrates the potential to increase hardwood feedstocks for both traditional uses as well as emerging biofuel industries.

Greater specific gravity of wood is a desirable trait for sawtimber and pulp production because it correlates with a range of factors, such as fiber content (Shmulsky and Jones 2019). The average specific gravity of the hybrid clones was greater than the native sweetgum and also exceeded what Miles and Smith (2009) found for loblolly pine (0.47 g/cm^3) and eastern cottonwood (0.36 g/cm^3). However, certain species of eucalyptus (0.52 g/cm^3) can have a greater specific gravity (Miles and Smith 2009) than the hybrid sweetgum clones in this study. Overall, the faster growth of the hybrid sweetgum is complemented by greater specific gravity, which taken together indicates hybrid sweetgum has positive attributes for incorporation in SRWC plantings.

When comparing hybrid and native sweetgum, the hybrid clones had greater volume for the same D^2H . This likely indicates less taper for the hybrid clones compared to the half-sibs, which is a desirable trait in a crop tree. Although many factors can affect stem taper, such as genetics, site quality, and planting density (Mahadev et al. 2002), planting densities for our stands were similar, and a range of site qualities were included for each genotype. In the case of biomass of harvested trees, we found larger differences between the hybrids and half-sibs than for volume when compared at the same D^2H . This can be attributed to the combination of the increased volume combined with greater specific gravity. While the volume for a given D^2H did not differ among hybrid clones, the specific gravities of AGHS-1 and AGHS-2 were greater than the other clones which resulted in greater biomass at a common size. This underscores the importance of clone choice when establishing a plantation.

We present MAI and CAI as green biomass because the stands were operationally managed and will be sold on a green weight basis. The average dry weight/green weight we measured was 0.46 and allows comparison to studies measured on a dry weight basis. Compared to what Ghezzehei et al. (2015) found at 6 years (10–12.1 Mg/ha/y green weight) for native sweetgum plantations, the CAI we measured for native sweetgum at 8.5 years (11.4

Table 3 Comparison of LSMeans for VOB, VIB, green biomass (whole stem), and dry biomass (wood only). For each variable, genotypes with the same letter were not significantly different

Genotype	VOB		VIB		Green Biomass		Dry Biomass	
	LSMean (m ³)		LSMean (m ³)		LSMean (Mg)		LSMean (Mg)	
AGHS-1	0.055	AB	0.048	A	0.056	A	0.026	A
AGHS-2	0.054	AB	0.048	A	0.055	A	0.024	A
AGHS-3	0.053	BC	0.047	A	0.048	B	0.022	B
AGHS-4	0.056	A	0.049	A	0.048	B	0.023	B
AGH-21	0.052	C	0.044	B	0.044	C	0.020	C

Table 4 Diameter at breast height (DBH), height, basal area (BA), and trees per hectare (TPH) following the 2022 growing season. Standard deviations are in parentheses

Site	Stand	Age	Genotype	Plots	DBH (cm)	Height (m)	BA (m ² /ha)	TPH
1	1	12	AGH-9	6	14.9 (0.9)	14.4 (0.5)	24.9 (2.1)	1351 (170)
2	2	11	Family 148	6	14.3 (0.9)	14.7 (0.6)	25.6 (1.8)	1496 (176)
3	3	11	Family 148	6	12.0 (0.9)	10.8 (1.0)	16.3 (2.5)	1388 (129)
4	4	10	AGH-21	6	13.4 (0.9)	12.4 (0.7)	20.7 (1.4)	1395 (138)
5	5	10	AGH-21	6	12.0 (1.4)	10.9 (1.3)	18.0 (3.1)	1485 (65)
6	6	10	AGH-21	6	12.6 (1.3)	12.3 (1.1)	17.2 (2.8)	1296 (138)
7	7	9	AGH-21	6	11.3 (0.5)	11.0 (0.4)	18.3 (0.8)	1721 (133)
8	8	9	AGH-21	3	10.7 (0.7)	8.5 (0.7)	12.8 (0.9)	1371 (133)
9	9	9	AGH-21	5	11.4 (1.3)	10.5 (0.7)	15.7 (1.8)	1478 (152)
9	10	9	AGHS-2	1	13.3 .	12.4 .	16.9 .	1199 .
9	11	9	AGHS-1	1	12.9 .	12.6 .	16.6 .	1254 .
9	12	9	AGHS-3	1	13.2 .	11.4 .	16.6 .	1186 .
10	13	8	AGHS-3	5	8.9 (1.3)	8.5 (1.0)	10.4 (2.0)	1621 (428)
10	14	8	AGHS-1	5	11.7 (0.8)	12.1 (0.8)	13.4 (1.2)	1216 (78)
10	15	8	AGHS-2	5	11.4 (0.4)	11.6 (0.3)	14.4 (1.1)	1354 (71)
10	16	8	AGHS-4	5	13.5 (0.7)	11.2 (0.5)	17.9 (2.1)	1202 (122)
10	17	8	AGHS-1	5	11.3 (1.5)	10.9 (1.1)	13.8 (2.5)	1341 (139)
10	18	8	AGHS-3	5	11.6 (0.7)	9.8 (0.5)	15.1 (2.1)	1338 (150)
10	19	8	AGHS-2	5	11.6 (0.6)	10.8 (0.7)	14.0 (1.5)	1280 (85)
10	20	8	AGHS-4	5	11.6 (0.7)	9.6 (0.6)	14.3 (1.6)	1314 (63)
11	21	8	AGH-21	5	9.6 (0.6)	8.4 (0.4)	12.6 (1.2)	1641 (161)
12	22	8	AGHS-1	3	11.8 (1.1)	11.9 (0.8)	11.0 (1.3)	963 (74)
12	23	8	AGHS-2	3	10.8 (0.8)	10.3 (0.2)	12.2 (2.8)	1286 (232)
12	24	8	AGHS-3	2	10.5 (0.8)	9.2 (0.7)	13.5 (2.0)	1496 (35)
12	25	8	AGHS-4	6	12.4 (0.8)	10.6 (0.2)	17.6 (1.7)	1401 (134)
14	31	7	AGH-26	5	8.7 (0.6)	8.0 (0.6)	10.5 (1.5)	1696 (102)
15	32	7	AGHS-4	4	10.3 (0.6)	7.2 (0.3)	8.7 (1.4)	987 (96)
16	33	6	AGHS-3	4	5.6 (0.8)	5.4 (0.5)	4.36 (1.3)	1716 (170)
16	34	6	AGHS-2	5	7.8 (0.3)	7.6 (0.6)	6.6 (0.8)	1361 (54)
16	35	6	AGHS-4	6	9.0 (0.7)	8.0 (0.4)	8.6 (1.8)	1283 (109)
16	36	6	AGHS-1	7	8.6 (0.4)	8.4 (0.3)	5.7 (1.1)	961 (160)
16	37	6	AGHS-1	1	5.5 .	5.6 .	2.9 .	1214 .
16	38	6	AGHS-2	1	6.1 .	6.1 .	4.4 .	1425 .
16	39	6	AGHS-3	1	5.8 .	5.5 .	3.8 .	1328 .
16	40	6	AGHS-4	1	7.6 .	6.5 .	5.7 .	1161 .

Table 5 Standing stem volume and biomass following the 2022 growing season. VOB is volume outside bark and VIB is volume inside bark. Green biomass includes wood and bark. Dry biomass is wood only

Site	Stand	Age (yrs.)	Genotype	Plots	VOB (m ³ /ha)	Green Bio-mass (Mg/ha)	VIB (m ³ /ha)	Dry Biomass (Mg/ha)
1	1	12	AGH-9	6	555.0	149.5	479.6	67.9
2	2	11	Family 148	6	595.2	160.3	514.2	72.8
3	3	11	Family 148	6	282.1	75.7	240.7	33.8
4	4	10	AGH-21	6	402.2	108.1	345.8	48.8
5	5	10	AGH-21	6	325.4	87.3	278.1	39.1
6	6	10	AGH-21	6	343.8	92.4	295.1	41.6
7	7	9	AGH-21	6	323.5	86.7	275.5	38.7
8	8	9	AGH-21	3	179.4	47.9	150.9	21.0
9	9	9	AGH-21	5	266.3	71.3	226.5	31.8
9	10	9	AGHS-2	1	331.0	100.6	288.3	46.0
9	11	9	AGHS-1	1	326.7	97.3	295.7	47.5
9	12	9	AGHS-3	1	302.0	86.1	262.5	38.5
10	13	8	AGHS-3	5	166.5	45.6	143.3	20.5
10	14	8	AGHS-1	5	263.7	78.5	238.3	38.0
10	15	8	AGHS-2	5	276.2	83.7	240.2	38.2
10	16	8	AGHS-4	5	330.9	91.9	300.0	41.9
10	17	8	AGHS-1	5	251.3	74.7	226.8	36.0
10	18	8	AGHS-3	5	250.9	70.8	217.6	31.7
10	19	8	AGHS-2	5	251.2	76.1	218.4	34.7
10	20	8	AGHS-4	5	235.7	65.0	212.0	29.5
11	21	8	AGH-21	5	180.7	48.1	150.9	20.9
12	22	8	AGHS-1	3	216.8	64.5	196.0	31.3
12	23	8	AGHS-2	3	214.9	64.9	186.6	29.6
12	24	8	AGHS-3	2	216.2	60.3	186.9	27.1
12	25	8	AGHS-4	6	312.5	86.5	282.3	39.4
14	31	7	AGH-26	5	147.1	39.0	121.2	16.7
15	32	7	AGHS-4	4	116.7	31.9	103.7	14.4
16	33	6	AGHS-3	4	70.0	17.1	58.7	7.9
16	34	6	AGHS-2	5	104.6	31.1	90.0	14.0
16	35	6	AGHS-4	6	130.0	35.3	114.9	15.9
16	36	6	AGHS-1	7	96.2	28.4	85.9	13.0
16	37	6	AGHS-1	1	57.6	16.7	50.2	6.7
16	38	6	AGHS-2	1	73.6	21.5	62.7	9.6
16	39	6	AGHS-3	1	59.0	14.7	49.7	6.7
16	40	6	AGHS-4	1	79.0	21.1	68.4	9.4

Mg/ha/y) was comparable and that of the hybrid sweetgum was greater (15.8 Mg/ha/y). Several studies measured the maximum potential of sweetgum by growing them under fertigated (fertilization plus irrigation) conditions. Compared to these studies our growth rates were lower than the potential growth rates under abundant water and nutrients, but exceeded growth rates when no treatment or irrigation only was applied. For instance, CAI at age 6 for fertigated stands in southeastern Georgia were 1.2, 5.3, and 12.7 Mg/ha/y dry weight for the Control, Irrigated only, and fastest growing Fertigated treatment respectively (Allen et al. 2005; Cobb et al. 2008). Likewise, we found MAI for green weight at age 8.5 of 8.6 and 6.1

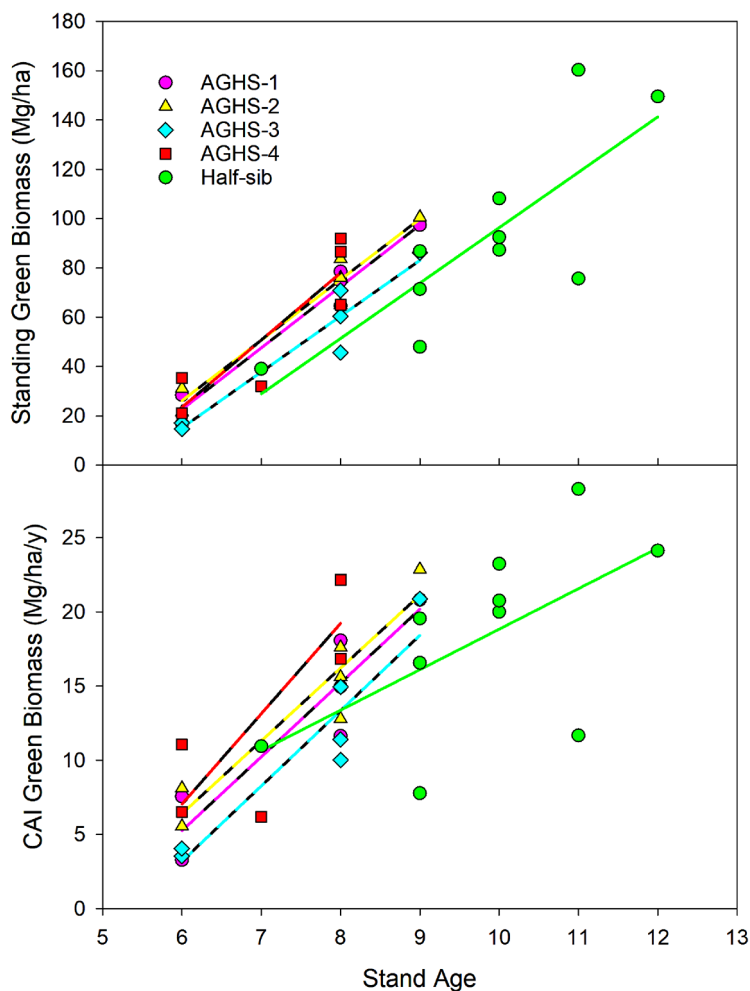


Fig. 3 Relationship between standing green biomass (wood and bark) and age after the 2022 growing season (top) and stand age and green biomass growth during the 2022 growing season

Table 6 Differences among hybrid clones for average tree height, DBH, and stand-level green biomass following the 2022 growing season and green biomass growth during the 2022 growing season ($n=5$). For each variable, means that share a letter are not significantly different ($p<0.05$). Standard errors are in parentheses

Genotype	Height (m)	DBH (cm)	GBio (Mg/ha)	Δ GBio (Mg/ha/y)
AGHS-1	9.8 (1.2) A	9.8 (1.2) AB	52.6 (12.6) AB	11.1 (2.6) B
AGHS-2	9.3 (1.1) A	9.6 (1.1) AB	55.5 (12.4) AB	11.9 (2.3) B
AGHS-3	7.7 (0.9) B	8.5 (1.2) B	41.7 (11.3) B	8.8 (2.2) B
AGHS-4	9.2 (0.9) A	10.8 (1.1) A	60.0 (13.9) A	15.8 (3.1) A

Mg/ha/y which fell between the range of values for fertigation trials in southwest Georgia, which had MAI at age 6 of 1.2 (control), 2.3 (irrigated only), and 6.5 (fertigated) Mg/ha/y

for dry biomass (Williams and Gresham 2006) and for trials in South Carolina which had MAI for dry biomass at age 9 of approximately 2.1 (control), 2.7 (irrigated), and 8.3 (fertigated) Mg/ha/y (Coyle et al. 2016). From these comparisons, the growth of sweetgum in our study was approximately half the potential growth achieved under fertigated conditions. However, our study was operationally managed, and stands were fertilized once or not at all.

An inherent challenge when comparing the hybrid and native sweetgum stands within our study was that the range of stand ages did not match among genotypes. On average, the hybrid stands were about 2 years younger than the half-sibs (6.4 vs. 8.6 years). However, the hybrid stands had greater standing biomass than the half-sib stands when calculated at a common age (73.3 vs. 51.9 Mg/ha at 8.5 years). There were two adjacent sites with identical soils and environmental conditions (site 10 with hybrid clones and site 11 with half-sib AGH-21) where the green biomass after eight years was 73.3 Mg/ha for the clones and 48.2 Mg/ha for the native half-sib, which were very close to the LSMeans calculated for the entire dataset and helps validate our approach. Likewise, site 9 contained clones AGHS-1, AGHS-2, AGHS-3, and native half-sib AGH-21. The green biomass at age nine was 71.4 Mg/ha for the half-sib and averaged 94.7 Mg/ha for the hybrids. Overall, the hybrid sweetgum outgrew the half-sibs even though only 50% of hybrid stands had been fertilized while 83% of half-sib stands had been fertilized.

Based on analysis of the data from the LSU location, branch: stem biomass ratios were lower for the hybrid clones than the native half-sibs perhaps indicating greater self-pruning among the hybrids clones (Adams et al. 2022) or greater partitioning of biomass to stem relative to branches. The lower ratios could be advantageous for stem-only harvest systems, but less important for whole-tree harvesting where the branches as well as stem are taken.

Comparing hybrid clones with native half-sibs confounds the level of genetic control with genotype. Using clones increases the potential genetic gain, with typical increases from 10 to 25% compared to half-sib families (Wu 2019). In our study, the hybrid clones had 41% greater MAI assessed at a common age. While we do not know how much of this gain was due to the level of genetic control vs. hybrid benefits, we compared the seedling stocks that were commercially available for deployment at the time of establishment. Development of native clones may negate some of the benefits of the hybrids, but hybrids also had greater wood-specific gravity, less taper, and less branch per stem.

While this study is most applicable to the region of southeastern Oklahoma, northeastern Texas, and northwestern Louisiana, plantations grown in areas with similar soils and climate could expect similar results. For example, the Kirvin soil series was present at nearly half of the sites, and it extends across the Western Gulf Coastal Plain to also include Arkansas (USDA NRCS Web Soil Survey). In areas with higher levels of precipitation or soils with a greater capacity to retain moisture and nutrients, the growth rates of the hybrids and the half-sibs would likely both improve.

Even though the hybrids generally grew faster than the half-sibs, soils, and other site differences may be more important than genotype in some cases. For example, sites 14 (AGH-26) and 15 (AGHS-4) were planted in the same year (2015) at the same planting density (1347 trees/ha) and received identical levels of management. However, site 14 had finer textured soils and greater average precipitation than site 15, and the half-sibs had greater green biomass production (10.9 vs. 6.2 Mg/ha/y) (Supplemental Table 6). This suggests that even though hybrid sweetgum typically exhibits exceptional growth rates on upland sites, excessive drainage, and decreased precipitation can cause a sharp decline in productivity.

In addition to climate and soils, regional variation in precipitation during 2022 likely also impacted growth of individual stands. However, teasing apart the effects of timing and the potential for multi-year impacts of precipitation patterns on growth is beyond scope of this study.

The hybrid clones exhibited greater growth rates than the native half-sibs under similar site conditions. However, all clones were not the same. Among hybrid clones, AGHS-4 produced the greatest stand-level green biomass while AGHS-3 was the smallest and produced the least. AGHS-1 and AGHS-2 had the greatest specific gravity. Based on these results, AGHS-4 should be selected to maximize production while AGHS-1 and AGHS-2 might be considered for applications where greater specific gravity is desirable.

Conclusions

Our study, that included Oklahoma, Texas, and Louisiana, explored the productivity of hybrid clonal plantations in comparison to native half-sib sweetgum plantations. The hybrids had greater productivity, greater specific gravity, less taper, and less branch/stem despite having less fertilizer input on average. While the hybrids provide a growth advantage, landowner profit is based on costs as well as production and involves rotation length and the potential for subsequent coppice stands. The hybrid clones may provide an opportunity to increase profitability of hardwood SRWC, but these other factors will need to be evaluated.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11056-024-10057-7>.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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