Title: Woody bioenergy crop selection can have large effects on water yield: A southeastern United States case study

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Abstract

Short-rotation woody crops in the southeastern United States will make a significant contribution to the growing renewable energy supply over the 21st century; however, there are few studies that investigate how species selection may affect water yield. Here we assessed the impact of species selection on annual and seasonal water budgets in unvegetated plots and late-rotation 14–15-year-old intensively managed loblolly pine (*Pinus taeda* L.) and sweetgum (*Liquidambar styraciflua* L.) stands in South Carolina USA. We found that while annual aboveground net primary productivity and bioenergy produced was similar between species, sweetgum transpiration was 53% higher than loblolly pine annually and 92% greater during the growing season. Canopy interception was 10.5% of annual precipitation and was not significantly different between the two species. Soil evaporation was less than 1.3% of annual precipitation and did not differ between species, but was 26% of precipitation in unvegetated plots. Annual water yield was 69% lower for sweetgum than loblolly pine, with water yield to precipitation ratios of 0.13 and 0.39 for sweetgum and loblolly pine, respectively. If planted at a large scale, the high transpiration and low water yield in sweetgum could result in declines in downstream water availability relative to loblolly pine by the end of the growing season when storage in groundwater, streams, and water supply reservoirs are typically at their lowest. Our results suggest that species selection is of critical importance when establishing forest plantations for woody bioenergy production due to potential impacts on downstream water yield.

Keywords: short-rotation woody crops, biomass, water balance, evapotranspiration, loblolly pine, sweetgum

1. Introduction

Renewable energy sources such as solar, wind, and bioenergy are projected to increase by 2.6% annually between now and 2040 [1]. The European Union (EU) 2020 Climate and Energy Package put into legislation in 2009 a target of 20% of EU energy from renewables by 2020. Biomass from forest and agricultural products will necessarily comprise a large share of the energy to achieve this goal [2]. However, the EU will need to import biomass from other nations due to a limited local supply and North America will be a potential source of forest and agricultural biomass to meet this demand [3]. Regardless of where biomass production occurs, increases in global demand will put additional pressure on forests and agricultural lands. For example, total potential biomass from forest and agricultural products in the United States for bioenergy production is predicted to increase nearly 250% between 2017 and 2040 [3]. This increase is driven primarily by increases in potential biomass from agricultural sources including crop residues, herbaceous crops (e.g., switchgrass, miscanthus, biomass sorghum, and energy cane), and short-rotation woody crops. While potential biomass available from forests (logging residues and whole tree biomass) is projected to remain relatively stable over the coming decades (approximately 86 million dry tons), potential biomass from short-rotation woody crops is predicted to increase from three to seven million dry tons from 2022 to 2040.

Forests in the southeastern United States have great promise for providing woody biomass for energy production, but additional demand placed on forest ecosystems could have negative impacts on other ecosystem services. Across the 13 southern states (Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia), there are 99 million ha of forest covering 46% of the total land area [4]. At the end of the 20th century, these southern forests accounted for 60% of the nation's timber products [5] and provided 31 billion kg of dry forest residue alone (not including purpose-grown woody bioenergy crops), or 55% of the total United States forest residue production [6]. Over 80% of forest biomass originates on privately owned forest land in the United States [3] and 87% of forested land in the southeastern United States is privately owned [4]; thus, private landowners in the region will be making individual management decisions to balance biomass production and profit with other forest ecosystem services.

While there is ample supply of woody biomass in the region, there has been growing concern about how increasing bioenergy production in the southeastern United States may impact the environmental resources [2, 7, 8]. Among the potential impacts, intensively managed woody crops may use more water than the land uses they replace depending on species selection [9]. Water is historically abundant in the Southeast, but climate change and increased frequency and severity of drought will limit water supply [10]. In addition, changes in forest land cover, species composition, and management will have an impact on water availability to humans and aquatic ecosystems [11-13]. From a water resource perspective, we will need to understand species-specific water use rates and impacts on water yield (i.e., the excess water that contributes to streamflow, groundwater recharge, or soil water storage) and downstream water availability [14].

Evapotranspiration is affected by the tree species that comprise a forest ecosystem [15, 16]. For example, growing season daily transpiration rates among southern Appalachian forest canopy species (adjusted for differences in tree size) can vary by more than four-fold, and co-occurring species can differ considerably in their responsiveness to climatic variation [15, 17, 18]. Species specific leaf habit and phenology (evergreen vs. deciduous) can impact the magnitude and seasonality of evapotranspiration [19, 20], as can functional rooting depth [21-

23], sapwood area [24], as well as xylem anatomy [15, 16] and related leaf water potential regulation strategy (i.e., iso- vs. anisohydric) [25]. Other components of evapotranspiration that can be influenced by species composition include soil evaporation and interception/evaporation of precipitation by the canopy and forest floor. Interception and evaporation can together be 10–15% of annual precipitation *P* [15, 26] and are affected by canopy closure and uniformity, bark characteristics, and leaf shape and inclination [27].

While information on relative productivity and water use among species exists, data describing the complete water budgets and energy production for managed mono-culture stands of different species commonly used as bioenergy crops under similar site conditions are lacking. King et al. [9] provided a thorough review of 371 water use studies and concluded that "the data needed to design water-efficient bioenergy cropping systems are currently not available" and that "a widespread network of research sites encompassing the major climatic zones and soils needs to be installed with an eye toward quantifying a site's water balance as a function of climate variation." Chiu and Wu [14] further suggested that in addition to climatic zones and soils, the choice of feedstock mix (i.e., species selection) is a factor that must be considered when assessing the impact of bioenergy production on water resources. There continues to be a need for field-based studies providing detailed knowledge of the ecophysiology and water relations of the major bioenergy crops [9].

Loblolly pine (*Pinus taeda* L.) and sweetgum (*Liquidambar styraciflua* L.) have potential as short-rotation woody bioenergy crops in the southeastern United States; however, very little is known about how species selection may affect water yield from forested catchments in the region. Forestry practitioners agree that loblolly pine (LP) is the primary candidate for bioenergy production and the benchmark from which to compare productivity of other potential woody crop species in the southeastern United States [28]. Sweetgum (SG) is currently considered the best hardwood option for most of the Southeastern region as it tolerates a range of site conditions [29, 30] and demonstrates fairly consistent production rates [28]. Previous studies suggest somewhat greater productivity for LP relative to SG [9, 31], although relative differences between species depend on site conditions and resource availability.

Differences in the anatomy and physiology between LP and SG may result in differences in water use. For example, LP has a tracheid xylem anatomy consisting of relatively smaller diameter water conduits and a tortuous flow-path while SG xylem has a diffuse-porous xylem anatomy with well-connected flow-paths and relatively larger vessels for transporting water [34]. SG and LP transpiration also differs in response to atmospheric conditions such as vapor pressure deficit and photosynthetically active radiation [35, 36]. A more conductive xylem anatomy associated with SG would suggest higher transpiration rates than LP during the growing season; however, the effects of these characteristics on transpiration and water yield have not been quantified in monoculture even-age stands (i.e., short-rotation woody bioenergy crops).

The objective of this study was to characterize and compare the annual and seasonal water budgets in relation to biomass and energy production for late rotation 14–15-year-old, intensively managed LP and SG stands in South Carolina USA. We hypothesized that 1) LP would use more water during the dormant season due to year-round transpiration and interception of this evergreen species, but that SG would use more water during the growing season due to differences in physiology, 2) the net effect of differences in seasonal water use will result in a negligible difference in annual water use and water yield, and 3) LP and SG will have similar water use efficiency (WUE: carbon gained per unit water consumed) and bioenergy WUE (WUE_b: energy produced per unit water consumed) due to similar annual water use rates and similar rates of productivity. In addition to LP and SG stands, we quantified the water budget of unvegetated bare (BA) plots to isolate the vegetation effects and to provide a basis of comparison for the 14-15 year-old stands relative to conditions at the time of planting. Our goal was to assess the overall potential impact of managed stands for bioenergy production on water yield, and how species selection may impact water availability on annual and seasonal time scales.

2. Methods

2.1 Site description

The US Department of Energy's Savannah River Site is a national environmental research park located near Aiken, SC, USA in the Carolina Sandhills ecoregion (Fig 1). The climate is humid continental with warm summers and mild winters [37]. Average annual temperature and precipitation for Aiken, SC between 1981 and 2010 was 17.5 °C and 1299 mm, respectively (www.dnr.sc.gov/climate/sco/ClimateData/8110Normals.php). Average minimum temperature in January is 0.4°C; average maximum temperature in July is 33.5°C. The Savannah River Site spans the Aiken plateau of the Sandhills physiographic region and the Pleistocene coastal terrace of the Upper Coastal Plain. Soils are predominately in the Blanton series (Loamy, siliceous, semiactive, thermic Grossarenic Paleudults) consisting of very deep, somewhat excessively drained to moderately well drained fine sands [38].

Our study utilized established forest plots from an existing short-rotation woody crop productivity project. The site, plant materials, and experimental design have been previously described in greater detail [39], and a number of previous publications describe stand responses to irrigation and fertilizer treatments [31] and disturbances [40], as well as general physiological

[41] and ecological processes [42]. Briefly, loblolly pine (*Pinus taeda* L.), sweetgum (*Liquidambar styraciflua* L.), American sycamore (*Platanus occidentalis* L.), and eastern cottonwood (*Populus deltoides* Bartr.) seedlings were planted in 0.2 ha plots (52.5 m × 42 m) at a 2.5 m × 3.0 m spacing in February 2000. We selected three replicate plots each of sweetgum (SG) and loblolly pine (LP) among fertilized plots in the original experiment (120 kg N ha^{-1} yr^{-1}). Resource amendment treatments (i.e., fertilization, irrigation, and herbicide) associated with the original productivity study ceased in 2010. We also masticated the vegetation in three other plots to create unvegetated bare plots (hereafter, BA) which received routine herbicide applications to prevent vegetation regrowth throughout the reporting period. A central subplot in each plot, 18 m × 22.5 m, was the focus of intensive measurements as described below.

2.2 Field measurements

Diameter at breast height, basal area, and sapwood area were measured in September 2015. Sapwood area was determined by extracting increment cores across a range of stem sizes for each species, and assuming the stem approximated a circle. LAI was measured indirectly using two optical plant canopy analyzers (LI-COR Inc.) in August of 2013, 2014, and 2015. One plant canopy analyzer was positioned in an open field (i.e., no canopy) adjacent to the forest plots while another plant canopy analyzer collected data every three meters along multiple transects within each plot to generate a single one-sided LAI value for each plot. Fine root mass was determined from five soil core profiles per plot using a 4.9 cm diam. push corer. Each core profile consisted of five different depths (0-25, 25-50, 50-75, 75-100, and 100-125 cm). Live fine root material was separated from soil and other organic matter via elutriation (Gillison's Variety Fabrication, Inc., Benzonia, MI, USA), sorted into different diameter categories (<0.5, 0.5-1.0, 1.0-2.0, >2.0 mm), and dried to a constant mass at 60 °C. The aboveground net primary productivity (ANPP) for LP and SG during our observation period was calculated using species- and site-specific allometric equations to determine annual changes in aboveground perennial biomass components [31]. The annual energy production (AEP) was calculated as described by King et al. [9] by multiplying ANPP by an assumed energy content of 16.73 MJ kg^{-1} for both LP and SG [43].

Precipitation (*P*, mm) was measured in each BA plot (Fig. 1) using tipping bucket rain gauges (TE525; Campbell Scientific, Inc.). *P* measured at a nearby weather station at the Savannah River Site from 1981–2010 was used as the basis of comparison to the long-term historical record. Daily potential evapotranspiration (PET) was estimated using the Priestly-Taylor method [44] with data collected at a nearby weather station. PET estimates were used to place the water budget component measurements into the context of water demand and to assess soil moisture limitation.

Canopy transpiration (E_t, mm) was estimated by measuring sap flow in the stem. Sap flow was measured on five trees in each plot using constant heat thermal dissipation (TD) sensors [45-47], constructed following Sun et al. [48]. Briefly, the sensors consisted of two probes, 2 cm long. The upper probe dissipated 0.2 W, whereas the lower probe remained unheated. The two probes were connected in series, in opposition, and the sensor output yielded a temperature difference that was then used to determine sap flux density [45]. Species-specific calibrations conducted in the lab and field accounted for differences in sapflow with sapwood depth and provided accurate measures of whole-tree water use [48, 49]. Two TD sensors per tree were placed at least 90° apart circumferentially. Sensors were insulated against temperature gradients and solar radiation using Styrofoam and reflective insulation. A voltage regulator and deep cycle marine batteries supplied 0.2 W to each heated probe. Sensors were queried every 60 s, and data recorded as 15-min means (CR1000 datalogger, AM1632 multiplexer, Campbell Scientific, Inc., North Logan, UT). Sap flow was estimated as the product of sap flux density (calculated from coefficients derived from species-specific calibrations as described above) and sapwood area. E_t was assumed to be negligible on the BA plots. Stand-level WUE for LP and SG was calculated by dividing ANPP by annual E_t. Similarly the WUE_b was computed by dividing AEP by annual E_t as described by King et al. [9].

Canopy interception (E_i, mm) was computed on a weekly basis by subtracting the difference between *P* and throughfall (TF, mm). Six TF collectors were randomly placed in each LP and SG plot to capture the spatial variability of TF under the forest canopy following Keim and Skaugset [50]. The installation was detailed in Vining [51] and is described briefly here. Each TF collector consisted of two 152.4 cm long, 3.8 cm diameter Polyvinyl Chloride (PVC) pipes each connected to 22.5 degree PVC angle fittings that were coupled to form a v-shape [52]. A 148 cm length of each pipe was cut axially to create a trough to collect the TF. The total overall horizontal length of two TF troughs of each collector was 274 cm. A t-fitting was placed between the angle fittings, and clear vinyl tubing connected the t-fitting to an 18.9 L plastic bottle. The TF volume collected in the bottle was converted to depth units by dividing by the horizontal surface area of the PVC troughs. E_i was assumed to be negligible on the BA plots.

Soil evaporation (E_s, mm) was estimated weekly using box lysimeters as described in Vining [51]. Briefly, the lysimeters were constructed of aluminum with internal dimensions of 60 cm wide, 80 cm long, and 50 cm deep. One lysimeter was installed in one of the three plots for each vegetation type (Fig. 1) such that the top was slightly above the ground level to ensure no surface water entered the lysimeter from the surrounding soil during intense rainfall events.

The soil excavated during installation was back-filled inside the lysimeter in layers to a density similar to the native soil and litter was replaced on the soil surface except in the bare plot, where soil was left bare. Soils were not sieved prior to back-filling and roots were left in to decompose. No live roots remained and the boxes were manually kept free of vegetation. Outflow from the lysimeter was collected in 50 L carboys (Nalgene, Inc.). Outflow volume was converted to depth units by dividing outflow by the surface area of the lysimeter. Volumetric water content in the lysimeter was measured using four soil-moisture sensors (EC-5, Decagon Devices Inc.), with two probes 30 cm and two probes 10 cm deep placed in parallel vertically 30 cm apart. Water balance on the lysimeters was determined weekly as the difference between TF and outflow while accounting for change in soil water storage measured with the soil moisture sensors.

Changes in soil water storage (ΔS, mm) in the upper 60 cm was estimated by measuring volumetric soil moisture content (θ, $mm^3\ mm^{-3}$) in each plot. Soil moisture content was recorded hourly using 12 cm long integrated temperature and time domain reflectometry probes (TDR, CS655, Campbell Scientific, Inc.) installed horizontally at 5, 10, 20, 35, and 60 cm depths. Soil texture and physical properties were within TDR manufacturer recommendations, thus the standard manufacturer's calibration equation relating θ to bulk dielectric permittivity was used. S was computed in depth units by summing the soil water stored in five layers defined by the depths of the soil moisture probes: 0–5 cm, 5–10 cm, 10–20 cm, 20–35 cm, and 35–60 cm. For a given layer, the θ was multiplied by the thickness of the layer to estimate S. The ΔS for a given time step was computed by taking the difference in S estimates between successive time periods.

Soil moisture release curves (relating θ to soil water tension) were quantified in the lab. Intact soil cores were collected at 5, 10, 20, 35, and 60 cm depths in each plot with a 5 cm diameter core sampler. Soils were transported to the lab and placed on a pressure plate apparatus

(1500F1, Soil Moisture Equipment Corp). Measurements were made in the 0 to 15 bar soil water tension range following equilibration at each tension step. Gravimetric water content was then measured for each soil water pressure. At the completion of these measurements, the samples were oven-dried at 105 °C for 24 h, and reweighed.

Water yield (Q, mm) was estimated by computing the water balance for the upper 60 cm soil in BA, SG, and LP plots:

$$Q = P - E_t - E_i - E_s \pm \Delta S$$

Where:

Q = water yield

E_t = canopy transpiration

E_i =canopy interception

E_s =soil evaporation

ΔS = change in soil water storage

Surface runoff was assumed to be negligible due to the low topographic gradients, intact forest floor, and the high infiltration capacity of the sandy soils. Stemflow was assumed to be negligible as other studies have found it to be a small portion of the water balance in LP [53, 54] and hardwood stands that included a large SG component [55], and it is highly variable in a forest stand making it difficult to measure within an acceptable level of accuracy [56]. The water balance, and all component fluxes, were measured and computed approximately at the weekly scale over a complete April–March water year beginning in April 2014 and ending in March 2015. The water year was used to minimize the effect of seasonal changes in soil water storage on the annual water balance [26]. The growing season was assumed to begin at the start of the water year on April 1 (DOY 90) and end November 30 (DOY 334) to approximate the growing season defined by the 50% probability frost-free period (>0°C) from March 26 – November 9 for Aiken, SC [57].

2.3 Data Analysis

Annual and seasonal total water balance components, except for E_s, were computed for each plot and mean values across the three plots for each vegetation type were compared with one-way analysis of variance (ANOVA) using JMP v12.2 (SAS Institute, Inc., Cary, NC, USA) assuming our samples were taken from normally-distributed populations of each water balance component for each vegetation type. Comparisons among vegetation treatments were conducted using two-tailed *t*-tests evaluated at $\alpha = 0.10$. E_s was measured in one replicate plot per treatment and assumed to represent E_s in all plots of that treatment. ET ($E_i + E_s + E_t$) for BA plots was not compared to mean values across plots LP and SG because E_s was the only component of ET in the BA plots and there was a single BA plot where E_s was measured.

3. Results

3.1 Vegetation characteristics

The SG and LP plots were similar in mean stem diameter, basal area, sapwood area ANPP, and AEP (differences between species were less than 14%), but SG LAI was more than two-times greater than LP during the study period (Table 1). The differences in LAI were largely driven by an ice storm during the winter of 2014 that damaged stems and branches of trees in the evergreen LP plots, but did not impact stems and branches in the deciduous SG plots, a response similar to what was observed after a previous ice storm impacted this site [40]. As a result, stand-level LAI estimates in the LP plots decreased from a mean of 4.57 m^2 m^{-2} in August, 2013, to a mean of 2.71 m^2 m^{-2} in August, 2014, while LAI of SG was virtually the same (5.54 m^2 m^{-2} vs. 5.55 m^2 m^{-2} for 2013 and 2014, respectively). By 2015, LP LAI partially recovered, increasing to 3.36 m^2 m^{-2}. Although some branch breakage occurred in LP trees selected for E_t measurements, the reduction in their leaf area was not consistent with the reduction in stand LAI.

3.2 Annual water budget

Differences in the annual water budget among treatments were driven primarily by differences in E_t and E_s (Table 2). The change in storage (ΔS) in the upper 60 cm soil over the water year was less than 10 mm (<1.0% of annual P) for all vegetation types. E_t was the largest component flux of the annual water budget in vegetated plots, representing 76% and 50% of annual P for SG and LP, respectively. E_t for SG was 53% greater than LP (872 mm vs. 571 mm, $p = 0.069$). Annual E_i was similar among LP and SG plots ($p = 0.549$), averaging 121 mm and 10.5% of P. Soil evaporative flux (E_s) was low for both SG and LP (<14.9 mm, <1.5% of annual P), but was 26% of annual P for BA (304 mm). Q computed by water balance was lowest in SG (139 mm, 13% of annual P), followed by LP (446 mm, 39% of annual P), and BA (830 mm, 73% of annual P). Q for SG was 69% less than LP ($p = 0.026$) and 83% less than BA ($p < 0.001$).

3.3 Precipitation

Annual and seasonal P was within 8% of the historical record, but larger differences were observed in some months (Fig. 2). Annual P was 1143 mm, only 3.4% less than the 1981–2010 mean (Fig 2, Table 2). More than half of the annual P (65%) fell during the growing season. Growing season P was only 1.1% less than the long-term mean, but monthly deficits of 42%, 34%, and 44% were observed in June, July, and October, respectively. Growing season surpluses of 57% and 60% occurred in April and May, respectively. Dormant season *P* (35% of annual *P*) was 7.9% less than the long-term mean, with largest monthly deficits of 32% and 38% occurring in January, and March, respectively.

3.4 Canopy Interception (E_i)

LP and SG canopy interception did not differ significantly ($p > 0.433$) at annual and seasonal scales due to the high variability of E_i within and among plots (Fig. 3, Table 2). On average, total annual E_i was 10.5% of *P* while growing season and dormant season E_i was 13.2% and 5.6%, respectively. There was considerable variability in E_i estimates among TF collectors for a given species and plot (Fig. A.1). In some cases, TF exceeded *P* for a given week, resulting in negative values for E_i. For some TF collectors, E_i was consistently negative, suggesting foliage and branch related "funneling" effect of the canopy above the collectors that concentrated TF. Standard errors for mean E_i across LP and SG plots were large relative to the mean values (Table 2), highlighting the high variability in E_i across plots for each vegetation type and contributing to our inability to detect significant differences between vegetation types. Mean cumulative E_i for LP and SG were within ~5 mm throughout the growing season (black line, Fig. 3), supporting the notion that growing season E_i was similar for both species. However, the difference in cumulative E_i between SG and PI increased from ~5 mm at the end of the growing season to 22 mm by the end of the dormant season, suggesting lower SG E_i in the dormant season.

3.5 Soil Evaporation (E_s)

Soil evaporation was very low in the LP and SG plots, but a relatively large flux for the BA plots (Table 2, Fig. 4). Annual E_s was 14.9 mm (1.3% of total *P*) for SG and -4.9 mm (-0.04% of total *P*) for LP, while E_s was 304 mm (26% of total *P*) for unvegetated BA plots. Weekly E_s was frequently negative for LP and SG (decreases in cumulative E_s in Fig. 4) possibly due to the timing of storm events relative to the time at which the outflow volume was measured for a given week. For example, if a storm occurred a few hours before the lysimeter outflow volume was measured, the soil in the lysimeter may not have drained to equilibrium by the time the outflow was measured. As a result, more outflow volume would be attributed to the subsequent week, resulting in an artificially low (perhaps even negative) E_s estimate for the subsequent week. However, week-to-week variations in lysimeter outflow should compensate over an entire year, resulting in a valid annual estimate of E_s. LP E_s over the water year was negative, suggesting that our TF estimates used to quantify TF over the area of the plots were not necessarily representative of the inputs for the lysimeter (essentially a 0.5 m^2 point). Regardless, E_s for both SG and LP was likely small relative to Et and uncertainties in Es measurement likely did not have a significant effect on the overall results. Unlike the LP and SG E_s, BA E_s represented a large proportion of the water balance. BA E_s over the water year was 304 mm (26% of total *P*). Growing season E_s from the BA plot was 274 mm (37.8% of growing season *P*) while dormant season E_s was 30.0 mm (7.9% of dormant season *P*). The mean daily E_s during the growing season was 1.13 mm d^{-1}, 4.6 times the dormant season E_s (0.24 mm d^{-1}).

3.6 Soil Moisture Content (θ)

Mean annual soil moisture content did not differ significantly among treatments at any of the measurement depths, but was lower in SG compared to BA in the growing season (Fig. 5).

Mean annual θ across all depths and treatments was 0.071 $mm^3\ mm^{-3}$ (treatment effect $p >$ 0.172). Growing season mean θ was 0.076, 0.050, 0.067 $mm^3\ mm^{-3}$ for BA, SG, and LP, respectively; only the difference between SG and BA was significant ($p = 0.0406$). Dormant season mean θ was similar among treatments at 0.084 $mm^3\ mm^{-3}$ (treatment effect $p > 0.4568$). While we did not detect significant differences in mean annual or seasonal θ between SG and LP, SG θ was consistently lower than LP at all depths in the growing season during extended periods without significant rainfall, and was consistently below the plant wilting point (Fig. 5). θ at these low levels occurred much less frequently in BA and LP at depths greater than 5 cm. The differences in θ between SG and LP suggest that growing season E_t was higher for SG than LP. The large number of days when θ was less than the plant wilting point in all soil depths <60 cm suggests that SG (and to a lesser extent LP) had access to soil moisture at depths below 60 cm.

3.7 Transpiration (E_t) and Water Use Efficiency (WUE)

Transpiration was the largest single component flux of the annual water budget for LP and SG, and was much higher for SG than LP (Table 2, Fig. 6). Annual E_t was 872 mm (76% of total *P*) and 571 mm (50% of total *P*) for SG and LP, respectively, with marked differences in seasonal E_t. E_t for the unvegetated BA plots was negligible by definition. Growing season E_t for SG (866 mm) was higher than LP (452 mm) ($p = 0.023$), representing 112% and 59% of growing season *P* for SG and LP, respectively. Mean growing season E_t rates were nearly two times greater and were more variable for SG (3.57 +/- 1.67 std dev $mm\ d^{-1}$) than for LP (1.83 +/- 0.76 std dev $mm\ d^{-1}$), and were highest in May and June for both species (Figs. 6 and 7). LP E_t during the dormant season (119 mm, 32% of dormant season *P*) was greater than SG E_t (6.1 mm, 1.6% of dormant season *P*). Differences in WUE were not significant ($p = 0.2583$) despite the large differences in E_t (Table 2); WUE for LP was 18.66±2.29 kg mm^{-1} H_2O and WUE for SG was 15.12±1.41 kg mm^{-1} H_2O. Likewise, WUE_b was similar in LP (31.22 ± 3.83 MJ mm^{-1} H_2O) and SG (25.30 ± 2.36 MJ mm^{-1} H_2O; $p = 0.2583$).

SG transpiration rates approached PET for much of the growing season until soil water became limiting, while LP rates were about one third to one-half of the potential (Fig. 7). E_t for SG was near PET in the early growing season until early June (mean 84% of PET April 1 – June 8) when soil moisture became limiting (Fig. 7). E_t for LP during the same period was 41% of PET. After June 8 through September 8, θ in SG was below the plant wilting point (soil water tension greater than 15 bar) most of the time at depths below 35 cm and frequently at depths above 35 cm (Fig. 5), reducing *S* and limiting E_t for SG relative to PET (mean 61% of PET). During the same period E_t for LP decreased to 30% of PET on average, consistent with episodic declines in θ below the plant wilting point. Storms in mid-September briefly increased θ and *S* and suppressed PET until early October when PET and E_t increased and θ decreased below the plant wilting point at most depths for both LP and SG. Mean E_t /PET from October 8 – November 25 was 0.95 and 0.40 for SG and LP, respectively. During the dormant season (December 1 – March 31), E_t for LP was 47% of PET on average. *S* in SG was less than LP at the start of the dormant season, but *S* for both species was similar by late January and *S* was higher for SG than LP by the end of the dormant season (March 31).

3.8 Water Yield

Annual water yield (*Q*), was 830 mm (73% of total *P*) for BA, 139 mm (13% of total *P*) for SG, and 446 mm (39% of total *P*) for LP plots (Table 2, Fig. 8). All treatments differed in their growing season *Q* ($p < 0.015$). While SG and BA *Q* did not differ in the dormant season, LP dormant season Q differed from both SG and BA ($p < 0.060$). Growing season Q for SG was -234 mm suggesting that soil moisture used for E_t was sourced at depths below the 60 cm depth on which the water balance was computed. Growing season Q was 179 mm (23% of growing season P) for LP and 456 mm (62% of growing season P) for BA. Dormant season Q for SG and BA were similar ($p = 0.460$), averaging 374 mm (93% of dormant season P). Q for LP was lower than SG and BA during the dormant season ($p < 0.059$), averaging 267 mm (66% of dormant season P).

4. Discussion

We characterized and compared the complete water budgets for late rotation 14 – 15-year-old, intensively managed LP, SG, and unvegetated BA plots in South Carolina USA. We hypothesized that: 1) LP would use more water during the dormant season due to year-round transpiration and interception of this coniferous species, but that SG would use more water during the growing season due to differences in ecophysiology; and, that 2) the net effect of these differences in seasonal water use would result in a negligible difference in water available for annual Q. Our results support our first hypothesis; E_t for LP was greater than SG in the dormant season (SG dormant season E_t ~0 mm, LP dormant season E_t =119 mm), but SG E_t was 92% greater than LP over the growing season. While we detected differences in E_t, SG E_i was not different from that of LP. However, our second hypothesis that Q was comparable at the annual scale was not supported. Differences in Q were driven by large differences in E_t; we did not detect significant differences in E_i and E_s between the species. Annual E_t and Q were 53% higher and 69% lower, respectively, for SG than LP. In BA plots, E_s was the largest water loss to the atmosphere (26% of annual P), but this loss was small compared to E_t of LP and SG resulting in higher Q (73% of annual P) than in the vegetated plots.

Our results show key differences in water use strategies for LP and SG. E_t for SG was near PET when soil moisture was available, but declined significantly under dry conditions. In contrast, LP was more conservative in water use; E_t for LP was lower than SG and PET but remained relatively stable throughout the growing season. It appears that the differences in E_t between LP and SG are directly related to structural and physiological differences between the two species. Despite the comparable ANPP among SG and LP and the higher E_t of SG, WUE and WUE_b did not differ among species. In addition to physiological differences, forest structure (e.g., leaf area, root density and depth, stem density, basal area) influences tree water use. In particular, leaf area is positively correlated with E_t [58, 59].

While basal area and mean sapwood area were similar for our two measured species (Table 1), the higher stand-level growing season LAI for SG (5.5 m^2 m^{-2}) than LP (2.7 m^2 m^{-2}) could partly explain the greater E_t for SG. However, the stand-level estimates of LAI do reflect the LAI of the trees instrumented to measure E_t. Much of the reduction in LAI of LP stands following the 2014 ice storm was due to canopy breakage of a few individuals. Although some branch breakage occurred in our measurement trees, the reduction in their leaf area was less than the reduction in stand LAI. Growing season LAI for the LP measurement trees during the 2014–2015 water year was likely closer to that measured in the 2013–2014 water year (4.57 m^2 m^{-2}) as shown in Table 1. Under this assumption, LP LAI was 18% lower than SG LAI during the measurement period. Additional E_t measurements made in partial water years 2013–2014 and 2015–2016 support the notion that LAI of the LP measurement trees was less affected by the ice storm than the stand-level LAI estimates would suggest, revealing similar differences in E_t between SG and LP to the 2014–2015 water year (Fig. A.2).

In addition to leaf area, fine root mass (<2 mm diameter) in the upper 50 cm of soil in the SG plots was nearly twice that of the LP plots (Fig. A-3), explaining the lower soil moisture in the upper 60 cm in SG compared to LP (Fig. 5) and partly contributing to the higher E_t. Growing season Q was negative for SG suggesting that SG roots accessed deeper soil moisture reserves than the 60 cm soil depth over which we computed the water balance to support the greater SG E_t rates. Meanwhile, growing season Q was positive for LP suggesting that either soil moisture in the upper 60 cm of soil was generally sufficient to support the lower LP E_t rates over the study period, or LP roots did not provide access to soil moisture deeper in the soil profile. SG are known to develop deep taproots with numerous lateral roots [32] while LP develop tap roots in early development that stop growing in favor of lateral roots [33], although some studies have shown that LP can also develop tap roots reaching 2–4 m in depth [60-62]. The greater E_t of SG than LP in this study could suggest that SG had deeper roots than LP if soil moisture in the upper 60 cm of soil was limiting for both species, however it was beyond the scope of this study to quantify differences in root depths. Others have found similar differences between E_t for SG and LP [35, 36, 63, 64] but there are few published data comparing the two species in planted mono-cultures of similar aged stands with similar stocking density and on similar site conditions. The few direct comparisons between SG and LP E_t are based on controlled chamber experiments. Like the present study, prior work suggested greater E_t for SG than for LP. For example, Levy and Sonenshine [36] conducted a controlled environment growth chamber study and found that SG E_t was up to eight-times greater than LP, depending on vapor pressure deficit. Similarly, Pataki et al. [35] conducted a closed chamber experiment and found that maximum daily mean E_t per unit leaf area was greater for SG (1.62 mmol m^{-2} s^{-1}) than for LP (1.09 mmol m^{-2} s^{-1}). In addition to closed chamber studies, our estimates of E_t for LP and SG stands are reasonable compared to other field studies in the literature. For example, Wullschleger and Norby [63] reported a mean growing season E_t rate for SG of 2.8 mm d^{-1} for a 12 year old stand with LAI of 6.3 m^2 m^{-2} in eastern Tennessee. This result is consistent with our mean growing season E_t rate of 3.57 mm d^{-1} considering the longer growing season and warmer air temperatures associated with our site. Domec et al. [64] estimated annual LP E_t of 644–777 mm yr^{-1} over three years in a 17 year-old stand of higher basal area (56.2 m^2 ha^{-1}) and LAI (3.0–4.2 m^2 m^{-2}) in a ditched and drained converted wetland plantation in the Coastal Plain of eastern North Carolina. Our LP E_t estimate (571 mm yr^{-1}) may be lower in part due to lower basal area, but also likely due to differences in soil moisture. Domec et al. [64] reported water table depths generally within 100 cm of the soil surface and soil moisture content at 20 cm was generally more than twice that of our study. In addition to the presence of a shallower water table, differences in soil texture could affect soil moisture and E_t. For example, soil textures in the Domec et al. [64] study were sandy loam (field capacity 0.56 m^3 m^{-3}) whereas our site consisted of fine sands (field capacity 0.08 m^3 m^{-3}). LP grown on sandy soils have lower E_t than LP grown on loamy soils, and LP E_t on sandy soils is more limited at higher (i.e., less negative) soil water potential [65]. It is possible that the large differences in E_t and Q between SG and LP we found in well-drained sandy-textured soils would not be as large at other sites with finer-textured soils and/or soils with lower drainage class because LP E_t would likely be greater than our results suggest. Despite the similarities in WUE between SG and LP, we would expect, based on our measurements and calculations, that E_t for SG would be consistently greater than LP at a given site with all other factors equal. However, it is important to note that our observations occurred during only a brief period of the harvest rotation. Holistic comparisons of water use and other environmental sustainability criteria ultimately require consideration of the entire stand history, from planting to harvesting.

Overall, the results of this study suggest that species selection can have a large influence on water yield serving downstream uses and should be a primary silvicultural consideration when assessing the sustainability of potential woody bioenergy crops. Differences in E_t between SG and LP had profound effects on Q, with potential implications for water availability for other uses. On an annual scale, Q from LP (39% of annual P) was 220% greater than Q from SG (13% of annual P) while Q from BA plots was greater than the vegetated plots (73% of total P). Q was negative in SG during the growing season, suggesting that soil moisture used for E_t was sourced at depths below the 60 cm depth on which the water balance was computed. The high E_t and low Q in SG could result in declines in downstream water availability relative to LP by the end of the growing season when storage in groundwater, streams, and water supply reservoirs are typically at their lowest. This effect would be more pronounced in dry years when there is less surplus P to generate Q after accounting for ET [66].

Clearly there are tradeoffs between managing for biomass and water, and species selection could be a useful tool to balance water and energy needs in woody bioenergy production. Our results suggest that SG uses 53% more water than LP to produce an equivalent amount of aboveground biomass and bioenergy. While the relative difference in E_t and Q between SG and LP may vary in different soil conditions across the southeastern United States, LP will likely remain a better choice than SG for most sites where water yield may be a concern. Given the equivalent ANPP for the LP and SG stands and the lower E_t for LP, it would be advantageous to plant LP on sites with sandy, well-drained soils to maximize Q production without a negative impact on biomass. On sites with finer-textured soils and/or lower drainage class the differences in E_t and Q may not be as large as what our study suggests; however, LP Q would still likely be higher than SG Q due to inherent differences in apparent rooting depth and water use efficiency.

5. Conclusions

In this study we characterized and compared the partitioning of P into E_i, E_t, E_s, S, and Q in relation to biomass and energy production for typical 14–15 year old, intensively managed LP and SG stands in South Carolina USA over the course of an April–March water year. We found that SG used 53% more water than LP to produce an equivalent amount of biomass and bioenergy on an annual basis. As a result, Q was much less for SG than LP over the water year. The differences in E_t were likely related to fundamental differences in water use efficiency between these species. These results suggest that species selection is of critical importance when establishing forest plantations for woody bioenergy production due to the potential impact on downstream water availability although other site factors may temper differences in water use among species. There is a lack of productivity and water use data across species under similar site conditions. Given the large differences in water use efficiency for bioenergy production observed in this study, similar efforts should be conducted to improve estimates of water use efficiency for other species used as bioenergy crops.

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Appendix A: Supplemental information

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Table 1 Mean (standard error) vegetation characteristics across plots for sweetgum (SG) and loblolly pine (LP).

Table 2 Mean (standard error) water balance components for the 2014–2015 April–March water year across plots for each vegetation type. Within rows, vegetation types not sharing the same letters denote significant differences among vegetation types for that water balance component.

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Fig. 1 Savannah River Site location in South Carolina, USA (inset) and vegetative plot locations. The first two characters of plot names identify the vegetation type (BA=bare, SG=sweetgum, LP=loblolly pine); the last character identifies the replicate plot number for that vegetation type.

Fig. 2 Monthly *P* during the 2014–2015 water year measured at the study site (circles) and 1981–2010 long-term monthly mean *P* (bars +/- SE).

Fig. 3 Mean cumulative E_i for SG (red), LP (blue), and Mean cumulative E_i LP – E_i SG (black circles) calculated from throughfall measurements recorded on approximately weekly intervals. Also shown is the total P (grey bars) for each week.

Fig. 4 Cumulative E_s for SG (red), LP (blue), and BA (black) based on lysimeter measurements on approximately weekly intervals.

Fig. 5 Mean daily soil moisture content (θ) across plots for BA (black line), SG (red line), and LP (blue line) at the 5 cm (A), 10 cm (B), 20 cm (C), 35 cm (D), and 60 cm (E) depths. Also shown are the mean moisture content for each depth at tensions of 0.333 bar (i.e., field capacity, green dashed line) and 15 bar (i.e., plant wilting point, brown dash-dot line). The soil moisture sensor published minimum θ is 0.05 $mm^3\ mm^{-3}$, thus values below this threshold may not be representative of actual θ.

Fig. 6 Mean cumulative (lines) and daily (bars) E_t for SG (red) and LP (blue).

Fig. 7 Mean daily E_t for SG (red line), LP (blue line), and PET (black circles) (A), mean daily soil moisture storage (*S*) in the upper 60 cm of soil for SG (red line) and LP (blue line) (B), and mean daily *P* (C). Areas shaded in grey indicate periods when the soil water content at the 35 cm depth in SG was less than the plant wilting point (greater than 15 bar tension).

Fig. 8 Mean cumulative *Q* for SG (red), LP (blue), and BA (black) based on weekly computed water balance.