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Evapotranspiration Partitioning of *Eucalyptus benthamii* and *Pinus taeda* During Early Stand Development

Seth E. Younger[1,2,3] · **C. Rhett Jackson**[1] · **Mackenzie J. Dix**[1,2] · **Peter V. Caldwell**[4] · **Doug P. Aubrey**[1,2]

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Abstract

Increasing demand for bioenergy from intensively managed woody crops raises concerns of increased evapotranspiration and potential decreases in water yield. *Pinus taeda* (loblolly pine) is currently the most cultivated species in the southeastern USA, the country's wood basket. However, *Eucalyptus* species could achieve greater productivity but with unknown ramifications for water budgets. To address the knowledge gap, we determined annual water budgets of loblolly pine and *Eucalyptus benthamii* (eucalypt) from growing years 3 through 5 in a replicated ($n = 3$) two-factor design comparing species and groundwater depth. Paired plots were established across a depth-to-groundwater gradient from shallow (~ 2 m) to deep (~ 8 m). Hydrologic budgets were constructed by measuring precipitation, interception, soil evaporation, and transpiration. Eucalypt evapotranspiration and above-ground biomass production for growing years 3 through 5 were on average 25 and 14% greater than pine, respectively; however, evapotranspiration did not differ across groundwater depths. At the end of growing year 5, eucalypt had higher transpiration and evapotranspiration per unit area than pine. Soil evaporation was substantial in young plantations (nearly 500 mm) in growing year 3 but declined as the canopy closed. Partitioning of evapotranspiration components in developing bioenergy plantations was dynamic due to canopy development driven decreases in soil evaporation and increases in transpiration and interception; total evapotranspiration was less variable from year to year. Water use efficiency (WUE, kg biomass/m^3 H_2O) per unit evapotranspiration was similar between species, but WUE per unit transpiration was higher in pine. Considering total evapotranspiration in young plantations can affect WUE interpretations.

Keywords Transpiration · Sap flow · Evaporation · Evapotranspiration · Biomass · Bioenergy · Water use efficiency

Introduction

The southeast USA is a leader in forest production and has the potential to be a significant producer of intensively managed biofuel feedstocks [1, 2]. The US Dept. of Energy has set a national target of 2022 for production of 16 billion gallons of cellulosic ethanol from bioenergy feedstocks, with 55–68% expected to come from southeastern forests [2, 3]. Thus, demand for forest products from short rotation woody crops (8–12 years) is expected to increase in the southeast USA, but there is little knowledge about the effects of accelerated stand development on water resources in the region where evapotranspiration (ET) is the largest component of precipitation (P) fate [4]. Loblolly pine is the dominant plantation species in the region making it an ideal benchmark for comparison [5, 6]. Pine production is supported by substantial physical, intellectual, and business infrastructures developed over more than 50 years [7]. There is interest in achieving higher productivity with species other than pine, such as *Eucalyptus* species (hereafter, eucalypt) that exhibit high productivity across much of the globe and in the southeast [8]; however, increased productivity may come at the expense of increased transpiration (Et) [9-12].

Realizing national woody feedstock targets while also sustainably managing water resources requires a better

✉ Seth E. Younger
seth.e.younger@gmail.com

[1] Warnell School of Forestry and Natural Resources, University of Georgia, 180 E Green Street, Athens, GA 30602-2152, USA

[2] University of Georgia's Savannah River Ecology Lab, PO Drawer E, Aiken, SC 29802, USA

[3] The Jones Center at Ichauway, 3988 Jones Center Drive, Newton, GA 39870, USA

[4] Southern Research Station, Center for Integrated Forest Science, USDA Forest Service, 3160 Coweeta Lab Road, Otto, NC 28734, USA

understanding of ET in intensively managed woody bioenergy plantations. Calculated as the sum of canopy Et, canopy interception (Ei), and evaporation from the soil surface or leaf litter (Es), ET typically accounts for 65% of P in southeastern US forests [4]. Intensive management increases leaf area more rapidly and has the potential to increase Et [13] and decrease streamflow. However, accelerated canopy development increases shade and leaf litter, potentially resulting in less Es. ET studies rarely measure Es under canopies [14] and instead assume it is negligible, estimate it with simple techniques, or use values from other studies [9, 14]. However, observations from lysimeters without canopy leaf or soil litter cover indicate that annual Es can be more than 25% of P [15]. High Es is possible in the first 1–5 years of plantations, when bare soil is common. In addition to Es, there is even less knowledge regarding young plantation ET [3]. To better understand ET of candidate bioenergy crops, it is valuable to estimate the Et and Es components of ET as directly as possible.

Tree Et is limited by soil water availability, which can vary across the landscape, and different woody crops may exhibit different capacities to exploit some water sources. For example, landscape position covaries with groundwater depth and soil water availability [16] meaning plantation placement can affect water availability and use [17, 18] and productivity [19]. Enhanced Et by eucalypt is a particular concern on the southeastern Coastal Plain where shallow groundwater is common and potentially accessible to deep rooting eucalypt [17, 18, 20-22]. The mean of reported maximal rooting depths for the eucalypt in southern USA is 15 m, while the mean of maximal rooting depths of pine (*P. taeda* and *P. elliottii*) is 3 m [20]. However, argillic horizons, which are acidic and dense, may act as a barrier to deep root production for many plant species including eucalypt [23]. Argillic horizons are a defining characteristic of the Ultisol soil order that dominates the timber-growing regions of the southeastern USA. The interaction of these factors affecting tree growth and water budgets makes comparative water budget studies particularly valuable.

Forest managers and policy-makers need species-specific ET data to inform best management practices and species selection [24], and studies need to provide information on the tradeoff between forest productivity and ET. Comparative hydrologic budgets from paired plots are useful to inform the potential impacts of bioenergy crop development and should quantify both water use and productivity to quantify stand water use efficiency (WUE), which accounts for the dry biomass produced per unit water [25]. WUE is commonly calculated as the biomass produced per unit overstory ET neglecting soil evaporation [25]. Using total ET in WUE calculations could have potentially important implications on species selection decisions in sparse canopy conditions where soil evaporation is a substantial portion of ET [15].

We know that species selection for short-rotation woody crops could have potentially significant impacts on freshwater availability in the southeast USA [9, 15]. However, few empirical data are available to assess trade-offs between productivity and ET that could inform management decisions [9]. Quantifying hydrologic budgets between native pine and non-native eucalypts is particularly important because (1) the forestry community has long had an interest in growing highly productive eucalypts [26], (2) a petition to the USDA Animal and Plant Health Inspection Service sought a determination of nonregulated status for freeze tolerant highly productive eucalypts (*Federal Register* vol 78, no 39, pg 13,309–13,312), and (3) ongoing eucalypt selection and genetic work to develop cold tolerance [27]. Freeze-tolerant eucalypts could accelerate and expand eucalypt planting in the southeast USA.

Here we developed comparative plot-level root-zone water budgets for a eucalypt species (*Eucalyptus benthamii*) and loblolly pine to assess differences in ET, its components, and WUE under similar site conditions and along a gradient of depth to groundwater. We established six sets of paired plots varying in landscape position and depth to groundwater (2–8 m deep) in which we measured or estimated all components of the water balance for growing years 3 through 5, including P, throughfall (Tf), Et, and Es. Canopy Ei was determined as the difference between P and Tf. Hydrologic budgets were constructed and used to estimate the water lost as recharge to groundwater (Rq). Rq is the residual of the rest of the water budget. The plots were placed on planar slopes, and interflow travel distances on these plots are only a few meters [28–31], so net imports or exports by shallow lateral flow over the Bt horizon were neglected. This root zone water budget was then used to evaluate potential impacts of the two species on water resources. The objectives of this study were to (1) develop hydrologic budgets in paired plots of 3–5-year-old pine and eucalypt trees to quantify differences in water budget components between the two species (i.e., Ei, Es, and Et) and (2) compare hydrologic budgets across plots varying in depth to groundwater to determine if groundwater depth (shallow versus deep) affects Et or ET overall. This work was guided by three hypotheses: (1) Et in eucalypt would exceed that of pine due to faster growth rates, (2) young plantations of the two species would differ in soil Es due to differences in canopy development, and (3) ET would be greater in shallow groundwater plots due to greater soil water availability and potential access to groundwater.

Methods

Study Site

The study was conducted within the US Department of Energy's Savannah River Site (SRS), a national environmental research park located near New Ellenton, SC. SRS spans the Aiken Plateau of the Sandhills physiographic region and the Pleistocene Coastal Terrace of the Upper Coastal Plain. The study plots are in the upper Fourmile Branch watershed (33.2647, – 81.6172) where a large-scale (150 ha) study has been ongoing since 2012 to assess the effects of intensively managed pine on water quality [32, 33] (Fig. 1). Groundwater observations collected between 2006 and 2012 from 26 piezometers uniformly distributed in the upper Fourmile watershed were kriged to generate a map of mean annual depth to groundwater. The groundwater map builds upon groundwater maps developed by the SRS [34, 35]. The groundwater depth map was utilized to identify areas of deeper and shallower groundwater as defined below.

The study site features gently rolling slopes and a hot, humid, temperate climate. Annual rainfall averages 1263 mm, and average annual ET in rural, mostly forested watersheds, in the region runs from 650 to 950 mm [4]. Average annual temperature is 17.3 °C, with summer temperature averaging 26.1 °C and winter temperature averaging 8.2 °C [36]. First order watershed relief is around 30 m, and slopes on the plots range from 0 to 20%, with slopes in the plantation areas usually less than 10%. Groundwater is near the surface at the toe slopes, and depth to groundwater increases with surface elevation.

The soils, mapped as Dothan and Fuquay series in the United States Department of Agriculture (USDA) soil classification system [37], were developed on unconsolidated fluvial and marine sediments, which comprise the surficial aquifer. All profiles have sandy A and E horizons of variable thickness that overlie clay-rich subsurface sandy clay loam Bt horizons that start at about 50 cm and are 2 to 3 m thick. Surficial A horizons are sandy (80–90% sand) with granular structure [37] and vary from little to no organic matter accumulation to significant organic matter in isolated discontinuous zones. E horizons are typically sandy to sandy loams and range from 10 to 60 cm in thickness and commonly found from 10 to 25 cm. Transitional EB horizons consist of sandy loam to sandy clay loam with hues ranging from 10YR to 7.5Y and typical depths of 25–45 cm. Bt horizons are found in all soil profiles at variable depths and are sandy clay to clay in texture with clay contents of 35% or more [38].

The experimental design was a replicated ($n=3$), two-factor design consisting of species (eucalypt and pine) and groundwater depth (shallow and deep). Six plot pairs (6 eucalypt and 6 pine) were established in two landscape positions, deep groundwater and shallow groundwater. Three pairs were in upper slope positions (plots 4–6) with deep groundwater (approximately 8 m deep) and three in toeslope positions (plots 1–3) with shallow groundwater (approximately 2 m deep) (Fig. 1). Trees were planted at a density of 1346 trees/hectare, and each plot was 0.125 ha in area with 168 trees in 12 rows of 14 trees with each tree occupying an average of 7.44 m^2. Measurements were focused on the 48 central trees in each plot which were marked with permanent tags. The site was ripped to 45-cm depth prior to planting, and seedlings were planted in the trenches. Pines were planted in March 2013, and the eucalypts were planted in October 2013. Silvicultural treatments consisted of annual fertilizer (averaging 110 kg N ha^{-1} $year^{-1}$) and herbicide

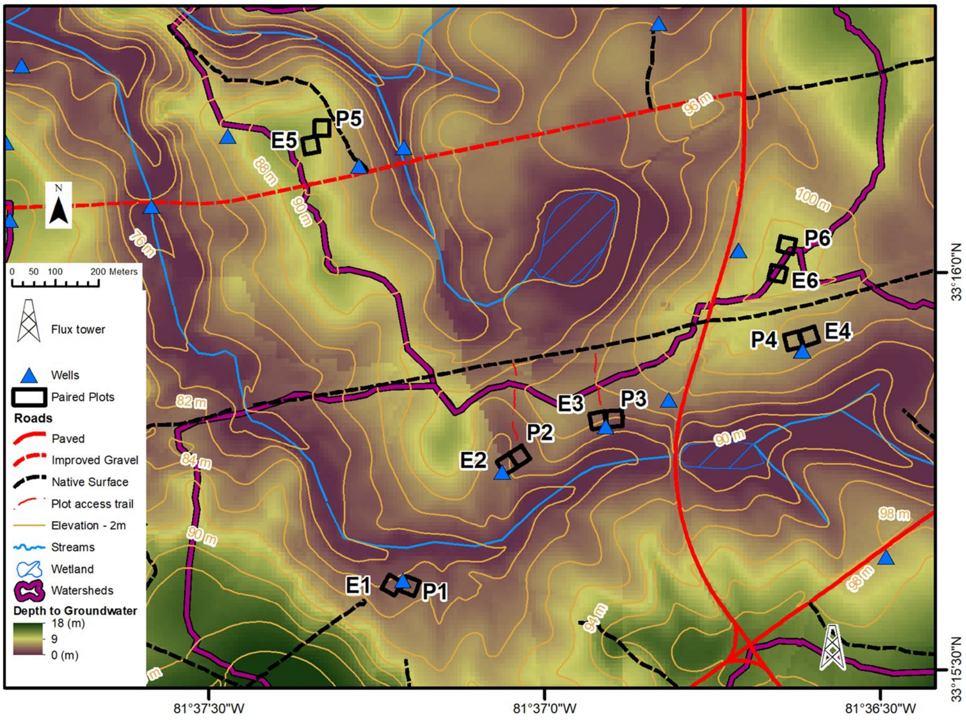

Fig. 1 Map of the study area showing watershed boundaries, streams, wetlands, kriged depth to groundwater, elevation contours, paired plots, and groundwater monitoring wells

for both species as described in detail in Ferreira, Rau, and Aubrey [39]. Pines were treated with fipronil injected at their bases to control a Nantucket pine tip moth (*Rhyacionia frustrana*) infestation at the end of the first growing season, after which the trees recovered, and no further treatments were required. Measurements began in April 2016 at the start of growing season 3 and continued through March 2019. Eucalypts were affected by cold snaps each winter resulting in foliage and stem damage. In growing years 1–2, dead trees were replanted, yet some canopy gaps remained. High winds from hurricanes Matthew, Irma, and Michael (October 2016, September 2017, and October 2018) damaged eucalypt canopies, and some trees were uprooted. Pines did not suffer similar damage from high winds.

Precipitation, Throughfall, and Interception

P was measured at a 15-min time step using tipping bucket rain gauges situated adjacent to each of the six paired plots (TE525: Campbell Scientific, Inc.). Weekly P totals were collected from each plot using standard rain gauges to verify tipping bucket depths. Any gaps in tipping bucket observations were filled with observations from the nearest standard rain gage or tipping bucket. Pan evaporation from NOAA station USC00380490, located in Barnwell, SC, approximately 25 km from the field site, and Penman–Monteith potential evapotranspiration (PET) calculated from tower data [40] within the study watershed are reported for comparison to measured hydrologic budget values.

Weekly composite Tf samples were collected from four samplers per plot for a total of forty-eight samplers placed within rows and sampling two trees each. Samplers were fabricated from 38.5 mm inside diameter plastic pipe with two 1.42 m limbs made from pipe cut in half to form a trough and connected at 22.5° angles to form a total collection area of 547 cm^2 draining to a central collector [41]. Canopy Ei was estimated as:

$$\mathrm{Ei} = P - \mathrm{Tf}$$

Soil Evaporation

Es was estimated using two sets of non-weighing lysimeters, with each set including three treatments, eucalypt canopy, pine canopy, and no canopy. One set was installed in a shallow plot (3) and one set in a deep plot (5) (Fig. 1) for a total of six lysimeters. Each lysimeter consisted of an aluminum box with a 0.5 m^2 surface area and a depth of 0.5 m and a sloped floor that drains to a collector. Each lysimeter was installed slightly above ground level to prevent overland flow from entering and filled with soil in the approximate layering of the undisturbed soil. We packed the layers to approximate the original soil, but the installation process unavoidably changed the soil structure and thus the hydraulic properties. However, the native shallow soils above 50 cm have limited structure; thus, the effect of soil disturbance inside the lysimeters likely had little effect on Es estimates. Vegetation was not allowed to grow in the lysimeters, but leaf litter was allowed to accumulate as the trees developed. Canopies around the lysimeters were not affected by mortality or storm damage meaning Es measurements are representative of closed canopy conditions. Outflow from lysimeters was collected in 55-L carboys, and the volume was recorded approximately weekly. Volumetric soil moisture inside the lysimeters was monitored at an hourly time step using time domain reflectometry (TDR) probes with two probes situated at 0–10 cm and two at 30–40 cm (Decagon $\mathrm{ECH_2O}$ EC-5). Es from the lysimeters was estimated annually and weekly as:

$$\mathrm{Es} = \mathrm{inputs} - \mathrm{outflow} - \Delta s$$

where inputs is the Tf (or P for unvegetated plots) and Δs is the change in soil water storage over the measurement period based on the lysimeter soil moisture measurements.

Transpiration and Evapotranspiration

Transpiration (Et) was measured in 5 trees in each of the 12 plots (30 per species, 60 total) using the Granier's thermal dissipation probe method [42, 43]. We selected transpiration measurement trees representing the range of tree diameter sizes within the plots at the end of growing year 2. Sensors were constructed with two probes, 2 cm long [44]. The probes were installed by removing the bark down to the cambium using a leather punch, drilling a 2 cm deep hole using a drilling template to ensure probes were 10 cm apart and in line with each other, and inserting each probe. The upper probe was powered constantly at 0.2 W. Thermocouples inserted into the center of each probe measured the temperature difference between reference and heater probes. As sap flows up through the stem, the temperature difference between probes decreases. The faster sap is flowing, the more similar probe temperature becomes. Accurate estimation of Et by the thermal dissipation method requires development of species and site-specific calibration coefficients [44-47]. Species- and site-specific calibrations were conducted using the potometer approach and are described in detail in [48]. Briefly, in the 2017 and 2018 growing seasons, 6 trees of each species were harvested, stems were recut under water, placed in potometers, instrumented with sap flow sensors, and allowed to transpire water for 2 days, while the potometer water levels and sap flux density were recorded at a 30-min time step. The measured potometer water use was regressed against measured sap flux density using the nls function in the R stats package. The non-linear models were used to estimate sap flux density in measurement trees throughout the study. Segmented calibration curves were generated based on the breakpoint between high and low transpiration rates. To generate segmented calibration curves, calibration data was first subset into two pieces, one subset below and one subset above the 95% of K breakpoint. The high and low sap flow subsets were then fit with separate power functions, one curve for K values below the 95% K threshold (K^{low}), and another curve for K values above the threshold (K^{high}) (Table 1). Sapwood area was measured in the sap flow calibration trees ($n = 6$ per species) and in intact trees ($n = 14$ per species) using the dye staining and increment boring method [43]. Relationships were fit between sapwood area and diameter at breast height (DBH), and the fitted relationships were used to estimate monthly sapwood area for the sap flow measurement trees. Sap flux density was converted to Et (L/h) using the estimated sapwood areas, and Et was converted from L/h to mm/h using the tree growing area (7.44 m^2). Annual tree level Et was calculated by summing the hourly Et estimates for each measurement tree. Mean annual Et of measurement trees was calculated by averaging the five measurement trees in each plot. To account for the effects of deceased trees, the mean annual plot level Et ($\mathrm{Et}_{\mathrm{plot}}$) was calculated by multiplying the mean sap flux density of each plot at each hourly time step by the total plot sapwood area (L/h) and dividing by the total plot area to get mm/h, then hourly values were summed for each year, and mean annual mm was calculated by species. A few measurement trees died over the course of the study and probes were moved from deceased trees to living trees of a similar size. The Et measurements for growing year 5 ended on October 25, 2018, before the end of our designated growing year on April 11, 2019, due to the difficulty of maintaining battery banks through extended cold periods that winter. The growing year 5 Et gap was filled at the plot level by quantifying the same period for growing years 3 and 4 as a percentage of annual Et and adding the equivalent missing percentage to growing year 5 plot totals. Annual ET was calculated as the sum of its components (Es, Ei, and Et).

Soil Water Perching and Groundwater

A shallow piezometer was installed into the top of the argillic horizon (~ 100 cm) in each plot, and soil water perching was monitored hourly using Odyssey™ capacitance water level loggers (Data Flow Systems, New Zealand). Groundwater levels in the surficial aquifer were monitored and recorded hourly using Odyssey™ capacitance water level loggers in a deeper piezometer adjacent to each plot pair. Groundwater piezometers were 4–12 m deep depending on landscape position. Dips in the groundwater time series caused by piezometer sampling were removed prior to further analysis. Odyssey™ accuracy is reported by the manufacturer to be ± 5 mm; however, user tests have reported substantial errors in some environments [49]. We manually checked Odyssey measurements periodically and found high agreement. Piezometer sounder measurements were recorded weekly in each shallow piezometer and monthly in each groundwater piezometer for quality control of the water level time series.

DBH and Biomass

DBH was measured annually at the end of the growing season for each tree in the central plots. DBH was measured with calipers for smaller stems and with DBH tapes for larger stems. The above-ground biomass was estimated using site and species-specific allometric equations developed in a previous study at the same site for pine [39] (see supplemental Table 2 in [39]) and at the conclusion of this study for eucalypt (Table 2). Eucalypt allometric equations were developed from 11 individual trees. Eucalypt stem and branch woody biomass (y) were estimated from measurements of 11 harvested trees ranging in DBH from 1.7 to 27.9 cm. Individual eucalypt trees were felled and separated into branch and stem components, and leaves were removed from branches. Fresh mass of branch and stem components were measured in the field immediately after felling. Subsamples of branch and stem components were placed in plastic bags, stored in a cooler, and transported to the lab for fresh mass determination, and then they were dried to a constant mass at 60 °C to determine the water content.

Table 1 Segmented sap flow power function equations developed from potometer measurements at our site for *Pinus taeda* and *Eucalyptus benthamii*

Species	K (%)	K-break	Function K^{low}	SE	Function K^{high}	SE
Eucalypt	95	0.401	$F_d = 271.87K^{1.613}$	13.39	$F_d = 588.03K^{2.910}$	45.41
Pine	95	0.518	$F_d = 81.97K^{1.091}$	11.81	$F_d = 129.12K^{1.534}$	33.85

K is the dimensionless sap flow index, K (%) and K-break represent the segmentation point as a percentage and absolute value for the K^{low} and K^{high} equations, Fd is sap flux density, and SE is the standard error for each non-linear equation. Detailed method descriptions for sap flux density equation development are described in [48]

Table 2 Allometric equations for *Pinus taeda* and *Eucalyptus benthamii* biomass developed at our site

Species	Model: $Y = aX^b + \varepsilon$			
	Component	Parameter		R^2
		a	b	
Eucalypt	Branches	2.094e-007	5.954	0.9572
Eucalypt	Stem	0.3530	1.835	0.9683
Pine	Branches	2.9619	2.7346	0.9884
Pine	Stem	6.1167	2.7090	0.9939

Fresh mass of branch and stem components were transformed into dry mass values by accounting for water content. Dry mass was related to DBH using a power function $Y = \alpha x\beta + \varepsilon$ where x is DBH (cm), α and β are regression parameters, and ε is a random normally distributed additive error term with zero mean and constant variance [50, 51]. Model parameters were estimated using PROC NLIN in SAS. Pine and eucalypt parameter values (Supplemental Figure S1) were applied to estimate stem and branch biomass for all live trees in each plot. The allometric equations estimate above-ground dry biomass components (kg/m^2) from annual DBH for eucalypt and annual ground line diameter (GLD) [50] for pine. The estimated branch and stem biomass were summed to obtain total aboveground biomass. Annual above-ground net primary productivity (ANPP) was calculated as the difference in biomass from 1 year to the next. WUE was calculated in two ways, first based on Et (ANPP/Et, WUE$_{\mathrm{Et}}$), which is the most common [25] and based on total ET (ANPP/ET, WUE$_{\mathrm{ET}}$).

Leaf area index (LAI) was measured at first light monthly in each plot using two LAI-2200C Plant Canopy Analyzers (LI-COR, Inc., Lincoln, NE) one measured reference conditions in open-sky conditions adjacent to plots and another measured below the canopy. Below the canopy, measurements were compared with open-sky measurements. Due to variation in eucalypt canopy densities because of wind and freeze damage, LAI measurements were taken at two levels, whole-plot average and within a cluster of healthy trees. Plot level measurements were taken in two directions, North and West. Cluster level measurements were collected by measuring LAI at eight locations within a cluster of trees. Cluster locations were matched with one of the leaf litter collectors in each plot. Leaf litter accumulation was sampled in five 0.5625 m^2 (75 × 75 cm) litterfall traps in each plot ($n = 30$ per species). The litter in each trap was collected monthly in a paper bag, oven dried, sorted into foliage or woody material, and weighed with a 0.01 g precision balance.

Fine roots were sampled in February 2017 and 2018 using a 4.9-cm diameter hollow core soil sampler and slide hammer. In each plot, a tree was selected, and five cores were collected in the northwest growing quadrant from 0 to 100 cm below the soil surface in 25 cm increments. Samples were stored in labeled bags and transported to the lab where they were washed by elutriation (Gillison's Variety Fabrication, Inc., Benzonia, MI), sorted, weighed, and scanned. The scanned roots were analyzed with WinRhizo image analysis software (Régent Instruments, Québec, Canada).

Data Analysis

Annual hydrologic budgets were constructed where inputs were P and Tf and outputs were Ei, Et, Es, and Rq. Water budget years were delineated to match the active growing season and weekly sampling dates. Growing year 3 spanned from April 12, 2016, to April 12, 2017, growing year 4 was April 13, 2017, to April 11, 2018, and growing year 5 was from April 12, 2018, to April 11, 2019. This arrangement of growing years is designed to start before spring green out when soil water storage is near its maximum and to end after the active growing season when soil water storage is near its minimum.

Statistical analyses were conducted to test for treatment effects on components of the hydrologic budget. Mixed-effects analysis of variance (ANOVA) was used to test for differences in annual plot means for litter production, LAI, NPP, Ei, Es, Et, ET, WUE$_{\mathrm{ET}}$, and WUE$_{\mathrm{Et}}$. Species, groundwater depth, and year were treated as fixed factors, and plot was treated as a random factor. Tukey's HSD tests were used for analysis between groups. Statistical analyses were calculated using R 4.1.2 (2020, R foundation for statistical computing, Vienna, Austria) and the nlme package.

Results

Average P for growing years 3 through 5 was 1291, 1032, and 1585 mm compared to a long-term annual average of 1263 mm. P varied seasonally, with the highest P in the summer months (Fig. 2). Annual P did not vary significantly across the plots ($p = 0.815$). Cold snaps with consecutive daily minimum temperatures below freezing were observed in the winters of growing year 3 (4 days), growing year 4 (4 days), and growing year 5 (11, 8, and 5 days).

Perching of soil water within and above the Bt horizon was more common in shallow groundwater plots than deep groundwater plots, especially following heavy P events or periods of sequential P events when soil storage was full. Based on the hourly piezometer observations, soil water was perched 25% of the time on average across shallow groundwater eucalypt plots versus 18% across deep groundwater eucalypt plots. In pine plots, soil water was perched 21% of the time in shallow groundwater plots and 12% of the time in deep groundwater plots. Perching was more common

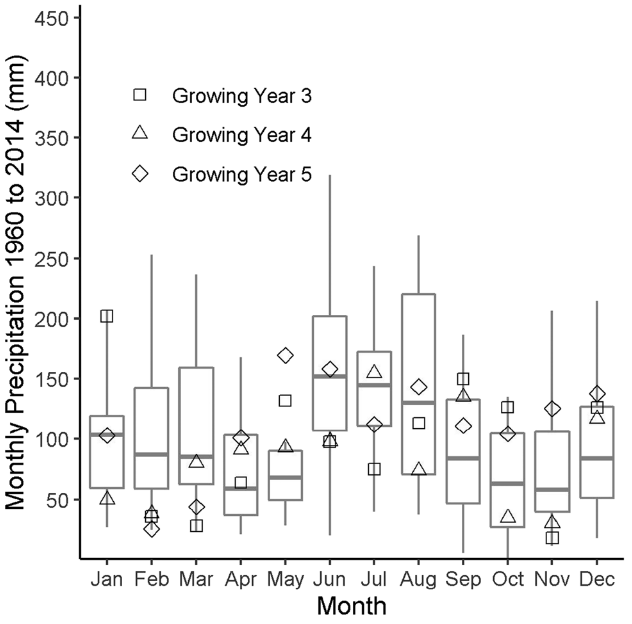

Fig. 2 Monthly total precipitation during the study period shown in black open symbols relative to distributions of monthly precipitation at Aiken, SC, from 1960 to 2014

in the dormant season than in the growing season. Mean perching duration in eucalypt plots was 27 and 17% for the dormant and growing seasons, respectively, and for pine, they were 22 and 13% (Fig. 3). Mean depth to groundwater was 2.47 m at the shallow plots and 6.61 m at the deep plots, although variability was high across shallow and deep plots. The depth to groundwater at shallow plots varied from 0.54 to 5.12 m and from 2.99 to 9.74 m at the deep plots (Fig. 3).

Eucalypt LAI was not influenced by groundwater depth ($p = 0.189$) but differed among species ($p < 0.001$) and growing year ($p < 0.001$); however, these effects were not independent (i.e., species × growing year interaction; $p < 0.001$). LAI was greater in pine than eucalypt across groundwater depth and years. LAI was similar between species in growing year 3 (about 2) and began diverging in growing year 4 when LAI in pine plots increased from 3 to 4. LAI in eucalypt plots decreased at the end of growing year 4 due to leaf frost damage (Fig. 4). As a result of mortality, mean tree density in eucalypt central plots decreased from 48 trees in year 1 to 43, 34, 33, and 24 trees for years 2 through 5. The mean number of central plot trees in pine plots remained 45 or more throughout the study.

Monthly average leaf litter production for eucalypts was 21, 66, and 30 g/m^2 for growing year 3 through growing year 5, and for pine, they were 15, 26, and 31 g/m^2. The annual total leaf litter production was not influenced by groundwater depth ($p = 0.101$), was greater in eucalypt plots ($p = 0.002$), and increased with growing year ($p < 0.001$), and these effects remained independent. Cumulative leaf litter was not influenced by groundwater depth ($p = 0.060$) was greater in eucalypt plots ($p < 0.001$) and increased annually ($p < 0.001$); these effects were not independent

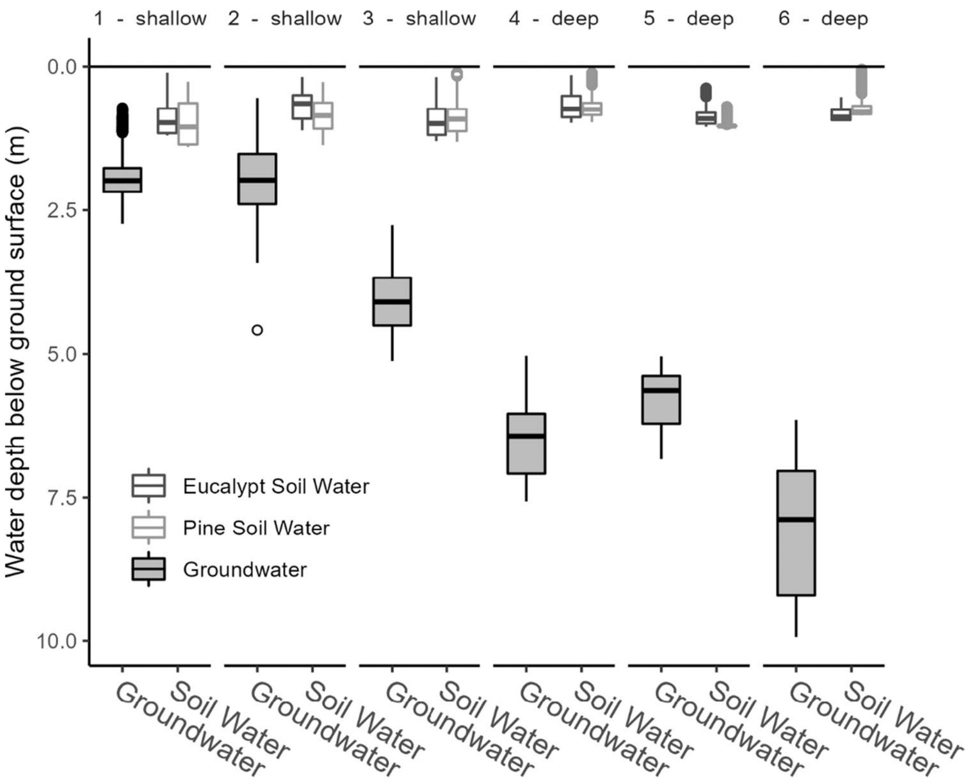

Fig. 3 Boxplots of hourly groundwater and perched soil water levels throughout the study. In four of the plots, water table elevations never intersect the perched zones, and they do so only rarely in the other two plots

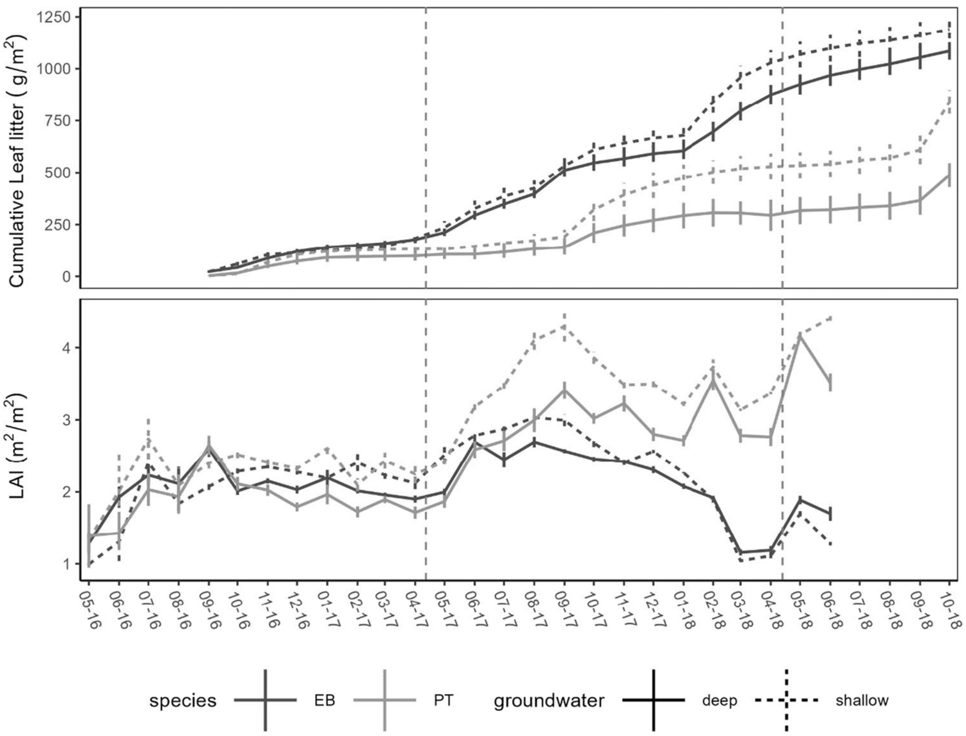

Fig. 4 Monthly leaf litter accumulation (m^2) and leaf area index (LAI) by species and groundwater treatment. Leaf litter collected in litterfall traps ($n = 60$). Lines connect monthly means, and error bars represent the mean ± 1 standard error. Vertical dashed lines indicate growing year transitions

(i.e., species × growing year; $p < 0.001$, groundwater × year; $p = 0.027$). Cumulative leaf litter did not increase in deep groundwater eucalypt plots from growing year 4 to growing year 5 (Fig. 4).

The mean DBH at the start of growing year 3 was 1.4 cm for eucalypt and 1.3 cm for pine, and at the end of growing year 4, they were 9.1 and 10.7 cm. Annual biomass accumulation was not influenced by groundwater depth ($p = 0.125$) and did not differ by species ($p = 0.187$) but did increase each growing year ($p < 0.001$); these effects were not independent (i.e., species × groundwater; $p = 0.019$). Eucalypt biomass accumulation was greater than pine in deep groundwater plots. Biomass estimated from allometric equations at the end of growing year 5 was 4.9 kg/m^2 for eucalypt and 4.3 kg/m^2 for pine (Fig. 5). Cold-induced mortality killed some of the largest eucalypt trees at the end of growing year 5 causing a reduction in mean DBH, but mean biomass increased due to growth of surviving trees.

Mean ANPP was 1.49 kg/m^2 for eucalypt and 1.43 kg/m^2 for pine. ANPP was not influenced by groundwater ($p = 0.224$), did not differ among species ($p = 0.861$), and did not differ among growing years ($p = 0.551$); these effects were independent.

Root surface area was not influenced by groundwater depth ($p = 0.142$), did not differ among species ($p = 0.054$),

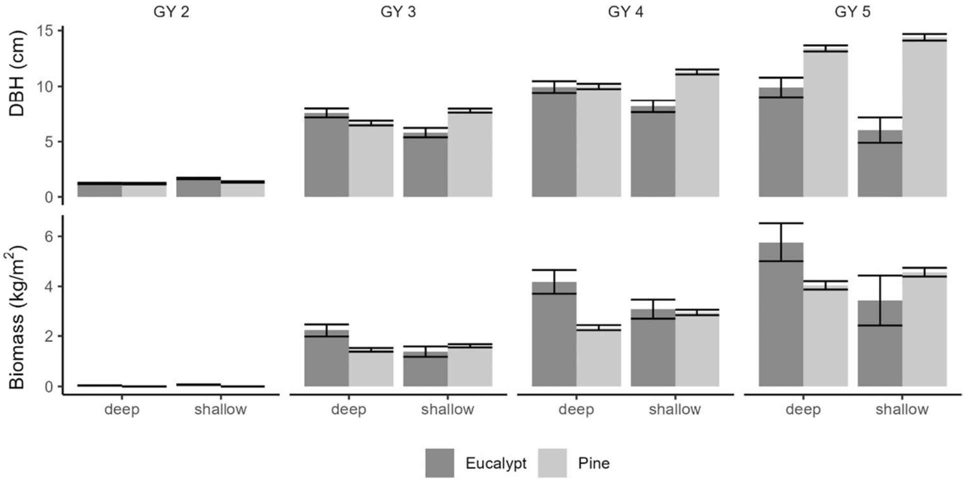

Fig. 5 Annual diameter at breast height (cm) and total biomass (kg/m^2) at the end of each growing season by species and groundwater treatment. Wind damage to individual eucalypt trees in growing year 5 caused an apparent reduction in DBH in eucalypt plots

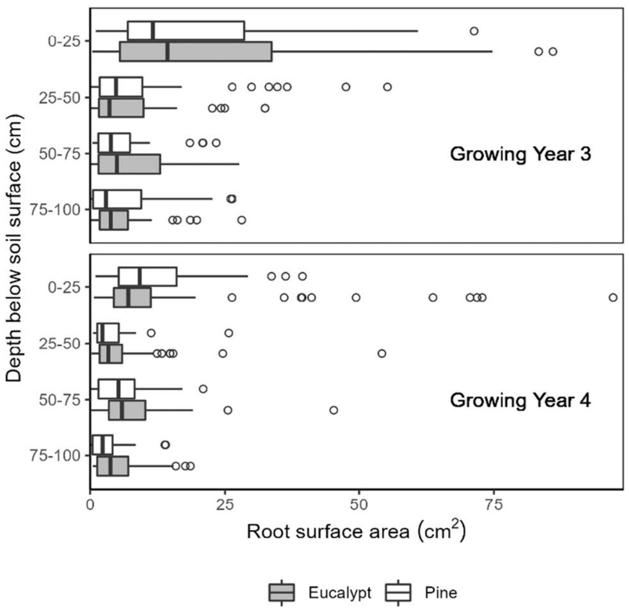

Fig. 6 Root surface area by soil depth increment, species, and growing year. Soil core samples for root analysis were collected at the end of growing years 3 and 4 from five soil cores adjacent to one tree in each plot

but did vary by growing year ($p < 0.001$) and soil depth increment ($p < 0.001$); these effects were independent. Sampled root surface area was greater in growing year 4 than growing year 5. Across plots most roots were observed from 0 to 25 cm below the soil surface. On average 61% of eucalypt root surface area was between 0 and 25 cm followed by 15, 14, and 10% in the 25–50, 50–75, and 75–100-cm depths, respectively. On average 60% of pine root surface area was in the 0–25-cm depth followed by 18, 14, and 9% in the 25–50-, 50–75-, and 75–100-cm depths, respectively (Fig. 6).

Ei was greater in shallow than deep groundwater plots ($p = 0.006$), was greater in pine than eucalypt ($p < 0.001$), and increased with growing year ($p < 0.001$); these effects were not independent (i.e., species × growing year; $p = 0.021$, groundwater × growing year; $p = 0.038$). Ei increased year to year for eucalypt but for pine only increased from growing year 4 to growing year 5 (Fig. 7). In deep groundwater plots, Ei increased year to year, but in shallow groundwater plots, Ei only increased from growing year 4 to growing year 5.

Bare plot Es was 593, 415, and 585 mm (46, 40, and 37% of P) for growing years 3, 4, and 5, respectively. In growing year 3, Es in the vegetated plots was just under 500 mm, nearly equal to that in the bare lysimeters, and it diminished by approximately 300 mm by growing year 4 (Fig. 7). Es did not differ by species ($p = 0.091$) but decreased with growing year ($p < 0.001$); these effects were not independent (i.e., species × growing year; $p = 0.014$). Es was similar between species in growing

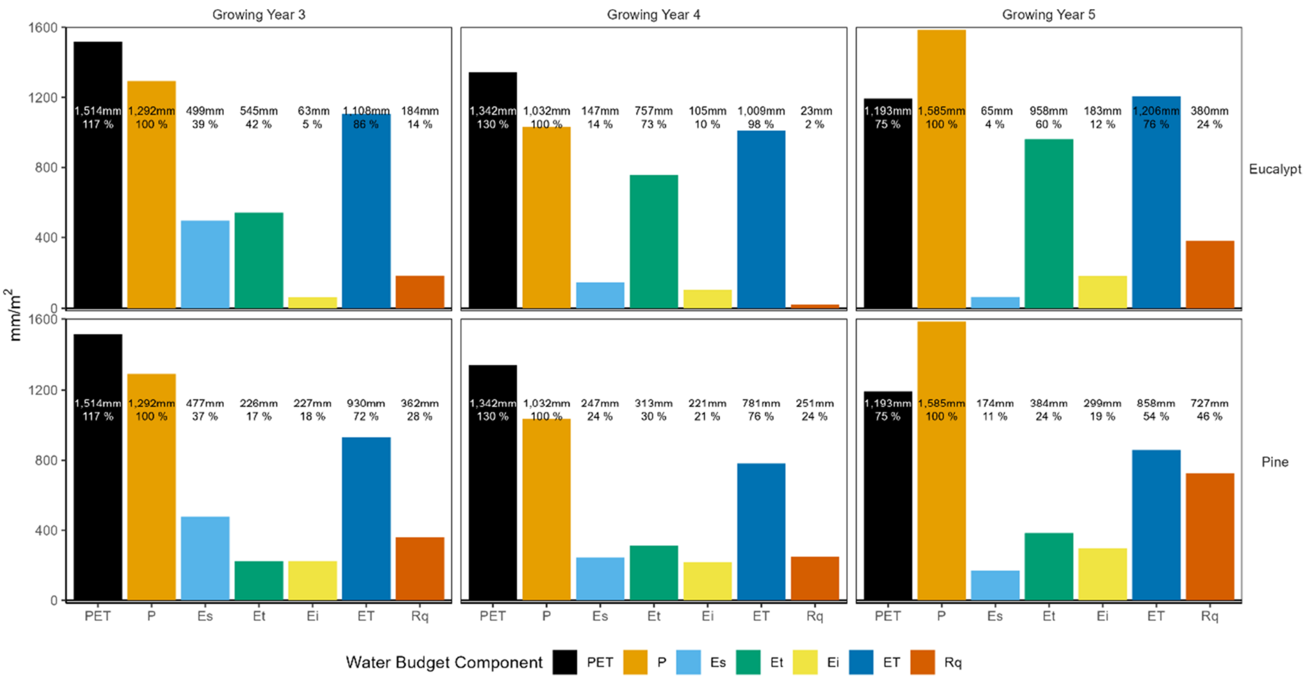

Fig. 7 Mean annual water budget components by species and growing year with labels representing fluxes in mm and percent of precipitation. PET Penman–Monteith potential evapotranspiration, P precipitation, Es soil evaporation, Et transpiration, Ei interception, ET evapotranspiration (Es + Et + Ei), and Rq recharge to streams and groundwater calculated as P – ET

years 3 and 4 but was higher in loblolly than eucalypt in year 5.

Annual Et was not influenced by groundwater depth ($p = 0.736$) but differed among species ($p = 0.002$) and among growing years ($p < 0.001$); these effects were not independent (i.e., species × growing year; $p = 0.030$). Et was higher in eucalypt than pine and increased most years with canopy development, although pine Et was not different between growing years 4 and 5 (Fig. 7). Annual Et_{plot} for growing years 3 through 5 was 486, 561, and 605 mm for eucalypt and 214, 295, and 357 mm for pine.

Annual ET over the 3 growing years averaged 1107 mm for eucalypt and 856 mm for pine. Annual ET (Es + Et + Ei) was not influenced by groundwater ($p = 0.547$) but was greater in eucalypt than pine ($p = 0.032$) and varied by growing year ($p = 0.016$); these effects were independent. In growing year 4, ET was lower than in growing years 3 and 5 due to lower P and PET (Fig. 7).

Annual total pan evaporation from the Barnwell, SC, NOAA station was 1700, 1501, and 1403 mm for growing years 3 through 5, respectively. Penman–Monteith PET calculated from local tower data was 1514, 1342, and 1193 mm for growing years 3 through 5. Rq varied as a function of P and ET and for growing years 3 through 5 was on average 266, 137, and 523 for eucalypt and 396, 298, and 785 mm for pine.

The mean annual WUE_{ET} for growing years 3 through 5 was 1.6, 1.9, and 0.41 kg/m^3 for eucalypt and 1.7, 1.5, and 1.9 kg/m^3 for pine (Table 3). Cumulative WUE_{ET} for growing years 3 through 5 was 1.35 kg/m^3 for eucalypt and 1.67 kg/m^3 for pine. WUE_{ET} was not influenced by groundwater depth ($p = 0.153$), did not differ among species ($p = 0.257$), and did not differ among growing years ($p = 0.316$); these effects were not independent (species × growing year; $p = 0.037$). For pine WUE_{ET} was greater in growing year 4 than growing year five. The mean annual WUE_{Et} for growing years three through five was 3.4, 2.7, and 0.41 kg/m^3 for eucalypt and 7.3, 4.2, and 4.5 kg/m^3 for pine (Table 3). Cumulative WUE_{Et} for growing years 3 through 5 was 1.98 kg/m^3 for eucalypt and 4.66 kg/m^3 for pine. WUE_{Et} was not influenced by groundwater depth ($p = 0.558$) but was greater in pine than eucalypt plots ($p = 0.002$) and decreased over time ($p = 0.003$); these effects were independent.

Table 3 Mean water use efficiency as biomass per unit evapotranspiration (WUE_{ET}) and as biomass per unit transpiration (WUE_{Et}) by species, growing year (GY)

Species	GY	WUE_{ET} (kg/m3 H2O)	WUE_{Et} (kg/m3 H2O)
Eucalypt	3	1.50	3.44
Pine	3	1.46	7.25
Eucalypt	4	1.83	2.67
Pine	4	1.32	4.19
Eucalypt	5	0.40	0.41
Pine	5	1.76	4.50

Discussion

In this comparison of intensively managed eucalypt and pine, we found that eucalypt produced more biomass over the 3 growing years (13.3%), transpired at a much higher rate (Et + 144%), and produced higher ET (184 mm/year + 23%) than pine. Eucalypts and pine had similar WUE_{ET} because they had similar differences in ANPP and ET. However, pine had higher WUE_{Et} because ET was comprised of a higher proportion of Es than Et compared to eucalypts. At the end of growing year 5, average WUE_{ET} was 1.27 for eucalypt and 1.50 kg/m^3 H_2O for pine, whereas WUE_{Et} was 1.98 for eucalypt and 4.66 kg/m^3 H_2O for pine. On a delivered dry biomass basis, eucalypt plantations would produce a similar amount of ET as pine plantations, but on a watershed-area basis, eucalypt would use more water and reduce water yield. Thus, the effects of switching from pine to eucalypt for woody biomass production depend on how the productivity differences affect total planted area for each species. Our finding of higher Et in eucalypt agrees with other results from the southeast USA [9] and Brazil [52, 53] but differs from a comparison of *Pinus radiata* and *Eucalyptus globulus* plantations in Australia [14], where there was no difference in Et. While only one variety of eucalypts was used in this study, we utilized the best available plant material at the time of planting, and we believe that the comparative ET and its components between pine and eucalypt provide valuable empirical evidence for the southeast US region.

Es has commonly been a neglected part of forest, and plantation water budgets and published Es rates are often estimated from soil moisture fluxes [25] but Es comprised a substantial part of the water budget in these young plantations. We measured Es for the purpose of closing the water budget but did not anticipate that Es would be as important as Et for years 3 and 4. There are limited published Es measurements for forest or young plantation soils. We know of lysimeter Es estimates from only two woody plantation studies [15] near our current study site comparing forested and non-forested Es using 0.5 m^2 lysimeters and [14] in Australia reporting Es from 0.031 m^2 lysimeters in eucalypt and pine plots. Caldwell et al. [15] reported that Es under 14-year-old pine canopies accounted for 0% of *P*, while Es from unvegetated plots accounted for 27% of *P*. The Es reported from lysimeter measurements in eucalypt plantations in Australia [14] was approximately 50% of precipitation or 219–264 mm, while pine was 15–19% of precipitation or 106–141 mm [14]. Reported Es rates from pine bioenergy plantations range from 73 to 310 mm with a mean of 251 mm [25]. Decreases in our Es estimates from over 500 mm in growing year 3 to less than 250 mm in growing years 4 and 5 coincided with leaf area production and leaf litter accumulation. This tradeoff between Es and Et is a water-saving benefit of intensive management, which generates greater leaf area and leaf litter earlier in the growing cycle shading the soil and reducing Es. Our data demonstrate that Es dynamics are especially important early in the plantation cycle when leaf litter accumulation is minimal and bare soil is common due to harvest and site preparation disturbance. Thus, it is important to consider Es when accounting for rotation length ET of short rotation woody crops [54].

In our study, Ei was greater in pine than eucalypt plots, which has also been found in other plantation comparisons of *Pinus* and *Eucalyptus* [14]. Our observed pine Ei rates of 18–21% of *P* were greater than other published rates for *Loblolly pine* at 4–15% of *P* [55] and less than *Pinus radiata* plantations in Australia at 27–50% of *P* [14]. There are no published Ei rates for eucalypt in the USA. Data from eucalypt plantations in Brazil and Australia indicate Ei rates in the range of 14.4–31.5% of *P* for eucalypts 2–6 years old [56] and 19% of *P* for *eucalypt* stands of varying ages [14].

Et in eucalypt plots was higher than in pine plots, which is in agreements with another study comparing 9-year-old plantations of the same two species in the southeast USA [9]. The Et_{plot} rates considered mortality at the plot level and were closer between the two species than Et, but eucalypt still had higher Et_{plot} than pine. Pine Et was comparable to observations from other young pine plantations [40]. King et al. [25] reported mean overstory Et from 24 pine studies at 410 mm/year. More specific to younger pines, Samuelson and Stokes [57] estimated Et of 223 mm for 4–5-year-old pines, and Gonzalez-Benecke and Martin [58] estimated Et rates for 11 year old pines in South Carolina at 248 mm/year. Eucalypt Et was higher than Et reported in other published studies outside of the USA [14, 59]. Et rates from 9-year-old eucalypt plots in North Carolina were 1077 mm/year. [9], which is higher than our observed Et but makes sense because our trees were younger and LAI was quite low by growing year 5 due to frost and storm damage.

Stemflow was not quantified in this study and thus is lumped with Ei. Published stemflow rates for young pine plantations range from 0.3 to 6.5% of *P* [55]. Published stemflow rates for eucalypt are in the range of 0.8–2.4% of *P* [56].

Previous studies show that groundwater depth affects Et [17, 18], but we did not find differences in Et or ET as a function of depth to groundwater. The range of our groundwater depths was smaller, and our trees were younger than those of [17, 18], which may have contributed to a lack of differences in Et by groundwater depth. In addition, soils at our site have Bt horizons with high water storage capacities and provide water through periodic droughts, which may render deep rooting less advantageous. The lack of differences in Et across groundwater depths suggests that availability of shallow groundwater does not increase transpiration at this stage of growth. Ultimately, rotation-length studies will help address the uncertainties we have regarding the dynamics of ET and groundwater use throughout stand development.

Eucalypt and pine had similar WUE_{ET}, but pine had higher WUE_{Et} due to higher Et in eucalypt. Our WUE_{Et} was 58% greater in pine than eucalypt, whereas Maier et al. [9] reported that eucalypt WUE_{Et} was 40% greater than pine, and faster growing trees tend to have higher WUE [60]. Our eucalypt WUE_{ET} was 1.35 kg/m^3, which is lower than the WUE_{Et} rates from other studies [53, 61-63] and can be attributed to additional water lost to Es. Our eucalypt WUE_{Et} was 1.98 kg/m^3, which is lower than the 2.86 kg/m^3 reported by Maier et al. [9] but within the range reported by other studies [53, 61-63]. Our pine WUE_{ET} was 1.67 kg/m^3, which is within the range of reported WUE for pine [57]. Our pine WUE_{Et} was 4.66 kg/m^3, which is higher than the range of reported WUE_{Et} (1.18–1.62 kg/m^3) for pine [57]. Some of the differences between WUE in our study and other published rates can be attributed to intensive management in our stands, younger stand age, and freezing effects in eucalypt limiting overstory development. The majority of published WUE rates are reported as WUE_{Et} rather than WUE_{ET} [25] because Es is rarely quantified directly. Our measured water budget components show that in young plantations neglecting Es and estimating WUE from Et alone results in a substantial difference in interpretation of WUE and highlights the importance of quantifying Es in young plantations and throughout short rotations.

The value of our biomass and WUE estimates may be limited by short duration measurements and a lack of Es measurements from years 0 to 2. Water use measurements are commonly conducted for 2–5 years (this study) [9], while intensive management rotation lengths are 8–12 years meaning we may not have an accurate overall picture of short rotation water budgets. Water use measurements commonly begin after canopy closure, while our data show that annual Es prior to canopy closure (500 mm/year) can amount to about half of ET after canopy closure [64, 65]. Thus, ignoring early plantation Es results in an underestimation of rotation-length ET estimates, especially for shorter rotations which are possible for intensively managed woody crops. Reducing Es by maintaining litter cover would have increased young plantation WUE_{ET} for both species but would not affect WUE_{Et}.

While our pine plots had very low mortality and are representative of typical intensively managed pine plantations, our eucalypt plots had substantial mortality later in the study from freezing. We based our analysis primarily on Et from living trees because our goal was to analyze ET of intact plantations that could be grown in the region, but tree gaps in eucalypt plots potentially affected the water budget components and our WUE estimates. Gaps in the eucalypt canopy likely resulted in increased aerodynamic roughness and increased exposure to sunlight for remaining edge trees [14], which could have increased Et per unit leaf area. Soils under canopy gaps may have had fewer tree roots sourcing water, which would have led to lower depletion from Et; however, these soils experienced less shading/solar radiation and received fewer leaf litter inputs which would have increased Es. Higher Es in canopy gaps would likely supplied atmospheric demand that would have otherwise been supplied by transpiration. Our Es measurements were likely less affected by canopy gaps than the other ET components because all lysimeters were located within clusters of trees that resembled a fully stocked stand. Without canopy gap and damage effects in eucalypt plots, the Et and ET rates would be more similar between eucalypt and pine as other studies have reported [14, 59]. However, the only other comparison of pine and eucalypt ET in our region generally supports our finding that eucalypt Et was higher than pine [9].

Commercial efforts to grow *Eucalyptus* north of the Gulf Coast have encountered periodic loss of trees or crown damage during cold snaps [26], and we experienced the same problem with a *Eucalyptus* variety selected to be cold hardy [66]. Due to extended periods of winter temperatures < 0 °C, our eucalypt plots had significant cold mortality initially and crown damage as trees developed. As a result of mortality and crown damage most eucalypt plots had some canopy gaps, however, each plot had at least one cluster of trees forming a closed canopy and measurements were focused on those clusters. Despite its productivity potential, our experience and that of others is that landowners do not want to plant eucalypt in the Southeast due to cold snaps, which will cause mortality [66]. To our knowledge, there are no seedlings available in the southeast that can withstand freezes, and the genetic work to enhance cold tolerance has ceased.

Conclusions

ET was higher in eucalypt plots than pine plots and this was driven primarily by higher Et. Eucalypt had 25 higher ET than pine during growing years 3 through 5 and produced 13% more biomass. Eucalypt and pine had similar WUE_{ET} because they had similar ANPP and ET. However, pine had higher WUE_{Et} because Es accounted for a larger proportion of ET in pine than in eucalypt. The WUE_{ET} data indicate that on a unit biomass basis, eucalypt would use a similar amount of water, but on a planted area basis, they would use more water. Thus, the hydrologic effects of switching from pine to eucalypt for woody biomass production depends on the land area of each species required to meet biomass production needs and the ability to preserve leaf litter during early stand development. Our WUE_{ET} and WUE_{Et} data highlight the importance of quantifying Es in young plantations where it can comprise a substantial portion of ET.

The relative proportions of water budget components were dynamic in growing years 3 through 5 for both species. Es in the vegetated plots was high during growing year 3 and decreased during growing years 4 and 5 along with canopy closure, leaf litter production, and increased Et. Es was high in the unvegetated plots for all three observed growing years. These observations show that in young plantations with open canopies, Es can be almost as high as Et from closed canopies and suggests that it is important to quantify hydrologic budgets from the time of plantation development to fully quantify stand rotation ET. Bare soil Es estimated from the unvegetated lysimeters accounted for 44% of P over the study period, consistent with a previous study in the region [15], indicating the need for forest managers to maintain organic cover on soils after harvest and planting to minimize water losses. Research is needed into how reducing soil evaporation might increase tree productivity and/or increase water yields.

Regionally severe cold snaps caused high mortality even among this *Eucalyptus* variant selected for cold hardiness. Past efforts to grow *Eucalyptus* north of the Gulf Coast have repeatedly encountered the same problem with cold weather mortality [26, 66]. These data indicate that more work is needed to select for cold hardiness if *Eucalyptus* are going to be grown in this region.

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Data Availability The data that support the findings of this study are included in the supplementary materials.

Declarations

Competing Interests The authors declare no competing interests.

References

1. Wear DN, Greis JG (2012) The southern forest futures project:technical report. Gen. Tech. Rep. SRS-GTR-178. USDA-Forest Service, Southern Research Station, Asheville, NC, p 542. https://doi.org/10.2737/SRS-GTR-178
2. Langholtz M, Stokes B, Eaton L (2016) Billion-Ton report: advancing domestic resources for a thriving bioeconomy. United States. https://doi.org/10.2172/1271651
3. Griffiths NA, Rau BM, Vaché KB, Starr G, Bitew MM, Aubrey DP, Martin JA, Benton E, Jackson CR (2018) Environmental effects of short-rotation woody crops for bioenergy: what is and isn't known. GCB Bioenergy 2019(11):554–572. https://doi.org/10.1111/gcbb.12536
4. Younger SE, Jackson CR, Rasmussen TC (2020) Relationships among forest type, watershed characteristics, and watershed ET in rural basins of the Southeastern US. J Hydrol 591. https://doi.org/10.1016/j.jhydrol.2020.125316
5. Kline KL, Coleman MD (2010) Woody energy crops in the southeastern United States: two centuries of practitioner experience. Biomass & Bioenergy. https://doi.org/10.1016/j.biombioe.2010.05.005
6. Hinchee M, Rottmann W, Mullinax L, Zhang C, Chang S, Cunningham M, Pearson L, Nehra N (2009) Short-rotation woody crops for bioenergy and biofuels applications. In Vitro Cell Dev Biol Plant 45(6):619–629. https://doi.org/10.1007/s11627-009-9235-5
7. Carter MC, Foster CD (2006) Milestones and millstones: a retrospective on 50 years of research to improve productivity in loblolly pine plantations. For Ecol Manage 227(1):137–144. https://doi.org/10.1016/j.foreco.2006.02.014
8. Hall KB, Stape J, Bullock BP, Frederick D, Wright J, Scolforo HF, Cook R (2019) A growth and yield model for eucalyptus benthamii in the Southeastern United States. For Sci. https://doi.org/10.1093/forsci/fxz061
9. Maier CA, Albaugh TJ, Cook RI, Hall K, McInnis D, Johnsen KH, Johnson J, Rubilar RA, Vose JM (2017) Comparative water use in short-rotation Eucalyptus benthamii and Pinus taeda trees in the Southern United States. For Ecol Manage 397:126–138. https://doi.org/10.1016/j.foreco.2017.04.038
10. Zhang L, Dawes WR, Walker GR (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resour Res 37(3):701–708. https://doi.org/10.1029/2000WR900325
11. Jackson RB, Jobbágy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, le Maitre DC, McCarl BA, Murray BC (2005) Trading water for carbon with biological carbon sequestration. Science 310(5756):1944–1947. https://doi.org/10.1126/science.1119282
12. Vose JM, Miniat CF, Sun G, Caldwell PV (2014) Potential implications for expansion of freeze-tolerant eucalyptus plantations on water resources in the southern United States. For Sci 60:1–13. https://doi.org/10.5849/forsci.14-087
13. Albaugh JM, Domec JC, Maier CA, Sucre EB, Leggett ZH, King JS (2014) Gas exchange and stand-level estimates of water use and gross primary productivity in an experimental pine and switchgrass intercrop forestry system on the Lower Coastal Plain of North Carolina, U.S.A. Agric For Meteorol 192(193):27–40. https://doi.org/10.1016/j.agrformet.2014.02.013
14. Benyon RG, Doody TM (2015) Comparison of interception, forest floor evaporation and transpiration in Pinus radiata and Eucalyptus globulus plantations. Hydrol Process 29(6):1173–1187. https://doi.org/10.1002/hyp.10237
15. Caldwell PV, Jackson CR, Miniat CF, Younger SE, Vining JA, McDonnell JJ, Aubrey DP (2018) Woody bioenergy crop selection can have large effects on water yield: a southeastern United States case study. Biomass Bioenerg 117:180–189. https://doi.org/10.1016/j.biombioe.2018.07.021
16. Schlichter T, Montes V (2012) Forests in development : a vital balance. Springer Science+Business Media B.V
17. Zolfaghar S, Villalobos-Vega R, Cleverly J, Zeppel M, Rumman R, Eamus D (2014) The influence of depth-to-groundwater on structure and productivity of Eucalyptus woodlands. Aust J Bot 62(5):428–437. https://doi.org/10.1071/BT14139
18. Zolfaghar S, Villalobos-Vega R, Zeppel M, Cleverly J, Rumman R, Hingee M, Boulain N, Li Z, Eamus D (2017) Transpiration of Eucalyptus woodlands across a natural gradient of depth-to-groundwater. Tree Physiol 37(7):961–975
19. Thelemann R, Johnson G, Sheaffer C, Banerjee S, Cai H, Wyse D (2010) The effect of landscape position on biomass crop yield. Agron J 102(2):513–522
20. Canadell J, Jackson RB, Ehleringer JR, Mooney HA, Sala OE, Schulze ED (1996) Maximum rooting depth of vegetation types at the global scale. Oecologia 108(4):583–595. https://doi.org/10.1007/BF00329030
21. Lintern M, Anand R, Ryan C, Paterson D (2013) Natural gold particles in Eucalyptus leaves and their relevance to exploration for buried gold deposits. Nat Commun 4
22. Morris JD, Collopy JJ (1999) Water use and salt accumulation by Eucalyptus camaldulensis and Casuarina cunninghamiana on a site with shallow saline groundwater. Elsevier, Netherlands 39(2–3):205–227. https://doi.org/10.1016/S0378-3774(98)00079-1
23. Benyon RG, Theiveyanathan S, Doody TM (2006) Impacts of tree plantations on groundwater in south-eastern Australia. Aust J Bot (2):181
24. Jr Watkins DW, de Moraes MMGA, Asbjornsen H, Mayer AS, Licata J, Lopez JG, Pypker TG, Molina VG, Marques GF, Carneiro ACG, Nuñez HM, Önal H, da NobregaGermano B (2015) Bioenergy development policy and practice must recognize potential hydrologic impacts: lessons from the Americas. Environ Manag 56(6):1295–1314. https://doi.org/10.1007/s00267-015-0460-x
25. King JS, Ceulemans R, Albaugh JM, Dillen SY, Domec J-C, Fichot R, Fischer M, Leggett Z, Sucre E, Trnka M, Zenone T (2013) The challenge of lignocellulosic bioenergy in a water-limited world. Bioscience 63(2):102–117. https://doi.org/10.1525/bio.2013.63.2.6
26. Kellison RC, Lea R, Marsh P (2013) Introduction of Eucalyptus spp. into the United States with special emphasis on the Southern United States. Int J For Res 2013:1–9. https://doi.org/10.1155/2013/189393
27. Hart PW, Johnson J, Paim R (2016) Status update on development of a eucalyptus plantation program in the southeastern United States and higher elevations of southern Brazil. Tappi J 15(3):148–155
28. Jackson CR, Bitew M, Du E (2014) When interflow also percolates: downslope travel distances and hillslope process zones.

Hydrol Process 28(7):3195–3200. https://doi.org/10.1002/hyp.10158

29. Du E, Jackson CR, Klaus J, McDonnell JJ, Griffiths NA, Williamson MF, Greco JL, Bitew M (2016) Interflow dynamics on a low relief forested hillslope: lots of fill, little spill. J Hydrol 534:648–658. https://doi.org/10.1016/j.jhydrol.2016.01.039
30. Jackson CR, Du E, Klaus J, Griffiths NA, Bitew M, McDonnell JJ (2016) Interactions among hydraulic conductivity distributions, subsurface topography, and transport thresholds revealed by a multitracer hillslope irrigation experiment. Water Resour Res 52(8):6186–6206. https://doi.org/10.1002/2015WR018364
31. Klaus J, Jackson CR (2018) Interflow is not binary: a continuous shallow perched layer does not imply continuous connectivity. Water Resour Res 54(9):5921–5932. https://doi.org/10.1029/2018WR022920
32. Griffiths NA, Jackson CR, Bitew MM, Fortner AM, Fouts KL, McCracken K, Phillips JR (2017) Water quality effects of short-rotation pine management for bioenergy feedstocks in the southeastern United States. For Ecol Manage 400:181–198. https://doi.org/10.1016/j.foreco.2017.06.011
33. Klaus J, McDonnell JJ, Jackson CR, Du E, Griffiths NA (2015) Where does streamwater come from in low-relief forested watersheds? A dual-isotope approach. Hydrol Earth Syst Sci 19(1):125–135. https://doi.org/10.5194/hess-19-125-2015
34. Flach GP, Harris MK, Hiergesell RA, Smits AD, Hawkins KL (1999) Regional groundwater flow model for C, K, L, and P reactor areas, Savannah River site, Aiken, South Carolina (U). Westinghouse Savannah River Company, Aiken, SC. https://digital.library.unt.edu/ark:/67531/metadc708339/
35. SRNS (2011) Savannah River Site Environmental Report for 2010, in: A.R. Mamatey (Ed.) Savannah River Nuclear Solutions, Aiken, SC
36. Squires MF, Vose RS, Applequist S, Durre I, Arguez A, Yin X, Heim RR, Owen TW (2012) NOAA's 1981–2010 U.S. Climate normals: an overview. Bull Amer Meteor Soc 93(11):1687–1697
37. Rogers VA (1990) Soil survey of Savannah River Plant area, parts of Aiken, Barnwell, and Allendale counties. South Carolina. https://www.osti.gov/biblio/5383134
38. Kilgo JC, Blake JI (2005) Ecology and management of a forested landscape : fifty years on the Savannah River Site, Washington : Island Press, c2005
39. Ferreira GWD, Rau BM, Aubrey DP (2020) Herbicide, fertilization, and planting density effects on intensively managed loblolly pine early stand development. For Ecol Manage 472:118206. https://doi.org/10.1016/j.foreco.2020.118206
40. Ruzol R, Staudhammer CL, Younger S, Aubrey DP, Loescher HW, Jackson CR, Starr GS (2022) Water use in a young Pinus taeda bioenergy plantation: effect of intensive management on stand evapotranspiration. Ecosphere 13(6):1–19. https://doi.org/10.1002/ecs2.4100
41. Keim RF, Skaugset AE (2003) Modelling effects of forest canopies on slope stability. Hydrol Process 17(7):1457–1467. https://doi.org/10.1002/hyp.5121
42. Granier A (1985) Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. Ann For Sci 42(2):193–200
43. Lu P, Urban L, Zhao P (2004) Granier's thermal dissipation probe (TDP) method for measuring sap flow in trees: Theory and practice. Acta Bot Sin 46(6):631–646
44. Sun HZ, Aubrey DP, Teskey RO (2012) A simple calibration improved the accuracy of the thermal dissipation technique for sap flow measurements in juvenile trees of six species. Trees Struct Funct 26(2):631–640. https://doi.org/10.1007/s00468-011-0631-1
45. Bush SE, Hultine KR, Sperry JS, Ehleringer JR (2010) Calibration of thermal dissipation sap flow probes for ring- and diffuse-porous trees. Tree Physiol 30(12):1545–1554. https://doi.org/10.1093/treephys/tpq096
46. Steppe K, Teskey RO, De Pauw DJW (2012) A Mriotte-based verification system for heat-based sap flow sensors, Acta. Horticulture 55–61. https://doi.org/10.17660/ActaHortic.2012.951.5
47. Dix MJ, Aubrey DP (2021) Recalibrating best practices, Challenges, and Limitations of Estimating Tree Transpiration Via Sap Flow. Curr Forestry Rep 7:31–37. https://doi.org/10.1007/s40725-021-00134-x
48. Dix MJ, Aubrey DP (2021) Calibration approach and range of observed sap flow influences transpiration estimates from thermal dissipation sensors. Agric For Meteorol 307:108534. https://doi.org/10.1016/j.agrformet.2021.108534
49. Larson P, Runyan C (2009) Evaluation of a capacitance water level recorder and calibration methods in an urban environment. http://www.umbc.edu/cuere/BaltimoreWTB/pdf/TM/2009/003.pdf
50. Coyle DR, Aubrey DP, Coleman MD (2016) Growth responses of narrow or broad site adapted tree species to a range of resource availability treatments after a full harvest rotation. For Ecol Manage 362:107–119. https://doi.org/10.1016/j.foreco.2015.11.047
51. Parresol BR (1999) Assessing tree and stand biomass: A review with examples and critical comparisons. For Sci 45(4):573–593
52. Vance E, Loehle C, Wigley T, Weatherford P (2014) Scientific basis for sustainable management of Eucalyptus and Populus as short-rotation woody crops in the US. Forests 5(5):901–918. https://doi.org/10.3390/f5050901
53. Stape JL, Binkley D, Ryan MG (2004) Eucalyptus production and the supply, use and efficiency of use of water, light and nitrogen across a geographic gradient in Brazil. For Ecol Manage 193(1):17–31. https://doi.org/10.1016/j.foreco.2004.01.020
54. Hatfield JL, Dold C (2019) Water-use efficiency: advances and challenges in a changing climate. Frontiers In Plant Science 10(103). https://doi.org/10.3389/fpls.2019.00103
55. Abrahamson DA, Dougherty PM, Zarnoch SJ (1998) Hydrological components of a young loblolly pine plantation on a sandy soil with estimates of water use and loss. Water Resour Res 34(12):3503–3513
56. Cardoso Ferreto DO, Reichert JM, Lopes Cavalcante RB, Srinivasan R (2021) Rainfall partitioning in young clonal plantations Eucalyptus species in a subtropical environment, and implications for water and forest management. International Soil and Water Conservation Research 9(3):474–484. https://doi.org/10.1016/j.iswcr.2021.01.002
57. Samuelson LJ, Stokes TA (2006) Transpiration and canopy stomatal conductance of 5-year-old loblolly pine in response to intensive management. For Sci 52(3):313–323
58. Gonzalez-Benecke CA, Martin TA (2010) Water availability and genetic effects on water relations of loblolly pine (Pinus taeda) stands. Tree Physiol 30(3):376–392. https://doi.org/10.1093/treephys/tpp118
59. White DA, Ren S, Mendham DS, Balocchi-Contreras F, Silberstein RP, Meason D, Iroumé A, Ramirez de Arellano P (2022) Is the reputation of *Eucalyptus* plantations for using more water than *Pinus* plantations justified? Hydrol Earth Syst Sci 26:5357–5371. https://doi.org/10.5194/hess-26-5357-2022
60. Otto MSG, Hubbard RM, Binkley D, Stape JL (2014) Dominant clonal Eucalyptus grandis×urophylla trees use water more efficiently. For Ecol Manage 328:117–121. https://doi.org/10.1016/j.foreco.2014.05.032
61. White D, Beadle C, Worledge D, Honeysett J (2016) Wood production per evapotranspiration was increased by irrigation in plantations of Eucalyptus globulus and E. nitens. New Forest 47(2):303–317. https://doi.org/10.1007/s11056-015-9516-2
62. Forrester DI, Collopy JJ, Morris JD (2010) Transpiration along an age series of Eucalyptus globulus plantations in southeastern Australia. For Ecol Manage 259(9):1754–1760. https://doi.org/10.1016/j.foreco.2009.04.023
63. Hubbard RM, Stape J, Ryan MG, Almeida AC, Rojas J (2010) Effects of irrigation on water use and water use efficiency in

two fast growing Eucalyptus plantations. For Ecol Manage 259(9):1714–1721. https://doi.org/10.1016/j.foreco.2009.10.028

64. Sun G, Noormets A, Gavazzi MJ, McNulty SG, Chen J, Domec JC, King JS, Amatya DM, Skaggs RW (2010) Energy and water balance of two contrasting loblolly pine plantations on the lower coastal plain of North Carolina USA. For Ecol Manag 259(7):1299–1310. https://doi.org/10.1016/j.foreco.2010.04.007
65. Grace JM, Skaggs RW, Chescheir GM (2006) Hydrologic and water quality effects of thinning loblolly pine. Trans ASABE 49(3):645–654. https://doi.org/10.13031/2013.20484
66. Butnor JR, Johnsen KH, Anderson PH, Hall KB, Halman JM, Hawley GJ, Maier CA, Schaberg PG (2018) Growth, photosynthesis, and cold tolerance of Eucalyptus benthamii planted in the piedmont of North Carolina. For Sci 65(1):59–67. https://doi.org/10.1093/forsci/fxy030
67. Doody TM, Colloff MJ, Davies M, Koul V, Benyon RG, Nagler PL (2015) Quantifying water requirements of riparian river red gum (Eucalyptus camaldulensis) in the Murray-Darling Basin, Australia – implications for the management of environmental flows. Ecohydrology 8(8):1471–1487. https://doi.org/10.1002/eco.1598