WATER USE OF AN INTENSIVELY MANAGED LOBLOLLY PINE PLANTATION: IMPLICATIONS OF RAPID TREE GROWTH ON STAND EVAPOTRANSPIRATION AND ITS COMPONENTS

by

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ABSTRACT

Increasing demand for plant-derived bioenergy is projected to expand tree plantations with intensive silviculture and improved tree varieties. A criticism regarding these plantations is their large water use to support fast growth and high productivity. However, use of improved varieties and high fertilizer and herbicide inputs will also lead to faster stand development, faster canopy closure, and changes in stand structure that can significantly influence water dynamics. Here, we studied the evapotranspiration (ET) of a young intensively managed loblolly pine stand and investigated the components of ET to determine the contribution of each to overall water use. We also compared ET with similar plantations receiving less intensive management to determine if our study stand used more water. We used the eddy covariance method to estimate ecosystem-level total ET (ET_{EC}), while plot-level estimates of ET (ET_P) were obtained via soil lysimeters, sap flow sensors and throughfall collectors, enabling measurement of the components of ET (soil evaporation, transpiration, and canopy interception, respectively). Results showed that ET increased over the fourth year since planting but decreased during the fifth year. Soil evaporation was the largest component of ET (36%), while transpiration and canopy interception accounted for 27% and 22%, respectively. Soil evaporation decreased through stand development while transpiration and canopy interception increased. Leaf area index (LAI) and precipitation were the most significant factors controlling ET and its components. Comparing the ET in this study with similar-aged plantations with lower LAI showed a higher water use. This high water use in the early stages of stand development wasn’t necessarily due to tree transpiration, but from high soil evaporation when the canopy is not fully developed. However,

the long-term implications of a shorter rotation age but more frequent harvest cycles can offset short-term advantages. While there are potential sources of uncertainty between the two methods, this study had the advantage of using multiple methods to understand the interconnected processes that contribute to ET. Therefore, it is recommended that long-term observation of ET using multiple measurement techniques to evaluate the impact of widespread loblolly bioenergy crops in the Southeastern US.

LIST OF ABBREVIATIONS AND SYMBOLS

LAI	Leaf area index (m^2 / m^2)
ET	Evapotranspiration; process of water transfer from the land to the atmosphere (via transpiration) (mm)
ET_{EC}	Evapotranspiration measured using the eddy covariance method
ET_P	Evapotranspiration measured by its components collected via plot measurements
Es	Soil evaporation; evaporation of water from the upper soil surface (mm)
T	Transpiration; water used by plants and evaporated from the leaf surface (mm)
I	Canopy interception; amount of precipitation intercepted by the canopy surface (mm)
Rn	Net radiation (W m^{-2})
VPD	Vapor pressure deficit
T_{soil}	Soil temperature (°C)
T_{air}	Air temperature (°C)
VWC	Volumetric water content of soil (%)
GS	Growing season months (April to September)
NGS	Non-growing season months (October to March)

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INTRODUCTION

Forest plantations with their high rates of productivity have been proposed as tools to mitigate rising atmospheric CO_2 concentrations (Hoffert et al. 2002; Jackson & Schlesinger, 2004; Pacala & Socolow, 2004). Increased productivity from fast-growing tree varieties treated with high levels of fertilizer and herbicide are now being considered as bioenergy crops to mitigate carbon emissions from fossil fuels (Griffiths et al. 2019). However, there is a cost to this high productivity with increased water use by the stand (Jackson et al. 2005). Although water use in forest plantations is affected by vegetation properties, such as the vertical height of plants, year-to-year variation in leaf area index (LAI) and rooting depth, as well as weather patterns (Waring & Schlesinger 1985), silvicultural treatments also increase water demand. Water use in forest plantations is intrinsically linked to improved varieties, intensive fertilizer and herbicide treatments, which leads to higher transpiration (T) rates compared to plantations with conventional genetics and silvicultural practices (Jokela et al. 2004; McLaughin et al. 2013; Bartkowiak et al. 2015), primarily because they expedite stand development.

The overall water balance of a forest, as well as the relative importance of the contributing components, changes dynamically through stand development. The use of improved varieties of trees in forest plantations, coupled with intensive silvicultural treatments, also leads to faster canopy development and greater water use (Jackson et al. 2007). Rapid canopy closure can reduce near-ground evaporation (E) by lowering soil temperature and reducing the amount of energy (net radiation) that reaches the soil surface (Porté et al. 2004, Royer et al. 2012; Villegas et al. 2010) while also contributing to higher rainfall interception that increases the proportion of water evaporated back into the atmosphere (Carlyle-Moses et al. 2011). As forest plantations grow and the ecosystem structure changes, the taller canopy will also increase aerodynamic conductance and become more coupled with the atmosphere, enhancing T rates (Cannell 1999). The role that ecosystem structure has is in influencing the partitioning of water in the system is therefore one of extreme importance (Marin et al. 2000; Dietz et al. 2006; Running & Coughlan 1988). Transpiration is a major component of ET in terrestrial ecosystems and usually accounts for 60-80% of the water cycle (Jasechko et al. 2013). Several studies have shown that the ratio of T to ET (T:ET) is positively correlated with vegetation cover and is independent of annual precipitation (Berkelhammer et al. 2016; Wang et al. 2010; Wang et al. 2014; Wei et al. 2017; Schlesinger & Jasechko 2014). This highlights the important effect that ecosystem structure has on water fluxes between the land and atmosphere. The difference between precipitation and ecosystem evapotranspiration determines the water yield in the form of runoff and drainage, which then supports downstream ecosystems and reservoir recharge (Ward et al. 2018). Therefore, ecosystem structure can have considerable ecological and economic consequences (Gedney et al. 2006; Katul et al. 2012; Milly et al. 2005; Reay et al. 2008; Rind et al. 1992). Unfortunately, one of the primary criticisms of forest plantations is their large water use, which has been shown to decrease annual streamflow and in extreme cases, dry nearby streams (Jackson et al. 2005). As such, even though cellulosic biomass is seen as a sustainable energy source it can potentially have a negative effect on the local water supply (Jackson et al. 2007).

As management of forest plantations shifts from conventional forestry to more intensive silvicultural practices to meet shorter rotation requirements to make the crop a viable biofuel, additional studies are needed to understand the implications of such shifts on water use by these young, rapidly changing stands. To develop a greater understanding of the links between rapid stand development and water use, this study focused on loblolly pine and its partitioning of precipitation during the early years of stand development. Loblolly pine (*Pinus taeda*) is widely cultivated and important timber species in the Southeastern United States because of its high productivity resulting from a long history of continuous tree improvement (McKeand et al. 2003; McKeand et al. 2006). This species makes up more than 50% of the standing pine volume in the region (Baker & Langdon 1990; Little & Viereck 1971) and is one of the strongest sinks of CO_2 in the continental US (400 to < 700 g C m^{-2} $year^{-1}$) (Novick et al. 2015). It is also considered as a potential short-rotation (~10-12y) bioenergy wood crop (SRWC) which is driven by tree improvement and more intensive management than conventional plantations (Griffiths et al. 2018). These faster-growing SRWC stands might offer greater potential for bioenergy feedstock and carbon sequestration but might also use more water, effectively "trading water for carbon" (Jackson et al. 2005).

Our objective was to study the relevant factors that influence ET and its components in a young intensively managed stand. We hypothesize that canopy development will change the components of ET by changing soil evaporation and loblolly pine T rates. In addition, these two components will follow different trajectories as the stand grows. Specifically, we hypothesize that soil evaporation rates will decrease due to increasing canopy cover that favors retention of soil moisture and increased canopy T. To determine how water is used and partitioned, we determined stand water balance by monitoring precipitation, canopy interception, soil evaporation, and transpiration for 31 months. Finally, the components of ET (i.e. soil evaporation, T, canopy water storage, and understory vegetation) were further analyzed to determine the influence of micrometeorological conditions and canopy development. Our findings of stand water use were then compared with stands that are managed with more conventional silviculture practices. We used two approaches to estimate stand water use – from aggregate estimates of ET components (transpiration, soil evaporation, and canopy interception) and from whole stand estimates (eddy covariance method). We compared these methods and determined differences between their estimates of ET, highlighting the sources of discrepancy specifically from assumptions and temporal and seasonal influences.

METHODS

Study Site

The study was conducted in an intensively managed loblolly pine stand dedicated to producing cellulosic biomass. Measurements were taken from April 2016 to March 2018 in a 119.8-ha watershed at the Savannah River Site located in the Piedmont of the Upper Coastal Plain physiographic province in South Carolina. The area was primarily agricultural fields before it was reforested and has been managed by the US Forest Service since 1951 (Griffith et al. 2019). The climate is humid subtropical with long-term average annual air temperature of 17.9°C; the lowest temperatures occur in January (8.2°C) and highest in July (33.2°C). Long-term average annual precipitation is 1403 mm with most of the rainfall occurring during summer (SERCC 2020). The soils are well-drained, loamy, and siliceous Ultisols of the Fuquay sand series (Rasmussen & Mote, 2007; Klaus et al. 2015; Du et al. 2016; Jackson et al. 2016). A loamy sand A horizon overlies a sandy E horizon and sandy clay loam argillic Bt horizon (Klaus et al. 2015; Du et al. 2016; Jackson et al. 2016). The land was primarily covered by mature pine stands with scattered hardwoods (Griffith et al. 2019) before harvesting of commercial timber occurred in spring 2012.

Prior to planting, the site was tilled, and herbicides were broadcasted using a mixture of imazapyr 4SL (1680 mL ha^{-1}) and glyphosate Rodeo (6720 mL ha^{-1}) to control woody and nonwoody vegetation. Between February 28 and March 3, 2013, bareroot loblolly pine seedlings (ArborGen Mass Controlled Pollinated AGM37) were hand-planted at a density of 1,346 trees ha^{-1}. Herbicide was again applied in 2013 and 2015 using a mixture of sulfometuron methyl (140 mL ha^{-1}) and imazapyr (280 mL ha^{-1}), respectively. Fertilizers were applied from 2013 to 2016 using the following concentrations: diammonium phosphate at 281 kg ha^{-1} (50.6 kg N ha^{-1} and 56.2 kg P ha^{-1}); in March 2014 using urea at 241 kg ha^{-1} (110.9 kg N ha^{-1}) in April 2013; a mixture of urea and diammonium phosphate at 313.6 kg ha^{-1} (106.6 kg N ha^{-1} and 26.9 kg P ha^{-1}) in February 2015; and urea at 425 kg ha^{-1} (196 kg N ha^{-1}) in September 2016. The site also experienced an extensive Nantucket pine moth (*Rhyacionia frustrana*) infestation during the summer of 2013, and thus the insecticide fipronil was applied in March 2014 at an equivalent rate of 1365 mL ha^{-1} (Asaro & Creighton, 2011). Applied silvicultural treatments are detailed in the report by Griffith et al. (2019) and Ferreira et al. (2020 & 2021).

Canopy Evapotranspiration

Evapotranspiration above the canopy (ET_{EC}) was measured using eddy covariance (EC) techniques (Kaimal and Gaynor 1991; Loescher et al. 2006). The concentration of H_2O was measured using an open-path LI-7500A infrared gas analyzer (IRGA, LI-COR Inc., Lincoln, Nebraska) and a high precision 3D sonic anemometer (CSAT-3, Campbell Scientific, Logan, Utah), which were logged at 10 Hz on a CR3000 datalogger (Campbell Scientific Inc., Logan, Utah). ET was derived from the formula:

$$ET = \frac{LE}{\rho_w \lambda_w} \quad \text{(Equation 1)}$$

where LE is latent energy (W m^{-2}), ρ_w is water density (997 kg m^{-3}), and λ_w is the latent heat of vaporization of water (2,260 kJ/kg).

Raw EC data were processed using EdiRe (v1.5.0.32), which performs a 2D coordinate rotation of the horizontal wind velocities to calculate turbulence statistics perpendicular to the local streamline. The time series examination occurs at 0.1 s intervals on both sides of a fixed lag time (± 0.3 s) to maximize the covariance between turbulence and scalar concentrations (Loescher et al. 2006). Fluxes were calculated at 30-min intervals, and corrections were performed for the mass transfer due to changes in density not taken into account by the IRGA and differences in the frequency response between the CSAT3 and LI-7500A (Webb et al. 1980; Massman 2000). To attain flux estimates independent of synoptic pressure fields, pressure corrections were conducted using the barometric pressure data collected from the flux tower. Processed flux data were filtered to remove erroneous 30-min fluxes resulting from systematic errors, such as: (1) excess moisture in the sampling path; (2) data retrieval and instrument calibration or maintenance; (3) excessive variation from the 30-min mean based on analysis of standard deviations and CO_2 statistics; (4) LE concentrations outside a reasonable range; or (5) poor coupling between the canopy and external atmospheric conditions defined by the friction velocity of wind, $u^* < 0.2$ m s^{-1} (Goulden et al. 1996; Whelan et al. 2013). To ensure data accuracy and consistency, the IRGA was calibrated every two months using a dew point generator (LI-610, LI-COR Inc., Lincoln, Nebraska), a zero-gas using pure nitrogen, and a reference CO_2 gas (496.6 ppm) as outlined in AmeriFlux protocols (Loescher and Munger 2006; Munger et al. 2012).

Missing values of LE and H were filled using a linear regression model with a moving window of observations (see Kunwor et al. 2015). Because standard methods of gap-filling LE and H as a function of net radiation (Rn) alone did not yield adequate fit statistics, regression models included not only Rn, but also vapor pressure deficit (VPD) , soil temperature at 8 cm depth (T_{soil}) and air temperature (T_{air}). Under most conditions, a moving window of 30 days was used. However, when parameter estimates were not significant ($p<0.05$), a 60-day window was used. During equipment outages where gaps of 30 days or less occurred, the 30 days prior and after the gap were used to parameterize the gap-filling equation. During the longer gap caused by hurricane Hermine, data from 90 days per-and post-storm were used to parameterize the gap-filling equation.

Canopy development

Canopy structure was measured monthly at the same locations within the footprint of the flux tower (n=20) using a Coolpix E5000 camera with an FC-E8 hemispherical lens (Nikon, Melville, NY, USA). Hemispherical photos were analyzed for canopy gap fraction and leaf area index (LAI) using WinScanopy (version 2010a; Regent Instruments, Quebec, QC, Canada). Canopy gap fraction measurements started at February 2017 after the tree height exceeded 1.4 meters. Litterfall traps (1x1 m^2) were installed within the footprint of the flux tower and adjacent to the LAI collection sites. LAI and litterfall were collected monthly and linearly interpolated to obtain weekly values.

Partitioning of Evapotranspiration

Component measurements of ET were measured from six plots located outside of the tower footprint, which incorporated variation across the entire watershed. These measurements included soil evaporation (Es), storage and outflow, tree transpiration (T), and canopy interception (I). The water yield of the site was determined using the water balance equation from Zhang et al. 2011 (Figure 1). Furthermore, since the study site is relatively flat, surface runoff was assumed zero. A second estimate of evapotranspiration, ET_P, was therefore defined as the sum of water efflux from soil evaporation, tree transpiration, and canopy interception. The disparity between ET_{EC} and ET_P was also determined to represent the unaccounted atmospheric water efflux from each method ($ET_U = ET_{EC} – ET_P$).

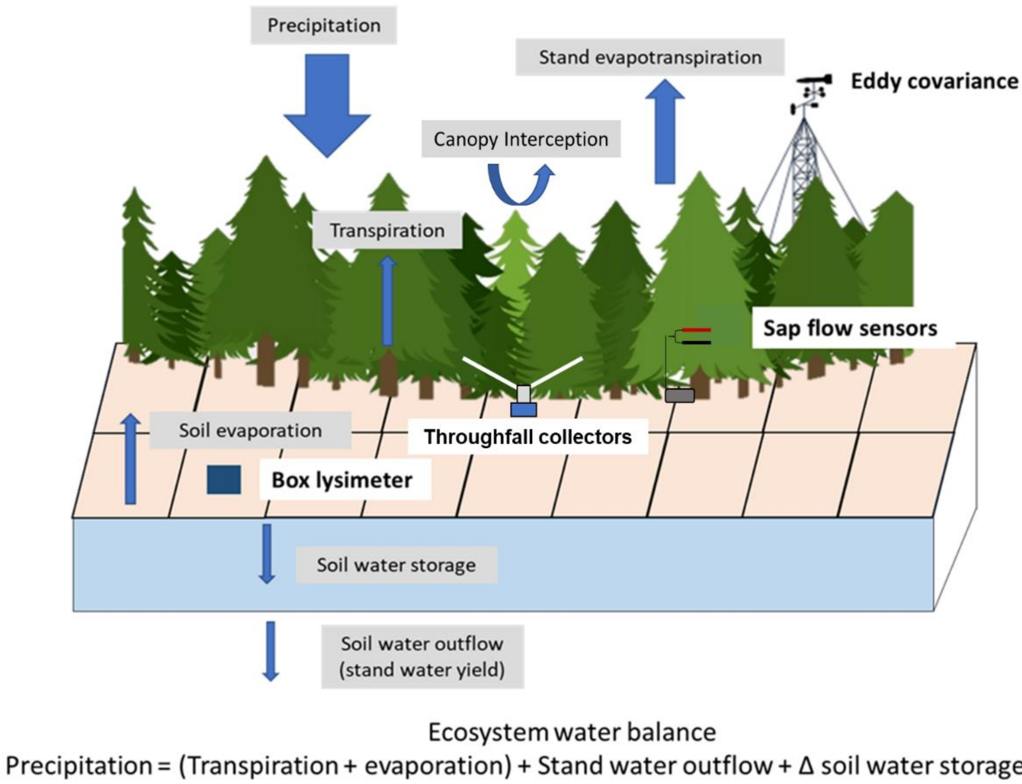

Figure 1. Experimental framework of the study that shows the pathways of water measured for the partitioning of evapotranspiration and deriving the stand water yield.

Precipitation and canopy interception

Precipitation (P) was continuously measured and reported as 15-min sums on each of the six plots using tipping bucket rain gauges (TE525; Campbell Scientific, Inc). Weekly precipitation totals were collected using standard rain gauges to verify the tipping buckets' depth. Throughfall (Tf) were measured using collectors made of 1.5" PVC limbs positioned near the base of the trees and drains into a central collector (Keim and Skaugset 2003). Throughfall volumes from four collectors in each plot (n=24) were collected weekly. Canopy interception (I) was estimated with the difference between precipitation and throughfall or as $I = P - Tf$.

Soil water evaporation

Soil evaporation was estimated using box lysimeters (0.5 m^2) which were installed to a depth of 0.5 m. Vegetation was removed from each box, to ensure that water was not lost from transpiration. The outflow volume was measured weekly while the volumetric soil moisture was recorded hourly using frequency domain reflectometry (FDR) utilizing two pairs of probes situated at 0-10 cm and 30-40 cm (Decagon ECH2O EC-5). Soil evaporation (Es) was estimated as:

$$Es = Tf - outflow - \Delta\ storage \qquad \text{(Equation 2)}$$

Tree Transpiration

To determine the canopy's T rate, 5 trees were instrumented with sap flow sensors in each plot (n=30) and measured using the Granier Thermal Dissipation Probe Method (TDP) (Granier 1985). The sensors were constructed following the methods in Sun et al. (2012). Continuous sap flow data was recorded using Campbell CR1000 dataloggers (Campbell Scientific Inc., Logan, Utah). Species-specific calibration for the sap flow sensors followed the findings of Younger et al. (in review) using eight (8) trees placed in potometers and instrumented with sap flow sensors. Sapwood area was measured from increment cores extracted from 29 additional trees in the summer of 2017 and 2018. Empirical measurements of sapwood area were then regressed against their diameter at breast height and the relationships were used to predict the sapwood area of the instrumented trees in the plots.

Statistical analyses

Data was collected for three growing seasons (April 2016 to October 2018). Growing season (GS) was defined as April to September while non-growing season (NGS) was from October to March. As a preliminary step, Principal Component Analysis (PCA) was performed to investigate data reduction and determine variables associated with seasonal interactions. Then, multiple and multivariate regression analyses were used to determine significant variables impacting patterns of ET and its components. A multiple regression model was estimated for each dependent variable (ET, soil evaporation, tree transpiration, canopy interception, and unaccounted portion). Model predictors included weekly averaged LAI and litterfall; weekly totals of precipitation and Rn; mean weekly T_{air}, RH, T_{soil}, soil heat flux, wind speed, soil volumetric water content (VWC), and vapor pressure deficit during the day (VPD). Seasonal interactions were also included for T_{air}, RH, litterfall, VPD, Rn, and LAI following the results of the PCA, after verifying low variance inflation factors (VIFs) to ensure the absence of multicollinearity (the maximum VIF < 5). Final models were selected via a stepwise model selection procedure using the Akaike information criterion (AIC). The final models were also subjected to the Durbin-Watson test to check for autocorrelation in model residuals. Multivariate analysis of variance (MANOVA) using Pillai's trace test statistic (Pillai 1955) was used to determine which variables had a significant effect on the group of components of ET. Independent variables that were identified as significant from the ANOVA tests were used as predictors. All statistical analyses were performed in R (R Core Team 2020).

RESULTS

Micrometeorology and Leaf Area

Annual precipitation in 2016 and 2017 were below (1011 mm and 981 mm, respectively) the long-term average of 1403 mm (SERCC, 2020), while the site received precipitation similar to the long-term average during 2018 (1405 mm). Average annual temperatures at the site from 2016 to 2018 were 19.6 °C, 18.3 °C, and 17.7 °C, respectively, above the long-term average for the region (17.3°C; SERCC, 2020). An above-average hurricane season was also experienced from September 2016 to March 2017 that brought higher than average precipitation during this period (Figure 2).

Canopy structure rapidly changed at the site. LAI increased four-fold over the course of the study (Figure 2). In 2016, mean LAI was 1.1 and continued to increase in 2017 (2.1) and 2018 (3.1). High LAI values were observed from May to September and declined from October to February. Litterfall also increased by two-fold from 2016 to 2017 but decreased by ~40% from 2017 to 2018. Pine needles comprised most of litterfall (> 90%) for both GS and NGS. Meanwhile, canopy gap fraction decreased by half from February 2017 (42%) to October 2018 (20%). Substantial drops in canopy gap fraction were mostly observed in June 2017 (< 30%) and in May 2018 (< 20%). As expected, canopy gap fraction showed strong negative correlation with

LAI (Pearson correlation coefficient r = -0.9), as stand development leads to fewer and smaller gaps in the canopy. Because of high multicollinearity between LAI and gap fraction, only the former was selected to represent canopy development for modeling and statistical analyses. As compared to gap fraction, LAI is also a better representation of the stand's aerodynamic roughness which is an important variable for water vapor exchange between vegetation and atmosphere (Baldocchi et al. 1997).

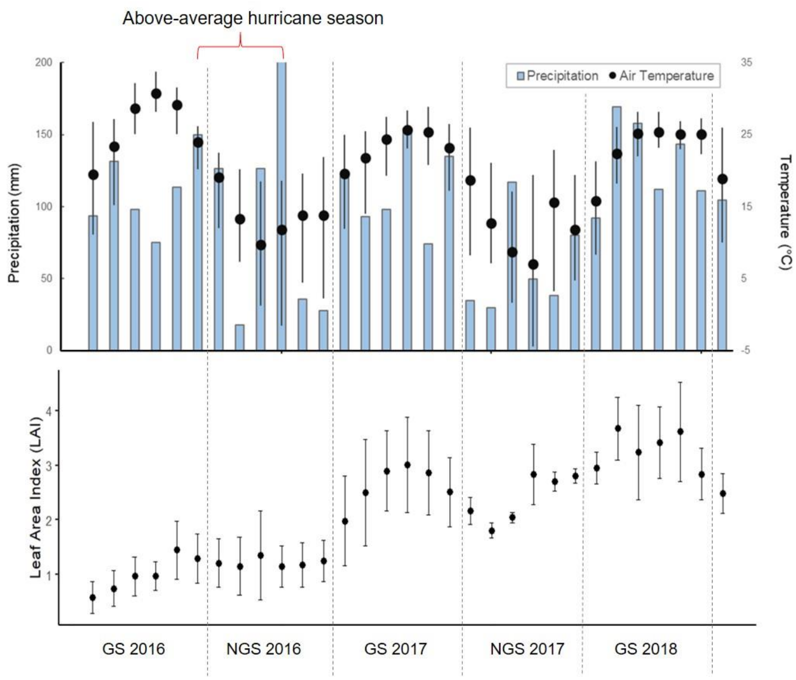

Figure 2. Monthly total precipitation, average air temperature, and average leaf area index (LAI) of the study site for three growing seasons from 2016 to 2018. GS is growing season (April to September), NGS is non-growing season (October to March).

Stand evapotranspiration trend

During the study, total precipitation at the site was 3114 mm, while evapotranspiration (ET_{EC}) reached 2189 mm resulting in a total stand water yield of 924 mm (Figure 3). When ET was partitioned, soil evaporation accounted for 36% of ET (919 mm), while sap flow and canopy interception accounted for 27% (704 mm) and 22% (565 mm), respectively. This led to 14% of ET to be unaccounted for (ET_U) (364 mm). This is most likely associated with the understory and transpiration from the few subdominant broadleaved shrubs that were not directly measured during the study. Total precipitation returned to the atmosphere via ET (ET:P) increased from 2016 to 2017 (76% to 85%) but remained constant in 2018 (83%). The contribution of soil evaporation to ET was 55% in 2016 and declined to 40% in 2017, and 16% in 2018. While T consistently increased its contribution to ET annually over the study period (21%, 28%, and 31% in 2016, 2017, and 2018, respectively). Canopy interception also showed a similar annual trend (18% in 2016, 22% in 2017, and 26% in 2018). Finally, the unaccounted portion of ET exhibited an increase from 2016 to 2017 (5% to 10%, respectively), and substantially increased again in 2018 (28%) (Figure 5).

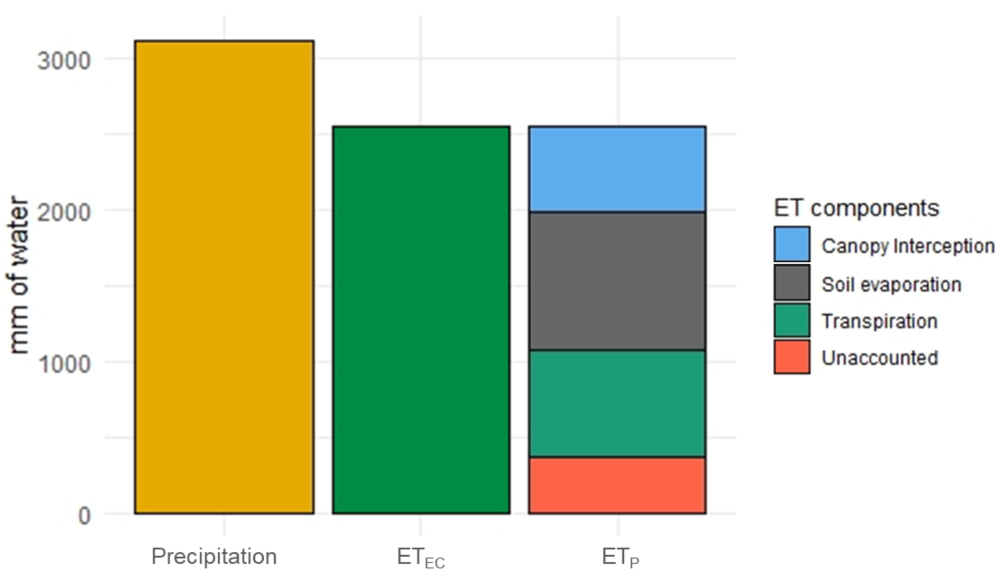

Figure 3. Total values of precipitation and ET measured via eddy covariance (ET_{EC}) and that measured by summing its components (ET_P) from April 2016 to October 2018.

When ET_{EC} and ET_P were compared by season, both showed higher values and variance during the GS than NGS (Figure 4). While ET_{EC} was higher than ET_P during the GS, it was similar during the NGS. This indicates that the sources of discrepancy between the two approaches are factors associated with the growing season, as explored further in section 4.1d of this study. Nevertheless, both approaches showed significant correlation (Figure S1).

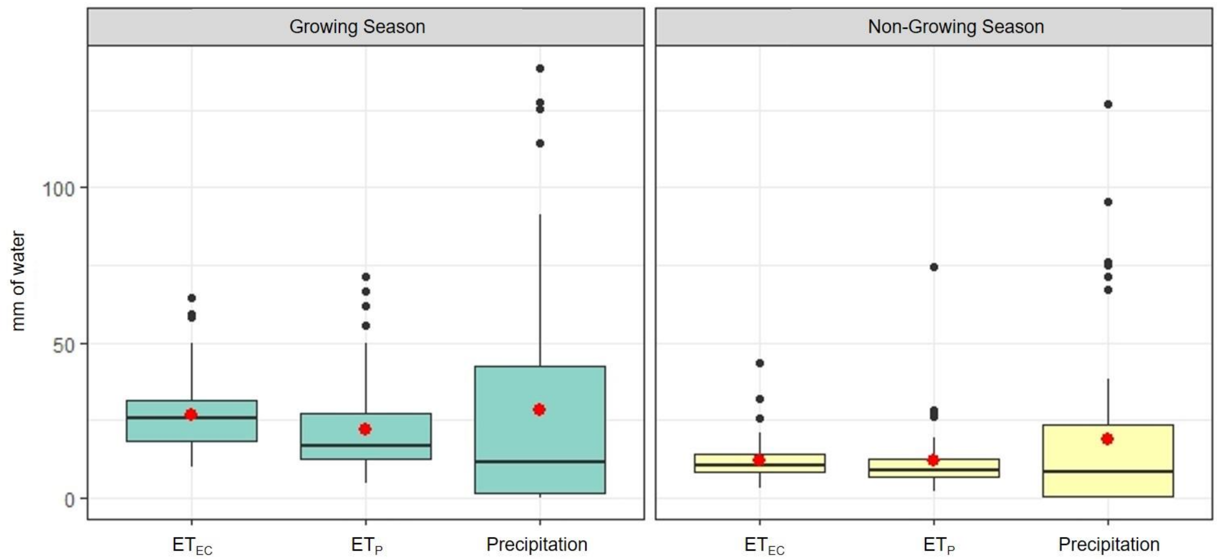

Figure 4. Distribution of monthly precipitation, ET measured by the flux tower (ET_{EC}), and ET measured by totaling its components from plot measurements (ET_P). Horizontal lines represent median while red dots denote mean values. Boxes outline interquartile range, vertical lines extend to 1.5 × interquartile range, with outliers individually marked.

ET components showed a consistent temporal pattern of declining Es while T slowly increased. Interception exhibited a relatively strong seasonal pattern. It was also exceptionally high in January 2017 because of the short-interval high precipitation recorded in that month. Es showed the highest change in variance throughout the study (Figure S2). As LAI continued to increase during the study, I and T also increased while Es decreased.

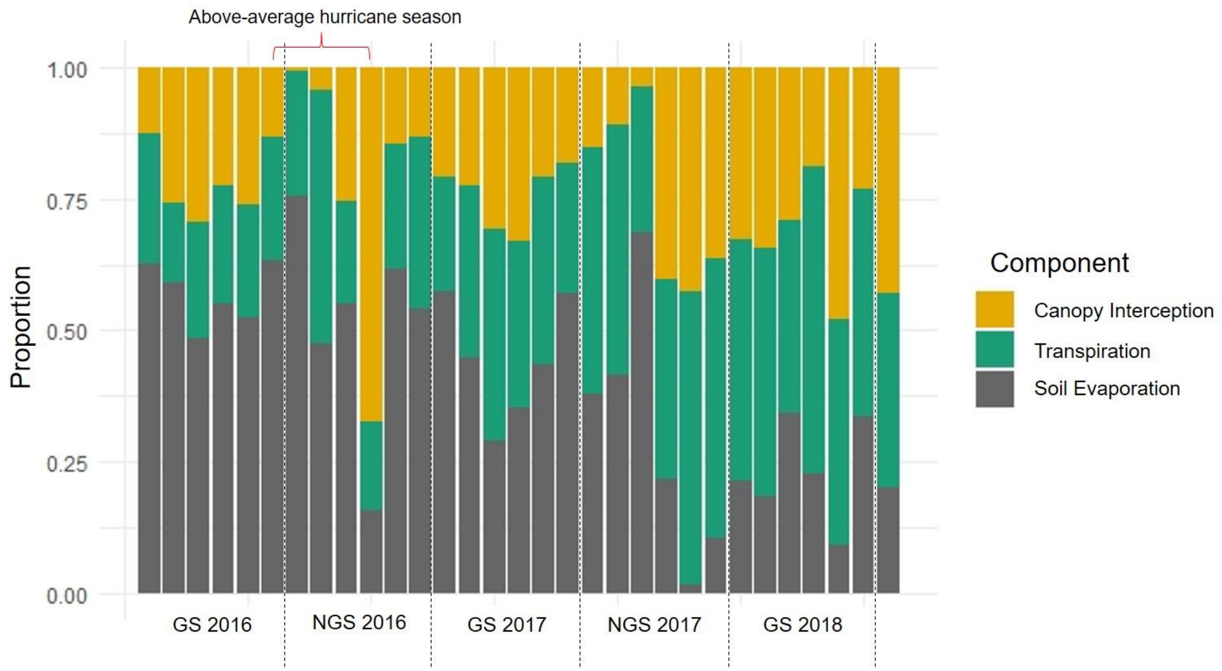

Figure 5. Monthly proportion of each ET component from April 2016 to October 2018.

Although ET_{EC} and ET_P were strongly correlated, ET_{EC} values were generally higher than ET_P. The unaccounted part of ET (ET_U), or the difference between ET_{EC} and ET_P, shows a strong seasonal pattern (Figure 6). ET_{EC} generally had higher estimates of evapotranspiration than ET_P during the GS while the opposite was observed during the NGS. However, the discrepancy during the NGS was lower than the GS in 2017. Again, this suggests that the factors that caused the discrepancy between the two approaches are associated with GS.

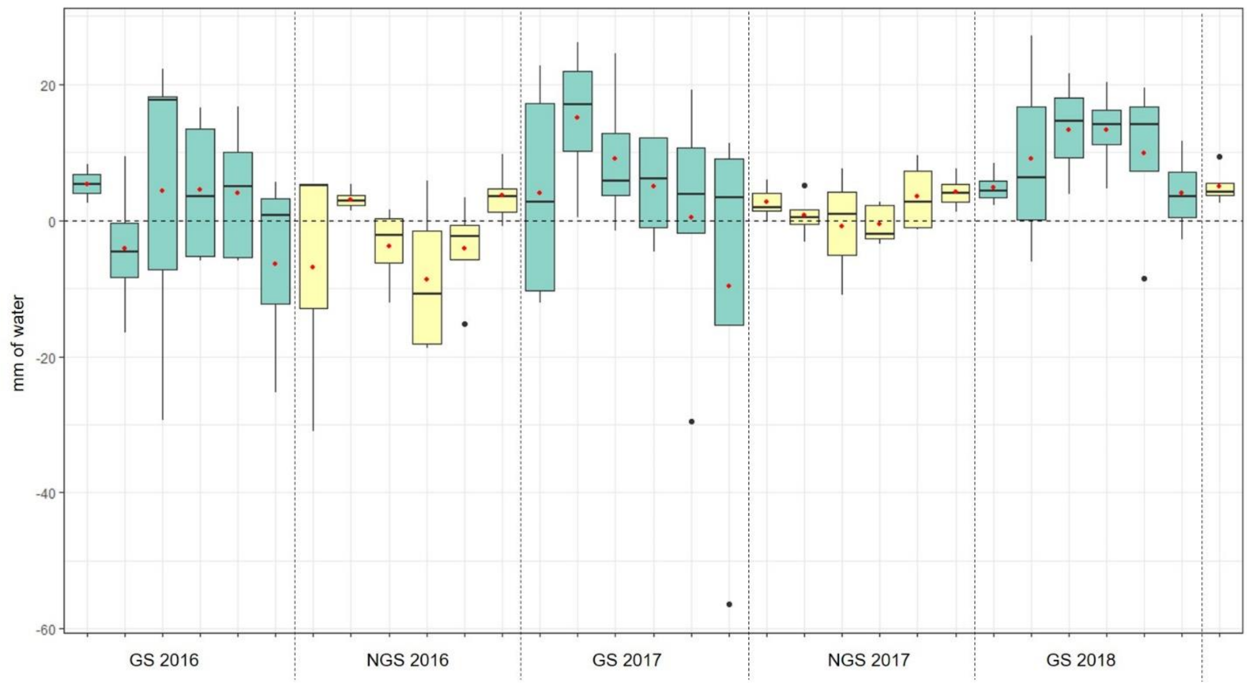

Figure 6. Distribution of weekly unaccounted ET (ET_U) from April 2016 to October 2018. Boxes outline interquartile range, vertical lines extend to 1.5 × interquartile range, with outliers individually marked. Mean values are designated with a red dot. Dotted line denotes no difference between ET_P and ET_{EC}. Positive values indicate that ET_{EC} was higher than recorded by ET_P. Negative values indicate that ET_{EC} was lower than recorded by ET_P.

Micrometeorological and Stand Structure Effects on ET and its components

Results of the PCA indicated that the first five principal components explained 85% of the variance in the independent variables. T_{air}, soil temperature, soil heat flux, wind speed, and RH, and litterfall showed high correlations (>0.5) with the first principal component for both GS and NGS. Meanwhile, Rn, LAI, VPD and precipitation were correlated with the second principal component. Observations also showed distinct groups for GS and NGS (Figure 7). Lastly, LAI, VPD, RH, Rn, and litterfall were highly influenced by season based on the direction (+ or -) of their eigenvalues for each season (S1).

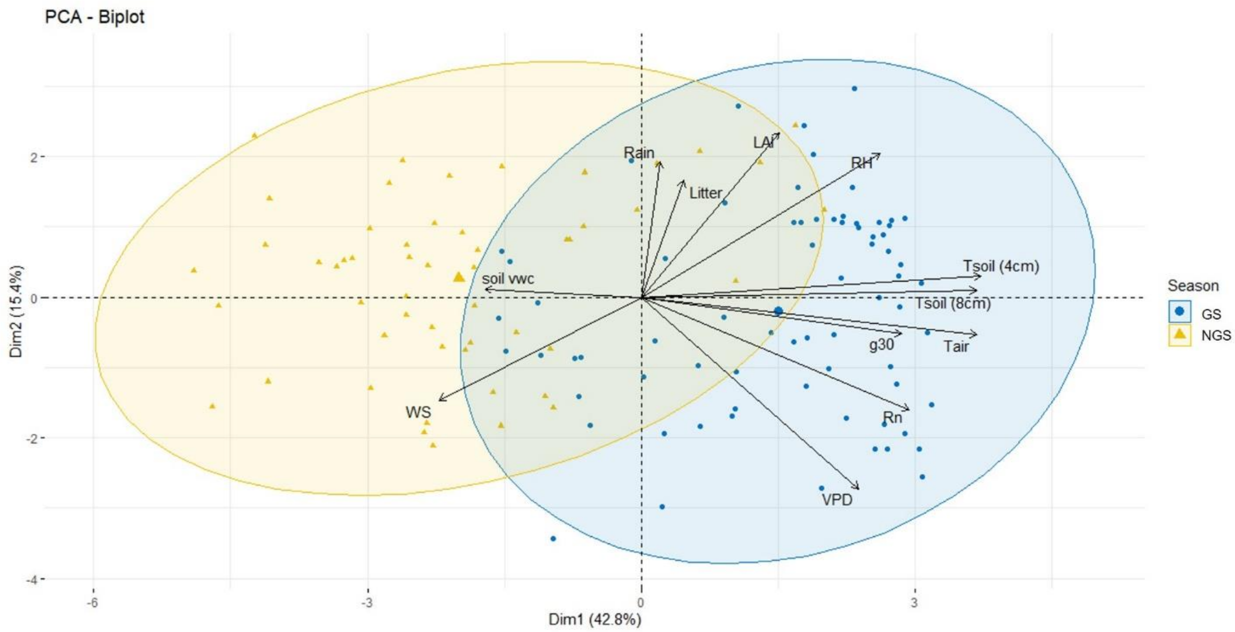

Figure 7. Biplot of the first two principal components from the Principal Component Analysis (PCA) of group of independent variables (WS = wind speed, Litter = total litterfall, soil vwc = soil moisture content, rain = precipitation, LAI = leaf area index, RH = relative humidity, Tsoil (4cm) = soil temperature at 4cm depth, Tsoil (8cm) = soil temperature at 8cm depth, Tair = air temperature, g30 = soil heat flux, Rn = net radiation, VPD = vapor pressure deficit) with observations grouped by season (GS = growing season, NGS = non-growing season).

Linear models showed that there was a significant increase in ET_{EC} as precipitation and Rn increased. Meanwhile, higher wind speeds decreased ET_{EC}. VPD and Rn also displayed a significant interaction with season that affected evapotranspiration ($p<0.001$; Table 1). Higher Rn resulted in increased ET_{EC} both during both seasons, but this increase was higher during GS

(Figure S3a). As VPD increased, ET_{EC} decreased during GS, while it slight increased during NGS (Figure S3b). For Es, increased precipitation had a large positive effect while increased LAI decreased it. Higher Rn also increased Es rates while higher soil moisture content decreased it. The explanatory power of this model was lower than the other components, and no significant interaction of season with the independent variables was found. Increased precipitation and LAI had a large positive effect on T. While increased VPD also increased T, a significant interaction between season and both VPD and Rn was also found ($p<0.001$). Increases in T were stronger with Rn in GS versus NGS (Figure S4a), while higher VPD decreased T during GS and increased T during NGS (Figure S4b).

Canopy interception rates increased as precipitation increased. Warmer soil temperature and higher soil moisture content were also associated with increased canopy interception, which were likely associated with the seasonal pattern of summertime rain. GS was also associated with higher interception rates than NGS, while higher litter input (again, likely associated with seasonal pattern of leaf growth in GS) and faster wind speeds had negative effects on canopy interception rates ($p<0.001$). Rn also had a significant effect on I which differed by season; I increased with higher Rn during the GS, while the effect of Rn during the NGS was minimal (although still positive) (Figure S5). ET_U decreased as precipitation increased, while increased LAI had a positive effect ($p<0.001$). Rn had a significant effect on ET_U, which depended on season. As Rn increased during the GS, ET_U also increased. However, increased Rn during the NGS slightly decreased ET_U (Figure S6). Finally, results of the MANOVA test showed that precipitation had the strongest global effect on ET and its components, followed by LAI and Rn, which interacted with season (p<0.001; Table 2). Wind speed, litterfall, and VPD, which interacted with season, were also significant global predictors.

Table 1. Partial regression slopes and standard errors from linear regression of evapotranspiration as measured by the flux tower (ET_{EC}), soil evaporation, sap flow, canopy interception, and unaccounted ET. Predictors with *, **, and *** are significant (p=0.05, ≤ 0.01, and ≤ 0.001, respectively).

	Partial regression slopes (Std. Error)				
Effect	**ET**	**Soil Evaporation**	**Transpiration**	**Canopy Interception**	**Unaccounted ET**
Net radiation	0.044 (0.020)*	0.042 (0.011)*	0.001 (0.006)	0.007 (0.009)	-0.001 (0.018)
Air temperature	0.573 (0.396)	-	-	-	0.213 (0.263)
Relative humidity	-0.028 (0.172)*	-	-	-	-
VPD	3.057 (8.283)	-	5.08 (1.677)**	-	-
LAI	-	-4.573 (0.702)***	1.377 (0.261)***	-	3.492 (0.948)***
Litterfall	-0.002 (0.001)	0.0004 (0.002)	-	-0.002 (0.001)**	- 0.001 (0.002)
Soil temperature	-	-	-0.064 (0.046)	0.332 (0.104)**	-
Soil moisture	-	-1.843 (0.668)**	-	1.002 (0.438)*	-
Rainfall	0.122 (0.022)***	0.224 (0.02)***	0.034 (0.006)	0.119 (0.01)***	-0.227 (0.023)***
Wind speed	-4.277 (2.077)*	-	-1.077 (0.554)***	-3.108 (1.181)**	-3.177 (2.309)
Season (growing)	-1.525 (14.767)	-3.982 (2.474)	-5.219 (2.281)*	0.179 (5.267)***	-17.611 (10.275)
Net radiation*season (GS)	0.102 (0.03)***	-	0.034 (0.008)***	-0.047 (0.014)**	0.08 (0.026)**
VPD*season (GS)	-24.953 (7.179)***	-	-8.349 (1.898)***	-	-

Litterfall*season (GS)	0.003 (0.002)	-	-	-	-0.005 (0.003)
Air temperature*season (GS)	-	-	-	-	-0.514 (0.371)
Model Adjusted R^2	0.68	0.558	0.667	0.59	0.622

Table 2. Type 3 tests of fixed effects from MANOVA of ET components (Canopy interception, Transpiration, Soil evaporation).

Effect	**DF**	**Pillai's trace**	**F-value**	**DF (num)**	**DF (den)**	**p-value**
Net Radiation	1	0.605	42.12	4	110	<0.001
Precipitation	1	0.787	101.8	4	110	<0.001
LAI	1	0.549	33.49	4	110	<0.001
Wind speed	1	0.117	3.63	4	110	0.008
Soil Moisture	1	0.080	2.40	4	110	0.054
Season	1	0.111	3.44	4	110	0.011
VPD	1	0.089	2.67	4	110	0.036
Litterfall	1	0.099	3.01	4	110	0.021
Net radiation × season	1	0.115	3.56	4	110	0.009
VPD × season	1	0.136	4.33	4	110	0.003

DISCUSSION

Evapotranspiration is a key hydrologic driver that returns 60-80% of terrestrial precipitation back to the atmosphere (Or et al. 2013). It is also an important nexus between terrestrial water, carbon, and surface energy exchanges (Zhang et al. 2016). Furthermore, ecosystem productivity and its water use (ET) are tightly coupled at multiple scales (Chapin et al. 2002; Waring & Running 2007). In over 40% of vegetated areas, water is the primary limiting factor for plant growth (Nemani et al. 2003) and the response of vegetation to water availability directly influences ET, carbon sequestration, growth, and productivity. The southern US is regarded as a 'water-rich' region and the 'timber basket' of the country. Thus, quantifying ET is essential as land conversion from natural ecosystems to plantation forests increases ecosystem water use as a trade-off for higher productivity (Sun et al. 2010). Here, we acknowledge that ET is a dynamic ecosystem process that is influenced by several different factors that contribute to changes in its components. Particularly, we studied the effect of a young rapidly developing stand and its water use. We predicted that canopy development would have the greatest influence on ET. We confirmed that canopy development had competing effects on each of the components of ET (Es, T, and I). During the early stages of the stand development, when trees were small and the canopy was open, soil evaporation was a substantially higher proportion of ET compared with transpiration and canopy interception. As canopy developed and closed, Es decreased while the proportion of T and I increased. Our findings highlight the importance of acknowledging how dynamic the various components of ET are. In addition, one must be able to characterize the individual factors and their drivers if we are to have a clearer understanding of how afforestation and faster stand growth contributes to the land-atmosphere hydrologic exchange.

Evapotranspiration components in intensively managed stand

The results of our analyses confirmed the first hypothesis that Es rates decreased while T increased during early stand development. In our study site, soil evaporation accounted for 36% of ET, considerably higher than a similar study which reported soil evaporation as 13% of ET (Domec et al. 2012). Estimates of T in our study (27%) were found to be smaller when compared to similar studies which observed ~33% contribution to ET (Domec et al. 2012). Meanwhile, I was found to be higher (22%) than reported in a previous study (12%) (Gavazzi et al. 2016). Because of improved planting stocks and intensive fertilizer and herbicide treatments, LAI in our study was already comparable with mid-rotation stands with conventional planting stocks and less intensive silvicultural treatments. LAI peaked at 3.7 in 2018 which is similar to 16-year old (3.9) and 19-year old (3.6) conventional loblolly stand (Sun et al. 2010; Domec et al. 2012). Compared to a similarly aged stand with conventional planting stock and conventional management (Domec et al. 2012), our study site's LAI was 3.5-fold greater at the same age. While canopy gap fraction rapidly changed from February 2017 to January 2018 decreasing from 42% to 27%. It then continued to decrease at a slower rate (February - October 2018) from 25% to 20%. We found that rapid stand development, as represented by rapid leaf area development and faster canopy closure, had a strong effect to the trajectories of the components of ET.

Canopy Interception

We attribute the higher canopy interception rates in this study relative to other studies to the rapid canopy development of this stand. Higher I may be due to variability and frequency of intense precipitation and storm events when data were collected. Interception rates can average from 25% during heavy rains of long duration to 100% during light rainfall (Gavazzi et al. 2016). Indeed, we found that precipitation had a strong positive effect on I (Table 1). However, the intensity and duration of precipitation also affects interception rates. In September 2016, a tropical storm (Hurricane Hermine) hit the site which brought above-average rain for that season. However, due to its brief and intense rainfall, canopy interception rates were low. Meanwhile, the highest precipitation in our site was recorded in January 2017 but rain events were less intense and longer in duration, resulting in the highest interception rates recorded for the study. We also found that during the GS, I rates were higher than NGS. In our study site, warmer months (GS) have less intense and longer rainfall events than colder months (NGS). Higher soil moisture content also corresponds to higher throughfall that indicates that the canopy water holding capacity was nearly saturated. Hence, during warmer months the canopy has high rainfall interception rates because of low intensity and longer rain events and greater LAI. During this period, soil moisture is also increased because of higher throughfall rates when the canopy is saturated with water. Meanwhile, faster wind speeds and more litterfall decreased canopy interception. Faster wind speeds can change the incident angel of rainfall and affect the amount of precipitation that falls to the effective canopy surface (Xiao et al. 2000). Moreover, as the effective surface of the canopy is reduced at the end of GS (although not as much when compared to deciduous species), litterfall is increased. At this point, canopy interception is reduced via the seasonal reduction of LAI, which coincides with this increase in litter production.

Soil Evaporation

There have been relatively few direct measurements of the fraction of ET attributed to Es (Herbst et al. 1996; Wallace et al. 1999), but it has been shown to be strongly dependent on soil wetness and plant cover (Jones et al. 2013). Soil texture, composition, and structure determine water potential and hydraulic conductivity which ultimately affects soil water potential (Saxton & Rawls 2006) and evaporation rates (An et al. 2018). One of the challenges of empirical Es measurements is the variation of these soil characteristics even within a small area, which can lead to large variability in measurements and difficulty in understanding the factors that influence it. Plant cover also affects Es. In ecosystems with LAI greater than 4, soil evaporation is relatively small (5% of ET) but can reach as much as half of total ET when LAI is below 2.0 (Jones et al. 2013). Indeed, this might have been the case when mean annual LAI increased from 1.1 to 3.0 from 2016 to 2018. This change in LAI was associated with a decrease in the fraction of Es from 55% to 16%. As LAI increases and soils are shaded, Es has also been reported to decline (Jackson & Wallace 1999; Wallace et al. 1999; Lin 2010) due to alterations in microclimate near the ground (Teare et al. 1973). Canopy structure and LAI are known to affect below-canopy radiation levels (Kuuluvainen & Pukkala 1989) which can potentially influence Es rates by lowering soil temperature and reducing the amount of energy (Rn) that reaches the soil surface (Porté et al. 2004, Royer et al. 2012; Villegas et al. 2010). Indeed, we found that Rn had a significant positive effect on soil evaporation (Table 1). Although near-ground Rn was not measured in this study, we suspect that it was reduced drastically when the canopy rapidly developed and closed. As a result, we attribute the decrease in Es to the reduction in near-ground Rn via rapid canopy closure. The accumulation of leaf litter on the forest floor also may have contributed to lower Es rates by covering the surface which increased resistances and prevented the capillary rise of liquid water from the soil underneath the litter (Varadan & Rao 1983; Bussière & Cellier 1994; Putuhena & Cordery 1996; Schaap & Bouten 1997; Findeling et al. 2003), although we didn’t find that litter was a significant predictor of Es in this study. We suspect that the effect of accumulated leaf litter to Es was underestimated here because plant growth, including litter accumulation, was controlled for lysimeter plots. Also, the large effect of LAI to Es may had dominated the effect of litter accumulation since litterfall has a lagged relationship with LAI dynamics. Canopy height may also have played a role in reducing Es. Increases in tree growth may lead to greater canopy roughness, which in turn can lead to the soil surface becoming decoupled with the atmosphere because of attenuation of wind due to the resistance of stems, branches, and leaves (Campbell & Norman 2012). During the study our tree height increased from approximately ~1.6 m to ~6.9 m (Starr unpublished data). Canopy growth and complexity also leads to higher boundary layer resistance at the soil surface and can decrease the evaporative demand between the soil and atmosphere, resulting in lower soil evaporation rates. The decreasing trend in Es rates in our study highlights the effect of canopy development through its influence on soil surface microclimate and through the restricting of water movement between the soil and the atmosphere. However, our results also found that among the components of ET, Es had the largest variability and was most difficult to understand. We attribute this uncertainty to the spatial variability of soil characteristics even within the watershed.

Tree Transpiration

Increased LAI (from 1.1 to 3.1) corresponded to increased T from 21% to 31% of the total ET measured by the eddy covariance tower. Other studies have reported similar proportions of T to ET (T:ET). For example, in loblolly stands at early-rotation (2.7 LAI), T:ET was 37% while it increased to 78% in an older stand with 4.3 LAI (Domec et al. 2012). This link between increased T:ET and LAI is intuitive since increasing vegetation cover also means more transpiring surface and more shading of soil (Nelson et al. 2020). The similarity in T:ET in our study site with other loblolly pine stands may also be a consequence of sites having sufficient water supply. At sites with water limitation, T rates have been shown to be insensitive to water availability until a significant portion of the available soil water is depleted (Chapin et al. 2002). If water is not a limiting factor then canopy structure, specifically leaf area, is the main regulator of water flux between the surface and atmosphere. Gonzalez-Benecke & Martin (2010) also reported that the T-induced water potential gradient from roots to shoots in loblolly pine stands was relatively constant even across different seed sources. If available soil water is not significantly reduced to the point of inducing plant water stress, loblolly pines maintain a relatively stable T rate. Moreover, in the context of biomass feedstocks, this provides evidence that improved varieties under intensive management have an advantage over conventional stands because of their high growth rate without significant increase in water use. Another variable that significantly affected transpiration was VPD. We found that T decreased as VPD increased in the growing season, but T only slightly increased as VPD increased in the non-growing season. VPD drives T and E, but on the other hand, also causes stomatal closure in plants thus inhibiting T. This saturating relationship between T with increasing VPD to prevent excessive water use and cavitation is evident from other studies (Nelson et al. 2020; Sperry et al. 1998; Adelman et al., 2008). However, our study showed that this relationship can be stronger during the growing season than the non-growing season. The difference in the magnitude of effect of VPD to T between seasons that we found in this study is attributed to the increase in evaporative demand during the growing season, which is intensified by higher LAI values relative to the non-growing season.

Relevance of multiple approaches to discriminate component effects to overall ET

Although the components of ET exhibited opposite trends throughout the study period, their combined effect on ET is based on their relative proportions each year. For example, from 2016 to 2017, the proportion of T and I combined is similar with Es (46%). ET increased during this period and is explained by the increase in T and I. Although Es slightly decreased during this period (2%), its proportion of ET was still high, so its decline did not reduce overall ET. Meanwhile, in 2018, ET decreased because Es was significantly reduced from the year prior (62%). Although T and I steadily increased during this period and even accounted for 57% of total ET, the extreme reduction of Es rates led to an overall decline in ET. This shows the large contribution of Es to ET in this young developing stand. Moreover, the decrease in ET in 2018 was not expected, especially when compared with other studies. In a chronosequence study where LAI increased from 0.55 (age 4 years) to 4.4 (age 16 years), annual ET increased by 30% (from 838 to 1087 mm) (Sun et al. 2010). However, our study was conducted in a stand that had more rapid growth relative to conventional plantations. However, ET didn’t consistently increase (680mm, 946mm, 886mm at age 3,4, and 5, respectively). Thus, without knowledge of the trajectories of the ET components, it would be difficult to determine what caused the decline in ET during the last year of the study. Here, we show that stand development had a large influence on ET, but more importantly, looking at its effect on each component provided an explanation on how ET partially decreased even though vegetation growth consistently increased.

As canopy structure and complexity increased with the addition of leaves and branches, it resulted in more T from the surface and greater rainfall interception capacity. Indeed, we found that when the canopy rapidly closed from 55% to 70% it led to a significant increase in the proportion of T and I to ET, while Es was largely reduced. This also agrees with findings that taller and rougher canopies lead to more coupling of the forest canopy and atmosphere by increasing the canopy boundary layer conductance (Campbell & Norman 2012; Clark et al. 2010), facilitating the removal of water via T (Cannell 1999). This shows that the rapid transition from a partially closed canopy (~50%) to a fully closed canopy can decrease ET by reducing Es which may lead to a reduction in water use over a rotation cycle. This has practical implications for forest plantation management that seeks to reduce stand water use.

Comparison of ET methods

When ET_{EC} was compared to $ET_{P.}$, it showed that the former was higher (17%). This discrepancy was highest during the growing season (up to 37%). This suggests that the sources of discrepancy might be from the understory and subdominant trees in the plot that were actively transpiring during the growing season but were not included ET_{P} portion of this study. However, this does not solely explain the discrepancy between the two methods since only a small portion of deciduous leaves from litterfall data was minor (~10%). Several methods exist to assess overall quantity of water flux in ET studies, and these measurement cross various spatial scales (e.g., individual plants, soil samples and soil profiles, atmospheric surface layer, and entire watersheds) (Nelson et al. 2020). These methods vary because of their differences in representation within a particular spatial and temporal scale, partitioning of components, and the unique set of assumptions, measurement errors, and biases that accompany them (Wilson et al. 2001). The eddy covariance method provides measurements of ET at high temporal resolution and at much greater scale than sap flow measurements. However, this method's representative region of measurement, or its 'footprint', changes in size and shape and is not fixed in time (Horst & Weil 1992; Baldocchi 1997). It is sensitive to weak turbulent periods, usually at night (Baldocchi et al. 2000) and cannot directly account for advection in heterogenous terrain. The sonic anemometer and infrared gas analyzer must also be dry to function; after rain events the sensors may thus underestimate evaporation from I and T (Stoy et al. 2006). Indeed, January and December where among the wettest months during our study period, especially in late 2016 and early 2017 when Hurricane Hermine hit the site as a tropical storm and the lysimeters and rain gauges recorded higher rates of precipitation than the EC tower. On the other hand, sap flow measurements are versatile for use in complex terrain and spatial heterogeneity does not limit its application. However, it is critical to perform species-specific and site-specific calibrations for sap flow sensors to ensure the best estimates of T possible (Dix & Aubrey 2021), and even then, radial gradients of sap flow in the sapwood can result in errors (Clearwater et al., 1999) which require scaling procedures to extrapolate from individual trees. Moreover, this method only measures one component of ET, which limits its ability to capture overall stand water use which is measured by EC. Perhaps the most variable component of ET measured in this study is Es as soil characteristics can greatly vary even within a watershed. The eddy covariance method and sap flow measurement might have less uncertainty than Es because the study site is an even-aged monoculture (less spatial and species heterogeneity), but soil characteristic can still differ from each measurement plots. This is supported by the results of the model for Es wherein it has the lowest explanatory power and had a relatively higher model intercept than the others. Finally, the temporal scale of data collection among lysimeters (weekly), sap flow (hourly) sensors, and the EC tower (hourly) may have also contributed to the discrepancy in measurements. The eddy covariance method is best for estimating ET at the fine temporal scale while plot measurements of the components of ET can be equally reliable for quantifying seasonal ET dynamics (Domec et al. 2012). Nevertheless, the two methods were still significantly correlated, and both were qualitatively similar. This also highlights the strength of using multiple methods when measuring ET. Since ET is a dynamic ecosystem process composed of interconnected processes, discerning the trajectories of its components is vital to understanding its overall behavior. Even though the two methods introduced uncertainties, the two approaches were able to ascribe the effect of rapid stand development to multiple water-related processes in the stand, which ultimately led to explaining the trajectory of overall stand water use.

ET comparison of an intensively managed loblolly pine stand with major forest ecosystems in the region

When comparing the ET rate of our study to several studies with less intensive management in the Southeastern US, the average annual ET of our study stand was higher than stands of similar composition and age (Table 3). Furthermore, our study site also had a higher

ET:P value (0.82) than stands of similar age but with lower LAI (Sun et al. 2010; Diggs 2004). Our stand ET:P was slightly lower than older pine plantations (10 years or older) with similar LAI (Sun et al. 2010; Gholz & Clark 2002). These findings do not support our second hypothesis that the intensively managed stand would have comparable water use to conventionally managed plantations of similar structure and age. However, this shows that leaf area, rather than age, should be used when comparing these sites. Indeed, the advanced genetics and silvicultural inputs effectively expedite stand development and the pace and pattern of forest structural characteristics that influence the ET partitioning. Although our site is younger than most used in research publication, its LAI was more comparable to older plantations than a stand with similar age. The proportion of ET:P also agrees well with LAI (ET:P increases as LAI also increases), except for the unmanaged site. The results of this study showed that ET temporarily decreased as LAI increased primarily due to the significant reduction in Es rates. However, as the canopy reaches full closure and LAI reaches a maximum, ET may increase again, driven by loblolly pine T and I. Considering the stand's full rotation age is 10-12 years, it is projected that average annual ET will be lower than estimated for conventional stands. Only a small increment in annual T and I rates are predicted to occur until the end of the rotation because the canopy is already near closure (80%). This implies that the intensively managed stand might have slightly lower annual ET than a conventional plantation at the end of its full rotation. Lower annual ET in the intensively managed stand also suggests that rapid tree growth does not necessarily come with higher tree water use and negative consequence to stand water yield. Rather, reduction in stand water yield was accompanied by high soil evaporative loss during the early stages of stand development. Moreover, it was mitigated in the intensively managed stand because of rapid canopy growth and shading of the soil surface. However, the results are more nuanced when extrapolated in the long-term. In the context of one rotation, loblolly pines can be a viable choice when management objectives are focused on producing biomass for cellulosic feedstock but is concerned with the possibility of enhanced stand water use. However, in the long-term, a shorter rotation means more frequent harvest cycles which can ultimately lead to higher water-use.

Table 3. Comparison of annual measured ET with other loblolly pine plantations with different management types in Southeastern US. Values in parentheses represent range.

Ecosystem	LAI	Management type	Method used	ET (mm/year)	P	ET/P	References
Loblolly pine plantation, 5 years old, SRNL, South Carolina	3.1	Intensive silviculture and improved loblolly pine variety	Eddy covariance; components measured (soil evaporation, transpiration, canopy interception)	1062 (873-1151)	1165	0.82	This study
Loblolly pine plantation 16 years old, North Carolina	4.4	Conventional plantation	Eddy covariance	1087 (1011–1226)	1238	0.88	Sun et al. (2010)
Loblolly pine plantation, 4 years old, coastal North Carolina	1.55	Conventional plantation	Eddy covariance	838 (755–885)	1274	0.66	Sun et al. (2010)
Loblolly pine plantation, 4 years old, Parker Track, North Carolina	N/A	Conventional plantation	Modeled (DRAINMOD)	895 (702–1078)	1152	0.78 (0.73-0.94)	Diggs (2004)
Loblolly pine plantation, 14–30 years old, Parker Track, North Carolina	4	Conventional plantation	Modeled (DRAINMOD)	997 (763–1792)	1538 (947–1346)	0.65	Amatya et al. (2006)

Loblolly pine plantation (PP), 25 years old, Piedmont North Carolina	5.5	Previously clear cut; unmanaged	Eddy covariance	658 (560–740)	1092 (930–1350)	0.6	Stoy et al. (2006)
Slash pine (Pinus taeda L.) plantation, clearcut, Florida	3	Conventional plantation	Eddy covariance	958 (869–1048)	959 (869–1048)	0.85 (0.84–0.86)	Gholz and Clark (2002)
Slash pine (Pinus taeda L.) plantation, 10 years old, Florida	5.1	Conventional plantation	Eddy covariance	1058 (994–1122)	1062 (877–1247)	1.0 (0.9–1.1)	Gholz and Clark (2002)
Slash pine (Pinus taeda L.) plantation, full-rotation, Florida	6.5	Conventional plantation	Eddy covariance	1193 (1102–1284)	1289 (887–1014)	0.93 (0.92–0.93)	Gholz and Clark (2002)

CONCLUSION

We found that in a young intensively managed loblolly pine stand, the components of ET show different trends owing to rapid canopy development. In general, ET declined due to a substantial reduction in Es while T and I rates were consistently increasing. A combination of micrometeorological factors and progress in stand structure influenced these components of ET, but LAI was found to be the most significant factor that affected the decrease in Es and increased T and I rates. We also compared ET in our intensively managed loblolly stand to other plantations studied in the Southeastern US. Although ET in our intensively managed stand is higher than similar-aged plantations, its total ET by the end of one rotation is projected to be lower than a conventional stand. This implies that the rapid tree growth in intensively managed stands of loblolly pine does not come with a significant increase in stand water use when compared with a plantation that has conventional management. When plantation managers are concerned with ‘trading water for carbon’ to meet demands for plant-derived bioenergy, utilizing genetically enhanced trees is a viable option. This is supported by the results of our study which showed that high water use in a highly productive tree plantation isn’t necessarily due to tree water consumption, but from losses from Es, especially during its early years when the canopy is not yet fully developed. Es can be decreased via rapid stand development, which can lead to shorter rotation age and lower total ET for each harvest. However, the long-term implications of a shorter rotation but more frequent harvest cycles can offset its short-term advantages. For future work, we recommend the study of ET components within and across rotations of intensively managed forest plantations to understand long-term impact to local water yield.

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