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Drought and thinning have limited impacts on evapotranspiration in a managed pine plantation on the southeastern United States coastal plain

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ABSTRACT

Managed and natural coastal plain forests in the humid southeastern United States exchange large amounts of water and energy with the atmosphere through the evapotranspiration (ET) process. ET plays an important role in controlling regional hydrology, climate, and ecosystem productivity. However, long-term studies on the impacts of forest management and climatic variability on forest ET are rare, and our understanding of both external and internal drivers on seasonal and interannual ET variability is incomplete. Using techniques centered on an eddy covariance method, the present study measured year-round ET flux and associated hydrometeorological variables in a drained loblolly pine (*Pinus taeda* L.) plantation on the lower coastal plain of North Carolina, U.S. We found that annual ET was relatively stable (1076 ± 104 mm) in comparison to precipitation (P) (1168 ± 216 mm) during the 10-year study period when the site experienced extreme climate (2007–2008) and forest thinning (2009). At the seasonal time scale, mean ET/P varied between 0.41 and 1.51, with a mean value of 1.12 ± 0.23 and 0.72 ± 0.16 for the growing and dormant seasons, respectively. The extreme drought during 2007–2008 (mean annual P, 854 mm) only resulted in a slight decrease (~8%) in annual ET owing to the shallow groundwater common to the study area. Although changes in leaf area index and canopy structure were large after the stand was 50% thinned in the fall of 2009, mean annual ET was similar and averaged 1055 mm and 1104 mm before (2005, 2006 and 2009) and after (2010–2015) thinning, respectively. Data suggested that annual ET recovered within two years of the thinning as a result of rapid canopy closure and growth of understory. Further analysis indicated that available energy was the key driver of ET: approximately 69% and 61% of the monthly variations in ET were explained by net radiation during the dormant and growing seasons, respectively. Overall, we concluded that drought and forest thinning had limited impacts on seasonal and annual ET in this energy limited forest ecosystem with shallow groundwater. The results from this study help to better understand regional ecohydrological processes and projecting potential effects of forest management and extreme climate on water and carbon cycles.

1. Introduction

Globally, terrestrial ecosystem evapotranspiration (ET) returns approximately 60% of annual precipitation (P) to the atmosphere (Oki and Kanae, 2006) and plays an important role in the regional distribution of water supply for both people and ecosystems (Sun et al., 2016). In the southeastern United States, ET from forested watersheds can vary from 50% of annual precipitation in the cool southern Appalachian Mountains to more than 90% in the coastal Florida flatwoods (Sun et al., 2002; Gholz and Clark, 2002). Changes in land cover and climate affect the regional hydrological cycle, energy balances, and ecosystem functions directly through altering ET processes (Ellison et al., 2017; Sun et al., 2010). Improved estimation of ET, especially under extreme climate such as drought (Vose et al., 2016), is needed to better understand terrestrial ecosystem processes and services (Oishi et al., 2018), and to project potential effects of forest management and

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climate change on water and carbon cycles (Duan et al., 2016; Sun et al., 2015a, b).

In contrast to spatial and temporal variations in forest potential ET, which depend on local atmospheric evaporative demand (Amatya et al., 2016; Rao et al., 2011), variations in actual forest ET are a function of interactions between climate, plant available water, stand characteristics (e.g., species, age) and silvicultural practices (Domec et al., 2012; Liu et al., 2017; Sun et al., 2001). In the southeastern U.S., previous studies (Lu et al., 2003; Oishi et al., 2010, 2018) suggested that ET is mainly controlled by atmospheric evaporative demand followed by the seasonal variations in leaf area index (Sun et al., 2010), whereas other studies showed the importance of available soil water and the plant rooting-depth in determining ET (Bracho et al., 2008; Hallema et al., 2014). Other studies on pine flatwoods in the southeastern U.S. concluded that ET did not differ significantly between managed mature forests and clear-cut sites during wet years and ET differences had only weak relations to vapor pressure deficit (VPD) and unsaturated surface soil water supply (Gholz and Clark, 2002). Overall, ET is still arguably the most uncertain ecohydrological variable for constructing ecosystem water budgets (Sun et al., 2011; 2015a; 2016; Tian et al., 2015) and for understanding the ecological impacts of extreme climate (Vose et al., 2016) and land use change such as urbanization (Hao et al., 2015).

Pine plantations are a major economic component in southern United States representing the most intensively managed forests in the world (Fox et al., 2007; Gavazzi et al., 2016). Among which, loblolly pine (*Pinus taeda* L.) is by far the single most commercially important plantation tree species for the region (McKeand et al., 2003). More than 1 million hectare of intensively managed loblolly pine plantations are found along the lower coastal plain in eastern North Carolina (Domec et al., 2012). However, these forests remain one of the few under-characterized ecosystems in the otherwise dense Ameriflux network of eddy covariance sites (Noormets et al., 2010). Unlike upland watersheds with hydrology dominated by hill slope processes, the hydrology of these flat and poorly drained landscapes on the coastal plains are characterized by shallow water tables that are strongly coupled with precipitation and ET (Amatya and Skaggs, 2001; Sun et al., 2002, 2010). Therefore, water fluxes and control mechanisms in coastal plain forests are expected to differ greatly from upland forests. Climate change projections predict an intensifying hydrologic cycle and an increasing frequency of droughts in the southern U.S. (IPCC, 2014; Strzepek et al., 2010), yet quantitative understanding of the extreme climatic effects (e.g., drought) on coastal ecosystem water exchange remains limited.

Due to concerns of possible impacts of expansions of pine plantations on water quantity and quality, evaluating environmental effects of forest management in the coastal regions has been the focal point of considerable research (Amatya et al., 1996; Amatya and Skaggs, 2001; 2008; McLaughlin et al., 2013; Sun et al., 2010; 2015a). Whereas many studies have addressed effects of thinning and artificial drainage on loblolly pine forest water balance components (Amatya et al., 1996; Amatya and Skaggs, 2001; Gavazzi et al., 2016; Grace et al., 2006; Sun et al., 2001), few studies have directly measured the impact of thinning on watershed-level ET. In addition, widely used hydrological models developed for these coastal regions have rarely been validated with measured ET (Amatya and Skaggs, 2001; Domec et al., 2012; Tian et al., 2015). To date, little is known about the long-term impacts of silvicultural practices (e.g., thinning) on ET variability of these coastal plain plantations on a seasonal and inter-annual basis (Sun et al., 2010).

We have maintained an intensive carbon and water balance research site (core AmeriFlux site) centered on an eddy covariance (EC) measurement system in a loblolly pine plantation on the lower coastal plain of North Carolina, USA (Domec et al., 2012; Noormets et al., 2010, 2012; Sun et al., 2010). Continuous measurements of water vapor and carbon fluxes, and associated micrometeorology were made over a 10-year period from 2006 through 2015. This time frame includes two consecutive years representing severe meteorological drought and one thinning treatment (~50% of the basal area removed). The datasets provide an opportunity to assess drought and thinning effects on ET at seasonal and annual time scales.

The objectives of this study are to: (1) quantify seasonal and inter-annual variability in ET in a loblolly pine plantation on the lower coastal plain; (2) assess drought and thinning impacts on ET of a coastal pine plantation at seasonal and annual time scales; and (3) examine external and internal drivers to explain long-term ET variability.

2. Methods

2.1. Site description

This long-term study was carried out in a loblolly pine (*Pinus taeda* L.) plantation, registered in the FLUXNET database as US-NC2. The study site (35°48′N, 76°40′W) is located on the lower coastal plain of North Carolina in the southeastern U.S., and is dominated by a humid subtropical climate. To improve soil hydrology for growing commercial pine plantations, the area is drained artificially by a network of drainage channels. Ditches with a depth of 0.9–1.0 m are spaced 80–100 m apart, and are connected by roadside collection ditches. Outflow is monitored on the downstream end of this drainage network using a V-notch weir. Parallel ditches and roadside canals divide the flat landscape into a mosaic of regularly shaped fields and blocks of fields (Grace et al., 2006; Sun et al., 2010). The long-term average annual precipitation in the study region was 1321 mm (1945–2014) and was evenly distributed over the year. The annual mean temperature was 15.5°C, with a high mean monthly temperature in July (26.6°C), and a mean monthly low in January (6.4°C).

The gaged 90-ha watershed for this study is covered with loblolly pine trees that were planted in 1992 at an estimated planting density of 1400 trees ha^{-1} with trees 1.5 m apart in 4.5 m spaced rows (Sun et al., 2010). In 2006, the stand basal area was measured as approximately 29 $m^2 ha^{-1}$, and tree density was about 655 trees ha^{-1}. An averaged canopy height was 13.8 m in 2006. The understory stratum was mainly composed of *Acer rubrum* (red maple), *Vitis* spp. (grape vine), *Rubus* spp. (blackberry) and *Arundinaria gigantea* (giant cane). Thinning was conducted in the fall (October–December) of 2009, removing every fourth row and selectively thinning remaining rows, which removed approximately 50% of the basal area (Gavazzi et al., 2016). Mean stand basal area for woody plants (diameter at breast height, DBH > 2.5 cm) was 34.2 $m^2 ha^{-1}$ before the thinning and 14.9 $m^2 ha^{-1}$ afterward. Mean canopy height was approximately 16.5 m after the thinning. The number of understory stems per hectare decreased by 40% immediately after thinning but has increased by approximately 60% per year since (Gavazzi et al., 2016). The soil type is classified as a Belhaven Series histosol and characterized by deep, well drained organic soil. The top layer for Belhaven soils has a total porosity greater than 0.75 $cm^3 cm^{-3}$ and organic matter content greater than 80% (Grace et al., 2006).

2.2. Measurements

Eddy covariance (EC) measurements of water fluxes and associated environmental factors were made during 2006 to 2015. The 23-m flux tower was installed in the middle of the watershed. The tower was surrounded in most directions by uniform canopies with similar species and age composition, which extended a uniform fetch of about 1000 m. The turbulent flux showed no directional variability, suggesting that the fetch was sufficient for periods when other quality control criteria were met (Noormets et al., 2010, 2012). The tower was equipped with an open-path infrared gas analyzer (Model LI-7500, Li-Cor Inc., NE, USA) and a three-dimensional ultrasonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, UT, USA), which were used to measure fluctuations and averages of the wind velocity, temperature, CO_2 and water vapor concentrations. Data were sampled at 10 Hz, averaged over 30 min, and directly recorded using the synchronous device for measurement (SDM) technique with a data logger (CR5000, Campbell Scientific, Inc.).

Along with flux measurements, standard meteorological data were collected above the canopy, including air temperature (T_a) and relative humidity (HMP45AC, Vaisala, Finland), net radiation (R_n, CNR-1, Kipp & Zonen, Delft, the Netherlands). Precipitation was measured by two tipping bucket type of rain gages (TE-525, Campbell Scientific Inc.), and one backup manual rain gage (Forestry Suppliers Inc., USA). Soil volumetric water content was averaged through the top 30 cm using a vertically inserted CS616 time domain reflectometer (Campbell Scientific Inc.). Shallow groundwater table depths were recorded on an hourly basis with an ultrasonic water level sensor (Infinities, Port Orange, FL, USA). Leaf area index (LAI) was measured either under clear skies with low solar elevation (i.e., early in the morning or late in the afternoon) or under overcast conditions, using a LAI-2000 Plant Canopy Analyzer (Li-Cor, Lincoln, NE, USA). Measurements were taken throughout the year at five locations (center and four cardinal directions 7 m from each plot center) within each of the four centrally located vegetation plots (Noormets et al., 2012).

2.3. Data processing and analysis

The 10-Hz EC data were processed with the EC_PROCESSOR software package (http://www4.ncsu.edu/~anoorme/ECP/). We omitted abnormal data that were measured during periods of inadequate turbulence ($u^* < 0.2$ m s^{-1}). Additionally, unrepresentative outliers were removed, for example, data points with LE > 800 W m^{-2} or LE < −200 W m^{-2} and H > 500 W m^{-2} or H < −200 W m^{-2}. The gap-filling methods of a look-up table and mean diurnal variations were used to fill gaps in flux measurement data attributed to instrument malfunction and bad weather conditions (e.g., precipitation) (Falge et al., 2001). Large gaps (e.g., missing data due to instrument malfunction from September 2011 to March 2012) in data of climatic factors (e.g., TA, VPD and R_n) was filled with data of US-NC1 site registered in the FLUXNET database (Sun et al., 2010), an adjacent site 3 km away from US-NC2, while R_n for a given month of the year was estimated to be consistent between the two sites from 2010 through 2012. Because latent heat correlates tightly with R_n (Sun et al., 2010), we used R_n to gapfill missing reference evapotranspiration (ET_o) and ET data at the monthly scale ($ET_o = 0.294\ R_n + 8.140$, $R^2 = 0.97$; $ET = 0.270\ R_n + 17.818$, $R^2 = 0.84$) for the same period due to instrument malfunction (from September 2011 to March 2012).

Energy budget closure was used to evaluate eddy covariance data (Wilson and Baldocchi, 2000). The energy budget closure for this site was estimated to be 0.89, a value considered rather high when compared to other sites within the eddy flux network (Sun et al., 2010; Wilson et al., 2002). This energy budget closure indicates that data at this site were reasonable for seasonal and annual ET analysis. The diagnostic parameter, the Priestley-Taylor coefficient (α) (Priestley and Taylor, 1972) was calculated based on daytime hours only ($R_n > 0$ W m^{-2}) during the period after excluding days with precipitation. Daily and monthly means of α were calculated by averaging half-hour values.

2.4. Calculations of diagnostic parameters

In addition to examining the dynamics of actual ET, we also investigated the behavior of a normalized ET metric (f_{RET}), which was defined as the ratio between actual ET and ET_o (Anderson et al., 2007). Normalizing by ET_o removes some degree of variability in ET due to seasonal variations in available energy and vegetation cover amount (Anderson et al., 2011). We use anomalies of f_{RET} (Δf_{RET}) to capture the ET signals of drought (Anderson et al., 2011, 2015) and forest disturbance (e.g., thinning, fire), calculated as:

$$\Delta f_{RET}(m, y_k) = \langle f_{RET}(m, y_k)\rangle - \frac{1}{n}\sum_{k=1}^{n}\langle f_{RET}(m, y_k)\rangle \tag{1}$$

where $\langle f_{RET}(m, y)\rangle$ is the f_{RET} composite for month m, year y; $f_{RET}(m, y)$ is the value for month m, year y and n is the number of years in the study period.

ET_o, defined as the potential evapotranspiration of a hypothetical surface of grass of uniform height, actively growing and adequately watered, was calculated using the FAO (Food and Agriculture Organization) Penman–Monteith equation as follows (Allen et al., 1998):

$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma\frac{900}{T_a + 273}u_2 VPD}{\Delta + \gamma(1 + 0.34u_2)} \tag{2}$$

here R_n is net radiation (MJ m^{-2}), G is soil heat flux (MJ m^{-2}), Δ is the slope of saturation water vapor pressure versus temperature curve (kPa °C^{-1}), T_a is air temperature (°C), VPD is vapor pressure deficit (kPa), γ is psychrometric constant (kPa °C^{-1}), u_2 is wind speed at 2 m height, and 900 is unit conversion factor.

Canopy conductance (g_c, mm s^{-1}) is major variable in controlling actual tree transpiration. It was calculated using the inverted form of the Penman–Monteith equation (Monteith and Unsworth, 1990):

$$g_c = \frac{\gamma LE g_a}{\Delta(R_n - G) + \rho C_p VPD - LE(\Delta + \gamma)} \tag{3}$$

where LE is latent heat flux density (W m^{-2}), R_n is net radiation (W m^{-2}), G is soil heat flux (W m^{-2}), ρ is air density (kg m^{-3}), c_p is specific heat of air (J kg^{-1} K^{-1}), and g_a is aerodynamic conductance of the air layer between the canopy and flux measurement height (mm s^{-1}), calculated assuming neutral stability as

$$g_a = [(u/u^{*2}) + 6.2u^{*-0.67}]^{-1} \tag{4}$$

where u is the mean horizontal wind speed above the canopy (m s^{-1}), and u^* is the friction velocity (m s^{-1}) obtained from EC measurements.

Priestley and Taylor equation, a simplified form of the Penman–Monteith model for estimating actual ET has been widely used for humid regions (Priestley and Taylor, 1972). The coefficient (α) (Priestley and Taylor, 1972) is often used to analyze the seasonal variations of controlling factors on ET (Vourlitis et al., 2015; Zha et al., 2010, which was calculated as:

$$\alpha = \frac{\Delta + \gamma}{\Delta}\frac{LE}{H + LE} \tag{5}$$

where H is sensible heat flux density (W m^{-2}). When α is greater than or close to 1, ET is mainly constrained by atmospheric demand. When α is less than 1, ET is mainly constrained by water supply.

3. Results

3.1. Environmental conditions

Mean annual R_n varied from 3106 MJ m^{-2} (in 2013) to 3327 MJ m^{-2} (in 2007) from 2006 to 2015, and it was 2221 MJ m^{-2} during the growing season (May-October) and 977 MJ m^{-2} during the dormant season (November-April) annually over the 10-year study period (Fig. 1a). Monthly R_n was highest in July and lowest in December, with a value of 451.2 ± 12.1 MJ m^{-2} and 67.7 ± 10.0 MJ m^{-2}, respectively. Mean annual T_a was 15.8 ± 0.4 °C and ranged from 15.1 °C (in 2014) to 16.4 °C (in 2015). Seasonal variation in T_a followed a similar pattern as that of R_n (Fig. 1b). The monthly mean T_a varied between 6.0 °C (in January) and 25.1 °C (in July). Monthly mean VPD varied between 0.30 kPa (during the dormant month of December) and 0.96 kPa (during the growing month of June), with a mean of 0.58 kPa. At the annual scale, the mean VPD in 2007 (0.68 kPa) was greater than that in the other years because of the lower precipitation but higher solar radiation (3327 MJ m^{-2}). Annual precipitation (P) was evenly distributed over the year, but highly variable (1168 ± 216 mm) between years. Annual P in drought years 2007 and 2008 was 801 mm

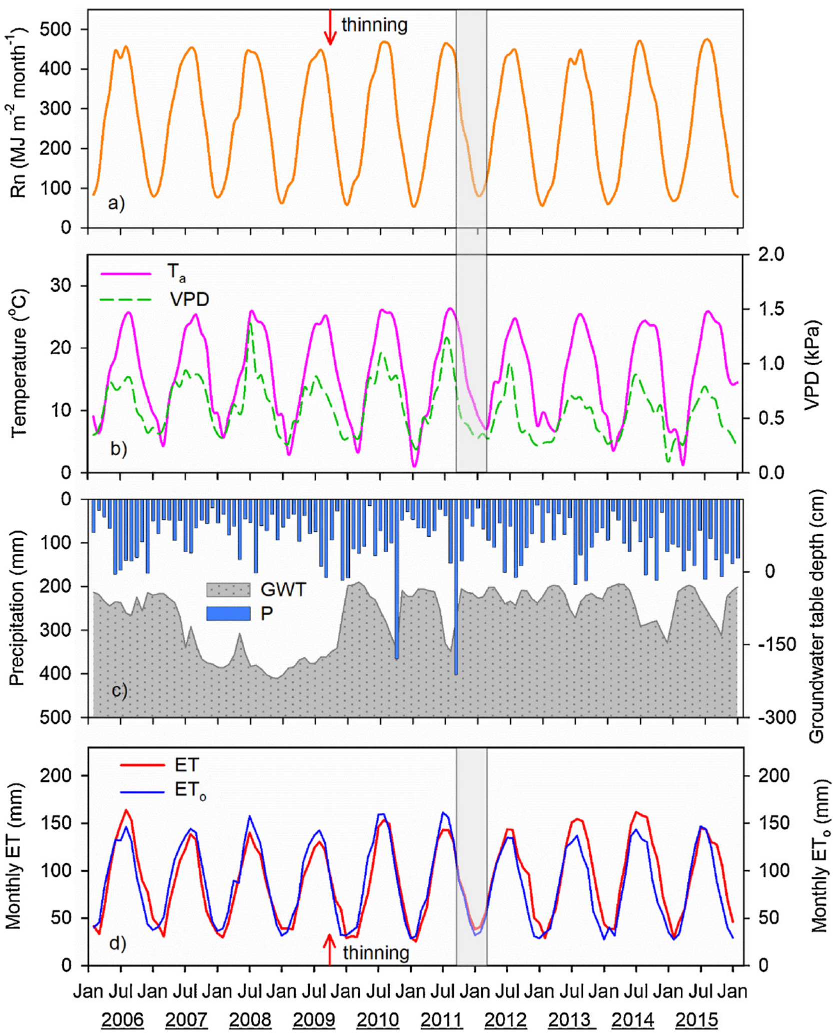

Fig. 1. Temporal dynamics of monthly net radiation (R_n) (a), monthly mean air temperatures (T_a), monthly mean vapor pressure deficit (VPD) (b), monthly precipitation (P), monthly mean groundwater table depth (GWT) (c) and monthly evapotranspiration (ET) and reference evapotranspiration (ET_o) (d) in a loblolly pine plantation on the lower coastal plain of North Carolina, USA, during 2006 and 2015. The red arrows indicate the thinning treatment conducted in the fall of 2009. The light grey areas in a) and d) indicate the gap-filled data (September 2011-March 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

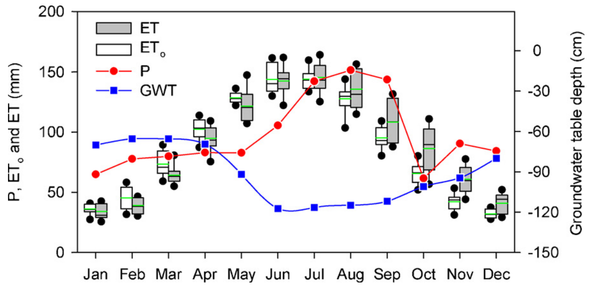

Fig. 2. Comparisons among mean monthly values of precipitation (P), reference evapotranspiration (ET_o, box-plot in white), actual evapotranspiration (ET, box-plot in grey), and groundwater table depth (GWT) over a 10-year period in a loblolly pine plantation on the lower coastal plain of North Carolina, U.S. The boxes extend from the lower to upper quartile values of the data, with a green dash marking the median. Whiskers extend to the 10th and 90th percentiles and dots represent the 5th and 95th percentiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and 907 mm, respectively. Compared to long-term mean annual precipitation (1321 mm) measured 8-km North at the Plymouth Weather Station in Washington County by NOAA (http://www.nc-climate.ncsu.edu/), both 2007 and 2008 represented extremely dry years. The groundwater table experienced a substantial drawdown in 2007 and 2008, and dropped to its lowest level (< -2 m) during the dry year of 2008.

3.2. Evapotranspiration dynamics

From 2006 to 2015, the mean annual ET over the loblolly pine plantation was 1076 ± 99 mm, ranging from 952 mm in 2007 to 1254 mm in 2014. Although P (1168 ± 216 mm) was highly variable inter-annually, ET remained relatively stable (Fig. 1c, d). Monthly ET was highest in July and lowest in January, with a value of 145 ± 12 mm and 35 ± 7 mm, respectively. During the observation period, the mean annual ET_o was estimated as 1038 ± 60 mm, and greater ET_o resulted in greater ET on both monthly and annual scales (Fig. 1d and 2). The regression analysis showed that the monthly ET and ET_o from 2006 to 2015 were positively correlated ($P < 0.001$), and approximately 84% of the monthly variation in total ET could be explained by ET_o (Fig. 1d).

P in the growing season (687 mm) was 40% higher than during the dormant season (480 mm). The mean cumulative ET (739 mm) in the growing season was much higher than the dormant seasons (337 mm), and even exceeded P. ET and ET_o during the growing season were 2.2 and 2.1 times greater than during the dormant season, respectively. Moreover, on average, the relatively high ET and ET_o in May and June resulted in an obvious decline in groundwater level (Fig. 2), which suggests a strong coupling relationship among precipitation, evapotranspiration and groundwater in the coastal plain forests.

Mean annual ET/P (i.e., evaporative index) was 0.92, ranging from 0.68 in 2015 to 1.19 in 2007, whereas mean annual ET_o/P (i.e., dryness index) was 0.89, ranging from 0.61 in 2015 to 1.38 in 2007 (Fig. 3). At the seasonal time scale, mean ET_o/P was 1.08 ± 0.31 during the

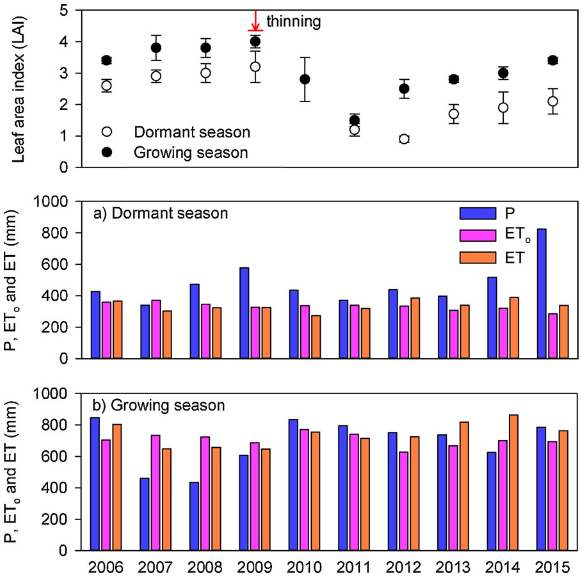

Fig. 3. Seasonal dynamics of leaf area index (LAI, mean ± standard deviation), precipitation (P), reference evapotranspiration (ET_o) and evapotranspiration (ET) in the loblolly pine plantation on the lower coastal plain of North Carolina, U.S. The red arrow indicates the thinning treatment conducted in the fall of 2009. In 2010, LAI was only measured in July, August and September. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

growing season and 0.74 ± 0.20 during the dormant season. Mean ET/P varied between 0.41 in the dormant season of 2015 and 1.51 in the growing season of 2008, with a mean value of 1.11 ± 0.23 and 0.74 ± 0.16 for the growing and dormant seasons during 2006–2015, respectively. Moreover, mean ET/P was much higher in the growing season of the drought years of 2007 (1.41) and 2008 (1.51) than in other years during the observation period.

3.3. Evapotranspiration responses to drought

As mentioned above, 2007 and 2008 represented two extremely dry years with mean annual $ET_o/P = 1.3$ (Table 1). Mean annual precipitation during these two drought years (854 mm/year) was 35% lower than mean annual value (1308 mm) of 2005, 2006 and 2009, which were chosen as a comparison (non-drought years) with similar mean annual precipitation to that of 2006–2015 (1168 mm) (Fig. 4a, b). Mean annual ET was 967 mm in drought years and 1055 mm in non-drought years. Drought resulted in slightly decreased (~8%) annual ET on average. In drought years of 2007 and 2008, annual ET exceeded annual precipitation, with a mean annual value of ET/P estimated to be 1.1.

We further examined temporal behaviors of the anomaly of monthly f_{RET} as a drought stress indicator during drought and non-drought years over the loblolly pine plantation. Negative deviations in the anomaly of monthly f_{RET} were found in the drought years of 2007 and 2008 (Fig. 5), meaning that it captures the drought signal well at the seasonal time scale.

3.4. Evapotranspiration responses to thinning

The 2009 thinning treatment reduced annual mean leaf area index by about 60% for 2011 (1.3 ± 0.3) compared to the pre-thinning year of 2009 (3.6 ± 0.5), respectively (Fig. 3). P, ET_o and actual ET estimates for the 3 pre-treatment (2005, 2006 and 2009) and 6 post-treatment years (2010–2015) are presented in Table 2, where the drought years 2007 and 2008 were removed to reduce bias in the assessment of thinning impacts. There was a slight decrease of cumulative ET over this pine forest in the first two years (2010 and 2011) after thinning compared to the pre-thinning years, with recovery of pre-thinning water use in the following years (Table 2; Fig. 4c, d). Although changes in LAI and canopy structure were large, annual ET estimates were similar and averaged 1055 mm and 1115 mm before (2005, 2006 and 2009) and after thinning (2010–2015). Results suggested that annual ET in the pine forest was relatively insensitive to management activities due to the rapid recovery.

Anomalies of the monthly f_{RET} presented in Fig. 6 illustrate thinning effects on seasonal ET. The f_{RET} anomaly values showed a corresponding decrease at the end of the 2009 followed by a steady recovery trend over the following several years, indicating a hydrologic recovery approximately two years after thinning.

3.5. Climatic and biological factors controlling ET

To address the relative importance of the environmental and biological controls on ET, seasonal behaviors of Priestley-Taylor coefficient (α) and surface conductance (g_c) were also investigated (Fig. 7). The mean monthly α at midday (12:00–13:00 central daylight time) for the growing and dormant seasons during 2006–2015 was 0.93 and 0.73, respectively. The α values were close to 1.0 indicating that available energy (R_n or VPD) rather than water supply controlled forest ET (Priestley and Taylor, 1972; Li et al., 2010; Zha et al., 2010). Seasonal variation patterns for g_c were similar to those of α (Fig. 7). However, when g_c was larger than 10 mm s^{-1}, the increase in α was insensitive to the increase in g_c as indicated by the smaller slope of the α-g_c curve (Fig. 8). Thus, when g_c was high during the peak growing season, the sensitivity of ET to physiological control (g_c) became low, and the effects of climate rather than soil water control on ET became more important.

Further analysis indicated that approximately 69% and 61% of the monthly variation in ET was explained by variations of R_n during the dormant and growing seasons, respectively. In contrast, T_a and VPD explained 54% and 67% of the monthly ET variations in the dormant seasons, 22% and 53% of the ET variations in the growing season, respectively. Therefore, energy availability as represented by R_n contributed most to ET variations over this coastal plain pine forest.

Table 1
A comparison of annual leaf area index (LAI), precipitation (P), reference evapotranspiration (ET_o), evapotranspiration (ET) and ratios of ET_o/P and ET/ET_o during drought and non-drought years (mean ± standard deviation) over the loblolly pine plantation.

	Year	LAI	P (mm)	ET_o (mm)	ET (mm)	ET_o/P	ET/ET_o
Drought year	2007	3.2	801	1106	952	1.38	0.86
	2008	3.4	907	1069	982	1.18	0.92
	Mean	**3.3 ± 0.1**	**854 ± 75**	**1087 ± 26**	**967 ± 21**	**1.3 ± 0.1**	**0.9 ± 0.04**
Non-drought year	2005	3.1	1467[a]	1069[a]	1024[a]	0.73	0.96
	2006	3.0	1272	1064	1170	0.84	1.10
	2009	3.6	1184	1014	972	0.86	0.96
	Mean	**3.2 ± 0.3**	**1308 ± 145**	**1049 ± 30**	**1055 ± 103**	**0.8 ± 0.1**	**1.0 ± 0.1**

[a] Data from Sun et al. (2010).

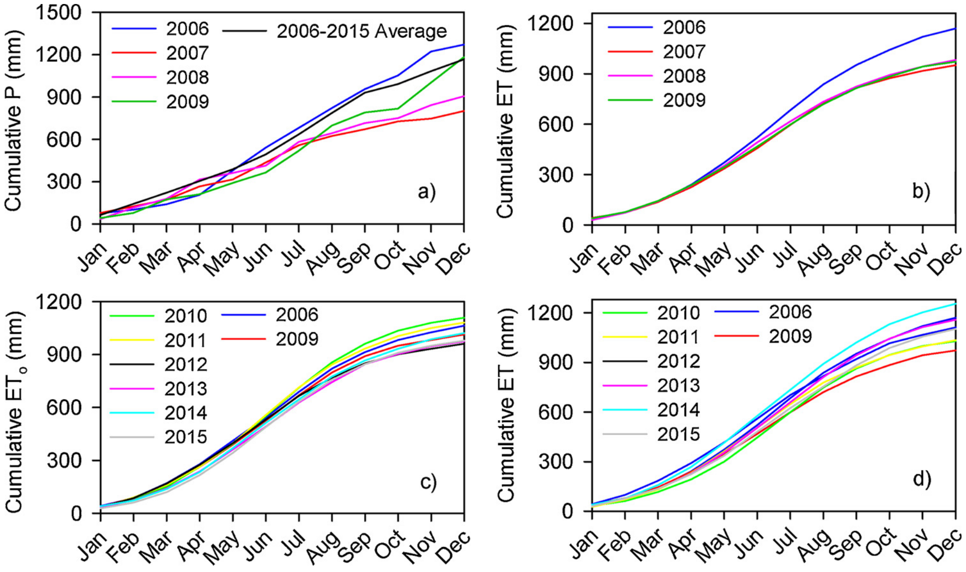

Fig. 4. Comparisons of annual cumulative precipitation (P, mm) and estimated evapotranspiration (ET, mm) during drought (2007, 2008) and non-drought (2006, 2009) years (a–b), and annual cumulative estimated monthly reference evapotranspiration (ET$_o$, mm) and monthly evapotranspiration (ET, mm) before (2006, 2009) and after (2010–2015) thinning (c–d) over the loblolly pine plantation.

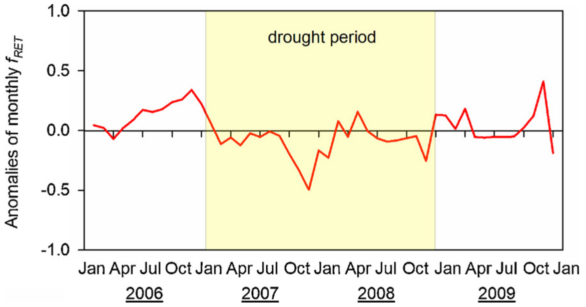

Fig. 5. Anomalies of monthly f_{RET} for the loblolly pine plantation during drought (2007, 2008) and non-drought years. f_{RET} represents the ratio between actual evapotranspiration (ET) and reference evapotranspiration (ET$_o$). The yellow area indicates the extremely dry years of 2007 and 2008. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

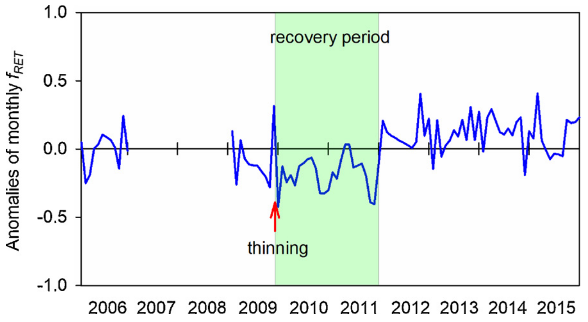

Fig. 6. Anomalies of monthly f_{RET} from 2006 to 2015 (the extremely dry years of 2007 and 2008 were not included). f_{RET} was defined as the ratio between actual evapotranspiration (ET) and reference evapotranspiration (ET$_o$). The red arrow indicates thinning conducted in the fall of 2009. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Correlation between monthly P and ET was insignificant ($P > 0.05$) in the dormant season. Soil moisture and LAI had a weak correlation with monthly weak correlations with the monthly ET variations in both seasons, however, the seasonal changes in both soil moisture and LAI, respectively, were in fact significant ($P < 0.001$) (Fig. 9). Given the above biological and climatic controls on actual water loss in the pine forest, a multivariate regression model was derived using stepwise multiple regression analysis: $ET = 0.258\ R_n + 0.097\,P + 12.034$ ($R^2 = 0.86$, $P < 0.001$).

4. Discussion

4.1. Variability of evapotranspiration

Our long-term study results showed that ET of the loblolly pine plantation exhibited large seasonal variations. This was consistent with

Table 2
A comparison of annual leaf area index (LAI), precipitation (P), reference evapotranspiration (ET$_o$), evapotranspiration (ET) and ratios of ET/P and ET/ET$_o$ over the loblolly pine plantation before and after thinning (mean ± standard deviation, the extremely dry years of 2007 and 2008 not included).

	Year	LAI	P (mm)	ET$_o$ (mm)	ET (mm)	ET/P	ET/ET$_o$
Before thinning	2005	3.1	1467[a]	1069[a]	1024[a]	0.70	0.96
	2006	3.0	1272	1064	1170	0.92	1.10
	2009	3.6	1184	1014	972	0.82	0.96
	Mean	**3.2 ± 0.3**	**1308 ± 145**	**1049 ± 30**	**1055 ± 103**	**0.8 ± 0.1**	**1.0 ± 0.1**
After thinning	2010	–	1270	1109	1029	0.81	0.93
	2011	1.3	1167	1082	1034	0.89	0.96
	2012	1.7	1189	962	1111	0.93	1.16
	2013	2.3	1134	975	1157	1.02	1.19
	2014	2.5	1143	1022	1254	1.10	1.23
	2015	2.8	1609	980	1102	0.68	1.12
	Mean	**2.1 ± 0.6**	**1252 ± 182**	**1022 ± 61**	**1115 ± 84**	**0.9 ± 0.1**	**1.1 ± 0.1**

[a] Data from Sun et al. (2010).

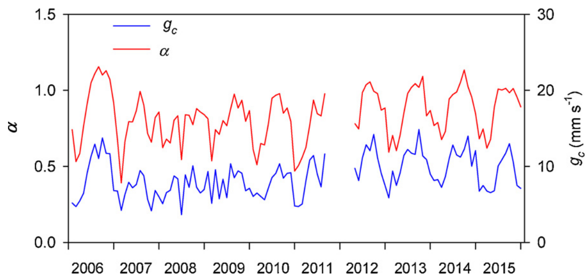

Fig. 7. Seasonal variations of the Priestley-Taylor coefficient (α) and surface conductance (g_c) at midday (12:00–13:00 central daylight time (CDT)) over a loblolly pine plantation on the coastal plain of the southeastern U.S.

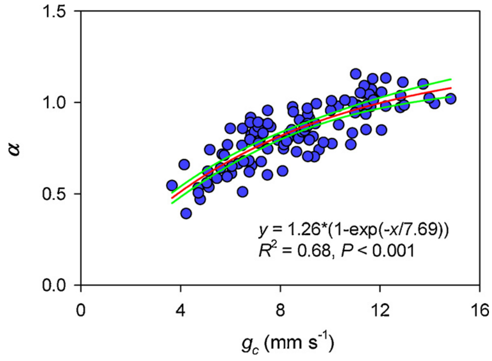

Fig. 8. The relationship between monthly mean Priestley-Taylor coefficient (α) and the canopy surface conductance (g_c) at midday (12:00–13:00 CDT). According to (Monteith, 1995), the asymptotic value of α typically ranges between 1.1 and 1.4 (1.26 at our site), and another constant in the fitted equation is typically ~5 mm s^{-1} (7.69 mm s^{-1} at our site). Green lines mark the 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3

A comparison of annual precipitation (P, mm), reference evapotranspiration (ET_o, mm) evapotranspiration (ET, mm) and ET/P ratio in major forest ecosystems in southeastern United States.

Forest types	P	ET_o	ET	ET/P	Reference
Mixed broadleaved deciduous forest	1091	1042	633	0.58	Oishi et al. (2010)
Temperate mixed deciduous forest	1454	835	486	0.33	Wilson and Baldocchi (2000)
Upland oak-dominated broadleaf forest	1189	–	571	0.48	Wilson et al. (2001)
Scrub oak forests	1031	–	725	0.70	Bracho et al. (2008)
Pine flatwoods	1149	–	812	0.71	Bracho et al. (2008)
Unmanaged mature cypress–pine plantation	1261	1431	1077	0.87	Sun et al. (2002)
Mature loblolly pine plantation	1524	1133	1054	0.70	Sun et al. (2002)
Mature deciduous hardwoods	1730	913	779	0.47	Sun et al. (2002)
White pine plantation	2241	–	1449	0.65	Ford et al. (2007)
White pine plantation	2014	1511	1509	0.75	Rao et al. (2011)
Mixed deciduous hardwood forest	2014	1079	1077	0.53	Rao et al. (2011)
4-6 years old loblolly pine plantation	1274	959	838	0.66	Sun et al. (2010)
13-15 years old loblolly pine plantation	1238	1128	1087	0.88	Sun et al. (2010)
14-23 years old loblolly pine plantation	1168	1038	1076	0.92	This study

reports for other coastal forests or woodlands (Bracho et al., 2008; Domec et al., 2010, 2012). Annual ET remained relatively stable over the studied period, although P (1168 ± 216 mm) was highly variable inter-annually (Fig. 1c, d). Low interannual variability in ET found in this study was also typical of other upland forests in the southeastern U.S. (Novick et al., 2015; Oishi et al., 2018). Mean annual ET was 1076 ± 99 mm with a range of 932–1254 mm. The magnitude of ET was similar to results previously reported for the same site by Sun et al. (2010), Tian et al. (2015), and Yang et al. (2017). The mean annual ET rate of the coastal loblolly pine plantation in the present study was close to that of the tropical rainforest ecosystems reported by Li et al. (2010), and even higher than that of the scrub oak and pine flatwoods ecosystems in east coast of central Florida reported by Bracho et al. (2008) (Table 3).

Theoretically, ecosystem level ET/P ratios depend on environmental fluctuations, vegetation type, and management (Sun et al., 2016; Torngern et al., 2018). The high ET/P ratio (Fig. 3) for the pine plantation forest in the present study indicated that most of precipitation was consumed by forest ET and only a small proportion contributed to runoff in this coastal plain forest area. ET/P for the pine forest varied between years and is typical of ecosystems with access to deep soil water sources. On average, annual ET/P (mean = 0.92) and ET_o/P (mean = 0.89) presented in this study fell between the theoretical Budyko (1974) space that relates mean annual evaporative index (ET/P) to mean annual dryness index (ET_o/P), and was close to the 1:1 line (ET/ET_o = 1) and the (1, 1) break point described by Williams et al. (2012).

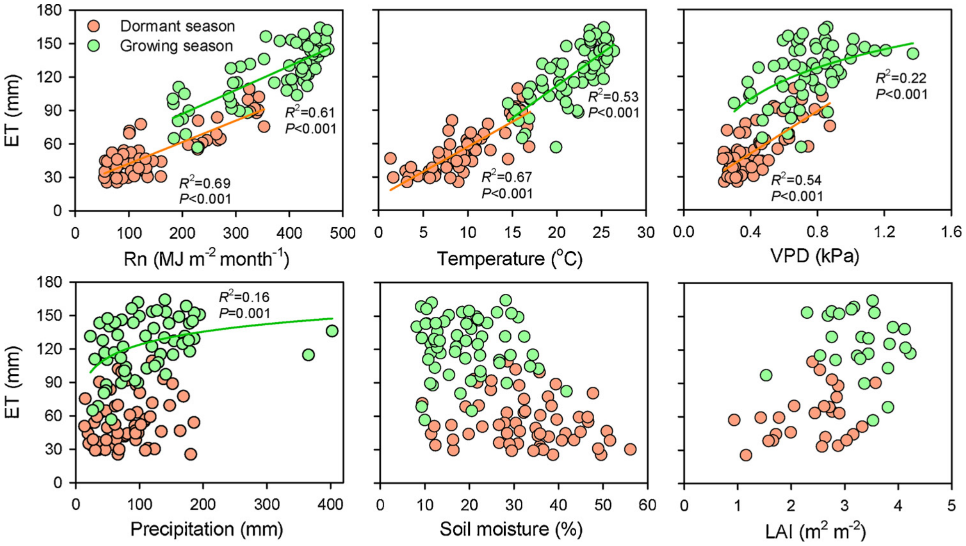

Fig. 9. The regressions between monthly evapotranspiration (ET) and monthly net radiation (R_n), monthly mean air temperature (T_a), monthly mean vapor pressure deficit (VPD), monthly precipitation, monthly mean soil moisture and monthly mean leaf area index (LAI) in dormant seasons (November-April) and growing seasons (May-October) over the 10-year study period, respectively.

4.2. Evapotranspiration responses to drought

The extreme drought during 2007–2008 resulted in a slight decrease (~8%) in annual ET in the present study (Table 1; Fig. 4a, b). This is in agreement with results reported by Domec et al. (2012) for the same site, and Oishi et al. (2010) for a drier piedmont region in the southeastern U.S. Based on a comparison of three methods to estimate ET, Domec et al. (2012) suggested that the severe droughts of 2007 and 2008 resulted in a < 5% reduction in annual ET compared with 2009 in the same forest stand. Similarly, using a water balance model (Water Supply and Stress Index), Sun et al. (2015b) estimated a 5%–10% reduction of mean annul ET around coastal plain of North Carolina during the most extreme drought events during 1962–2012.

The slight reduction in annual total ET of 88 mm (Table 1) in the pine forest could be partly explained by the reduction in canopy interception. Interception reduction alone during 2007 and 2008 was estimated to be 76 mm and 60 mm per year, respectively, if we assume an interception rate of 15% (Gavazzi et al., 2016; Sun et al., 2010). So tree transpiration, understory transpiration, and soil evaporation were responsible for the reduction of ET by 20 mm per year. As previously reported in loblolly pine ET studies (Domec et al., 2009, 2012; Phillips and Oren, 2001), tree transpiration is often responsive to a decrease in soil moisture, with a decrease by > 30% when relative extractable soil water drops below 50%. However, soil evaporation and understory transpiration, the other two components of stand ET, were both estimated to be relatively higher in the dry years of 2007 and 2008, due to the changes in understory vegetation structure and leaf area (Domec et al., 2012). Moreover, an increased soil evaporation during drought period (compared with non-drought periods) was also reported by Oishi et al. (2010) in a mixed forest at the Duke Forest Ameriflux hardwood site, central North Carolina.

Our results suggested that coastal pine forest, with shallow water tables and deep rooting system (~2 m), was able to maintain similar annual ET in years with significantly lower precipitation than average. During drought, the groundwater table dropped (Fig. 1). The decrease of groundwater table depth suggests that plants used groundwater as water source during drought to meet atmospheric evaporative demand and maintain their growth (Sun et al., 2010, 2015b). In addition, it has been shown that during the dry period approximately 80 mm of soil water could replenish the upper soil layers though hydraulic redistribution from deep roots (Domec et al., 2010). This mechanism might also moderate the dramatic decrease in tree transpiration.

4.3. Evapotranspiration responses to thinning

Thinning is a silvicultural practice used to maintain tree growth, control forest composition and structure, improve forest “health”, and enhance hydrological services such as water yield (Dore et al., 2012). Because reduction in leaf area from thinning leads to a higher albedo and lower net radiation (Montes-Helu et al., 2009), thinning treatment was commonly associated with increasing outflow and decreasing ET (Brown et al., 2005; Dore et al., 2010; Sun et al., 2015a). Paired watershed studies on thinning effects showed that mean daily outflow increased in a loblolly pine plantation watershed (Grace et al., 2006). However, most of these studies have been conducted only for a short period and did not quantify the effects of thinning over the time period for hydrologic recovery (Amatya and Skaggs, 2008). On an annual scale, total ET did not change much after thinning in our present study (Table 2; Fig. 4c, d), consistent with the results reported by Sun et al. (1998) and Gholz and Clark (2002) for similar landscapes in the southeastern United States. Based on a paired watershed approach, the effects of thinning on hydrology of a drained pine forest in coastal North Carolina were also evaluated, where total annual outflow from the thinning treatment (50% thinning) was found to be similar to the control (Amatya and Skaggs, 2008). This supports the above conclusion that ET in the coastal pine forest might be insensitive to thinning on an annual scale due to the relatively mature individuals with well-developed canopy, and the rapid recovery in understory density and ground cover (Gavazzi et al., 2016).

The effects of thinning on ET are complex for several reasons: (1) the decrease in overstory leaf area and increase in understory leaf area alter the radiation partitioning and precipitation interception at the ecosystem scale; Canopy rainfall interception over ten years (from 2005 to 2014) was estimated in an earlier study (Gavazzi et al., 2016). Thinning in the fall of 2009 was reported to decrease rainfall interception by only 5% at the annual scale, and quickly returned to pre-thinning levels. (2) the increase in contribution of soil evaporation to the overall site water balance; (3) the partitioning of transpiration between understory plants and overstory trees to total ET is affected (Domec et al., 2012; Boggs et al., 2015) due to improved light and water conditions. Based on paired watersheds, characterized as 35-year-old mixed pine–hardwood stands in the Piedmont region of North Carolina, Boggs et al. (2015) suggested that the harvesting of trees alters transpiration of residual trees; residual trees used 43% more water in the growing season postharvest than the pre-harvest growing period. Increased tree transpiration resulted in a 10% reduction in stream discharge.

In addition, a number of earlier studies noted the rapid recovery in understory density and cover in response to overstory harvesting or thinning (Amatya and Skaggs, 2008; Boggs et al., 2015; Gavazzi et al., 2016). This was also demonstrated by the time series of anomalies in the monthly f_{RET} over the loblolly pine plantation, where an approximately two year's hydrologic recovery period (Fig. 6) was identified. The speed of recovery is similar to the result reported by Amatya and Skaggs (2008) for a loblolly pine forest on the coastal plain in North Carolina.

4.4. Environmental and biological controls on evapotranspiration

The Priestley and Taylor (1972) α coefficient can be used to diagnose how biotic factors control forest ET relative to the available energy. The monthly Priestley-Taylor coefficient (α) ranged from 0.40 to 1.16 over the 10-year study period (Fig. 7). Mean annual value of α for this pine forest was close to the value for a tropical rain forest reported by Li et al. (2010), but greater than that of a temperate deciduous forest (Wilson and Baldocchi, 2000) and a subtropical coniferous plantation

Table 4
The annual precipitation (P, mm), evapotranspiration (ET, mm) and the Priestley-Taylor coefficient (α) estimated in different forest ecosystems.

Forest types	P	ET	Reported α values	Reference
Tropical rainforest	1322	1029	1.02	Li et al. (2010)
Temperate deciduous forest	1454	486	0.72	Wilson and Baldocchi (2000)
Subtropical coniferous plantation	945	772	0.57	Tang et al. (2014)
Coniferous boreal forest	493	280	0.48	Brümmer et al. (2012)
Coniferous temperate forest	1455	407	0.57	Brümmer et al. (2012)
Amazonian semi-deciduous forest	2137	965	0.75	Vourlitis et al. (2015)
Coastal Douglas-fir forest	1888	434	0.80	Humphreys et al. (2003)
Coastal pine plantation	1168	1076	0.83	This study

(Tang et al., 2014) (Table 4). Mean monthly α was greater than or close to 1, indicating that the seasonal variation of ET was mainly controlled by the regulation of the atmospheric demand rather than by the land surface (Wilson and Baldocchi, 2000; Yan et al., 2017).

The results reported here, which are based on direct water flux and meteorological measurements, clearly demonstrated that R_n was a major factor in temporal variation in ET (Figs. 7, 9) in the coastal plain pine forest, consistent with the previous studies (Sun et al., 2002, 2010). Although changes in canopy structure (e.g., LAI) were large after the 50% thinning treatment (the fall of 2009), total R_n and mean albedos (not shown) in the monitored site exhibited both little inter-annual variations during the study period from 2006 to 2015. This partially explained the relatively stable ET time series for the pine forest on an annual scale.

5. Conclusions

The 10-year study that covered two consecutive years representing severe meteorological drought and one thinning treatment provided an exceptional opportunity to investigate the long-term impacts of variations in both external and internal drivers on variability in ET of the pine plantation. We found that annual forest ET was relatively stable due to shallow groundwater level and deep rooting system in this coastal ecosystem. Annual ET declined slightly in the first two years after thinning (50%) with recovery to pre-thinning water use by the third year due to the rapid recovery of vegetation. Compared with other upland forest ecosystems in the southeastern U.S. coastal pine plantation forests exchange relatively large amounts of water with the atmosphere through ET.

The present study shows that the groundwater table is critical in sustaining ET during short-term (e.g., 2 years) extreme droughts. Thus, the groundwater table plays an important role in forest ecosystem resilience. Novel forest management practice such as control drainage (Amatya et al., 1996) that aims at regulating water quantity and quality through water table regulation may become more important in mitigating extreme climate such as drought in the future. The role of understory layer in regulating total ecosystem ET should be considered when evaluating the effects of over story thinning on watershed hydrology. The changes in understory have direct and indirect influences on the components of total forest ET (e.g., understory transpiration and canopy interception, soil evaporation). More cautions should be paid to the changes in understory (e.g., density, ground cover) in modeling effects of forest management on watershed hydrology.

Climate in the southern U.S. is projected to be more variable and forest management become more intensive to meet multiple demands in the future. The outcomes of this study provide valuable insights in understanding ecohydrological processes in plantation forests and are useful for modeling the potential effects of climate change and forest management on water and carbon cycles in the coastal plain region.

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