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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