LONG-TERM POTENTIAL AND ACTUAL EVAPOTRANSPIRATION OF TWO DIFFERENT FORESTS ON THE ATLANTIC COASTAL PLAIN

D. M. Amatya, S. Tian, Z. Dai, G. Sun

ABSTRACT. *A reliable estimate of potential evapotranspiration (PET) for a forest ecosystem is critical in ecohydrologic modeling related with water supply, vegetation dynamics, and climate change and yet is a challenging task due to its complexity. Based on long-term on-site measured hydro-climatic data and predictions from earlier validated hydrologic modeling studies, this study compared different methods for estimating monthly and annual potential evapotranspiration (PET) for two Atlantic coastal plain forests. One study site is a naturally drained mature pine mixed hardwood forest in South Carolina (SC), and the other site is a drained pine plantation forest in North Carolina (NC). The Hargreaves-Samani (HS) method was used for estimating grass PET for the SC site, while the Penman-Monteith (PM) method was used for calculating a standard grass reference (REF-ET) and simulating forest PET for the NC site. Daily HS-grass PET was used as an input in the Thornthwaite water balance (WBA) model, which was validated with long-term monthly streamflow to obtain simulated ET for the 1946-2008 period at the SC site. A process-based field-scale model, DRAINMOD-FOREST, was used for quantifying ET for the 1988-2008 period for the NC site by using REF-ET and forest PET as inputs separately. The monthly ET/PET ratios were further calculated for both sites. The long-term mean annual HS-grass PET was 1137 (±69) mm at the SC site. HS-grass PET for a recent four-year (2011-2014) period was 11% higher than the forest PET obtained by the PM method using above-canopy microclimate data and canopy resistance parameters. The long-term annual ET/HS PET varied from 0.76 to 1.0, with an average of 0.92. Annual PM-forest PET simulated using the validated DRAINMOD-FOREST model at the NC site varied from 1014 to 1335 mm with a long-term mean of 1146 ±87 mm, which is about 13% higher than the REF-ET (1010 ±123 mm) at the NC site but very similar to the values obtained for the HS-grass PET for the SC site. The estimated annual ET/PM-forest PET ratios varied from 0.81 to 0.97, with an average of 0.90. We also found similar seasonal values and variations of ET/HS PET at the SC site and ET/PM PET at the NC site, both of which were largely different from the ET/REF-ET values and their seasonal distribution reported for another pine forest site (Parker Tract) in coastal NC with eddy flux-based measurements of ET. Results from this study showed large difference of PET estimations by using different methods, particularly for the grass and forest reference. This study also highlighted the importance of properly defining and estimating forest PET, rather than using the standard REF-ET, and related mean monthly ET/PET ratios for estimating ET for a forest reference in forest hydrologic models and water balance studies.*

Keywords. *Drainage, DRAINMOD-FOREST, Hargreaves-Samani, Penman-Monteith, Reference evapotranspiration, Streamflow, Thornthwaite water balance model.*

Forests are an integral component of the landscape, and maintaining their functional integrity is fundamental for the sustainability of ecosystems and societies alike. Accordingly, advances in forest hydrological science, its applications, and tool development, analogous to those for agricultural production, have been emphasized in recent years to address current complex issues, including land use and climate change, wildfires, changing patterns of development and ownership, and changing societal values in larger landscapes (de la Critaz and Barten, 2007; NRC, 2008; Jones et al., 2009; Lockaby et al., 2011; Amatya et al., 2011, 2015a; Vose et al., 2012; Creed et al., 2014). Evapotranspiration (ET) is a major component of forest water balance (Vorosmarty et al., 1998; Jung et al., 2010; Fisher et al., 2011) and also a key hydrologic flux that links water, energy, and biogeochemi-

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cal cycles in forests (Sun et al., 2011a, 2011b). Furthermore, changes in land use and management further complicate how ET affects the net water balance. Therefore, it is becoming increasingly important for accurately estimating ET for a given vegetation that accounts for its interaction with soils and climate. ET can be derived from a range of measurement systems including lysimeters, eddy covariance, Bowen ratio, water balance (gravimetric, neutron meter, other soil water sensing), sap flow, scintillometer, and even satellite-based remote sensing and direct modeling (Wilson et al., 2001; Williams et al., 2004; Allen et al., 2011; Baldocchi, 2014).

Given its simplicity, in most hydrologic studies and modeling applications, ET is estimated or modeled using potential evapotranspiration (PET) as a limiting factor for non-limited soil moisture conditions (McKenney and Rosenberg, 1993; Federer et al., 1996; Allen at al., 1998; Fisher et al., 2005; Harder et al., 2007; Nghi et al., 2008; Dai et al., 2010, 2013; Jovanovic and Israel, 2012; Kim et al., 2013; Prudhomme and Williamson, 2013). Recently, Katerji and Rana (2011) provided a detailed discussion on concepts of PET, originally developed by Thornthwaite (1948) for crop water requirements, as applied in hydrology, climatology, agronomy, and ecology. Many methods have been developed to quantify PET for well-watered short grass in various geographical regions (Penman, 1948; Thornthwaite, 1948; Turc, 1961; Hamon, 1963; Monteith, 1965; Priestley and Taylor, 1972; Hargreaves and Samani, 1985; Jensen et al., 1990). In recent years, the concept of reference ET (REF-ET), which is equivalent to the PET estimated by using the physically based Penman-Monteith (PM) method (Monteith, 1965) for a standard 12 cm well-watered grass, has been developed (Jensen et al., 1990; Allen et al., 1998). Most recently, the FAO-56 PM model (Irmak et al., 2013), a slight modification of the original PM method, has been widely accepted as a standard REF-ET (ET_o) for a grass reference to compare PET of all other crops (Jensen et al., 1990; Amatya et al., 1995; Allen et al., 1998; Prudhomme and Williamson, 2013). All other methods, other than REF-ET, are also generally used for estimates of PET for short grass based on study and management objectives, data availability, and geographical locations (Jensen et al., 1990; McKenney and Rosenberg, 1993; Amatya et al., 1995; Federer et al., 1996; Allen et al., 1998; Fisher et al., 2005; Lu et al., 2005).

Methods and tools are continuously used in ecohydrologic models (e.g., SWAT, WaSSI, MIKESHE, DRAINMOD, and others) to assess the impacts of land and water management, land use change, and climate variability on hydrology and water quality at watershed or regional scales. However, there is a growing concern about the applicability of such REF-ET and other PET methods for grass reference as actual evaporative demand (Katerji and Rana, 2011) when hydrologic analyses and modeling studies are conducted for landscapes containing forested lands. Recent studies have shown that both forest PET and ET can exceed the corresponding PET and ET values for short grass and crops depending on site conditions (Sun et al., 2010, 2011a; Katerji and Rana, 2011; Rao et al., 2011; Domec et al., 2012; Amatya et al., 2014), except for a study by Brauman et al. (2012) for a very humid Hawaiian site. One of the main reasons for these increased values in forest PET and ET was potentially the difference in vegetation characteristics, such as leaf area index (LAI), stomatal conductance (g_s), and canopy resistance (r_c), and microclimate. Furthermore, forests that are substantially tall likely have reduced albedo and plant-specific stomatal and aerodynamic control of vapor transfer different from that of grass (McKenney and Rosenberg, 1993; Fisher et al., 2005; Rao et al., 2011; Brauman et al., 2012; Mohamed et al., 2014).

However, there is only limited information on estimating PET for a forest reference (Federer et al., 1996; Fisher et al., 2005; Lu et al., 2005; Douglas et al., 2009; Rao et al., 2011; Mohamed et al., 2014). Rao et al. (2011) contrasted three common PET models (FAO-56 REF-ET, Hamon PET, and Priestley-Taylor PET) for grass reference by comparing their PET values with estimated actual ET at monthly and annual temporal scales from two forested watersheds (coniferous and deciduous) in upland western North Carolina. The authors found that the annual PET of the conifer watershed was higher than that of the native deciduous watershed due to the lower albedo of the conifers. The authors also derived monthly calibration factors (different from the “crop coefficient”) for REF-ET and Hamon PET using the Priestley-Taylor (PT) PET, which provided the most reasonable estimates of forest PET. Similarly, in some other studies, the PT method and its modified version were shown to perform better than the PM method when eddy covariance based measured ET was used for comparison of the PET methods for some forest types in Nevada (Fisher et al., 2005) and Florida (Douglas et al., 2009). Douglas et al. (2009) noted the sensitivity of the PM method to the limited transferability of its model parameters (e.g., canopy resistance as site specific) as a reason for its poorer performance. Their studies using eddy flux based ET were limited to a two to three year period and are difficult to apply at other sites due to the large resource requirement. Analyzing data from around the world, Mohamed et al. (2014) also demonstrated that the ratio of evaporation (e_a) for a vegetated wetland and open water evaporation (e_w) (similar to PET) is site-specific, and a function of the biophysical properties of the wetland surface, and the rate can depend on local hydro-climate conditions. Their study demonstrated that the PM model provides a suitable basis to interpret e_a/e_w for various wetland types, similar to ET/PET variations. Unfortunately, there is only limited information on the relationship between ET and PM PET estimates for forest ecosystems using measured ET data. Furthermore, to our knowledge, there have been no studies on derivation of PM PET using longer-term data that can capture the seasonal and year-to-year climatic variability for any forest reference, as well as the ET/PET factors, as a “crop coefficient” in forest hydrology modeling and water balance studies.

The objective of this study is first to evaluate long-term monthly and annual PET by two different methods for two matured pine forest sites on the Atlantic coastal plain. Accordingly, based on availability of data, temperature only based Hargreaves-Samani (HS) grass PET was calculated for a simple Thornthwaite water balance (WBA) model for a naturally drained forest site in South Carolina (SC), and a process-based model (DRAINMOD-FOREST) was used to simulate the PM-forest PET for an artificially drained pine forest site in North Carolina (NC). Secondly, we tested a hypothesis that the monthly PM-forest PET estimated with above-canopy measured climatic data and vegetation parameters at the SC site is higher than the REF-ET and/or HS-grass PET. Thirdly, both models, validated against long-term streamflow data from the respective sites, were used to obtain simulated long-term monthly and annual ET for these two similar coastal forest sites. Additionally, we compared the calculated long-term mean monthly ET/PET ratios and their seasonal variations using the two PET methods for these two forest sites and contrasted them against the ET/REF-ET ratios from a similar forest site in the North Carolina coastal plain where ET was measured using an eddy covariance (EC) system. The long-term simulated mean ET/PET ratios and their seasonal distribution for the managed pine forest at the NC study site may serve as a basis for forest managers and hydrologists to estimate water use of similar forests at large scales, using them as "crop coefficients" in modeling and water balance approaches. The various methods analyzed here are summarized in table 1.

SITE DESCRIPTION

The two main study sites are located in the Santee Experimental Forest in South Carolina and in Carteret County in North Carolina, both of which are on the Atlantic coastal plain (fig. 1). The third site at the Parker Tract in Washington County, North Carolina, with eddy flux measurements for pine forest ET (Sun et al., 2010), was used for comparison purposes. All three coastal plain forest sites have a PET/P ratio, defined as the "dryness index" (Sun et al., 2011b; Creed et al., 2014), a ratio between temperature-based PET and annual precipitation (P), of less than 1.0.

SANTEE SC SITE

This study site established in 1963 is located at 33.15° N and 79.8° W within the Santee Experimental Forest, a part of the USDA Forest Service Francis Marion National Forest near the town of Huger in South Carolina (fig. 1). Our study site, a second-order watershed (WS79, 500 ha) containing two first-order watersheds, WS77 (treatment, 155 ha) and WS80 (control, 160 ha), drains to Turkey Creek at the headwaters of the east branch of Cooper River, which forms the Charleston Harbor System. These natural-

Table 1. Description of PET method, measured/calculated/simulated ET, and ET/PET ratios at three sites.

Site	Model Used	Data Period	PET Method Used	PET Input in Model	PET Adjustment	ET Type	Other PET Methods	ET/PET Ratio
Santee SC	Thornthwaite water balance (WBA)	1946-2008	Hargreaves-Samani (HS) for grass	Estimated externally	Calibration using 2003-2008 PM PET for grass	Calculated monthly basis	PM for grass	ET/HS grass PET
Carteret NC	DRAINMOD-FOREST	1988-2008	Penman-Monteith (PM) for pine forest	Simulated internally	Adds canopy interception to PM PET for total PET	Simulated daily basis	PM for grass	ET/PM forest PET
Parker Tract NC (Sun et al., 2010)	Does not apply	2005-2013	FAO-56 PM for grass (REF-ET)	Does not apply	None	Measured using eddy covariance on 15 min	-	ET/REF-ET

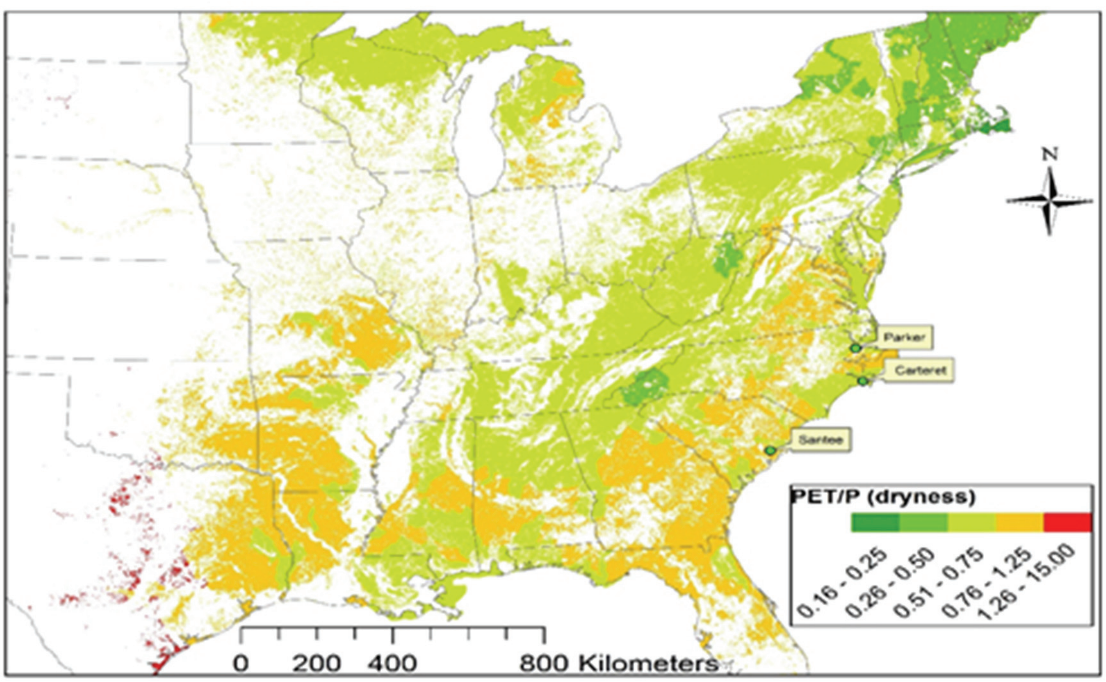

Figure 1. Locations of the Santee Experimental Forest site in South Carolina and the Carteret and Parker Tract Managed Pine Forest sites in North Carolina along the Atlantic coastal plain (after Sun et al., 2011b).

ly drained watersheds are relatively flat (<1% slope). Soils are moderately well to somewhat poorly drained in the upland and poorly drained in the riparian zone. Vegetation is dominated by hardwoods with some pines on WS80 and mostly loblolly pine (*Pinus taeda* L.) on WS77. Watershed WS77 has undergone prescribed burning treatments every two to three years for operational management. Details of the study site can be found elsewhere (Amatya and Trettin, 2007; Dai et al., 2013).

Carteret NC Site

The study site located in Carteret County, North Carolina (34° 48′ N, 76° 42′ W), is owned and managed by Weyerhaeuser Company. Research at the site was initiated in 1986 by North Carolina State University with initial field data collection beginning in 1987 and continuous hydrologic data collection beginning in 1988. The site consists of three artificially drained experimental watersheds (D1, D2, and D3) on a managed loblolly pine plantation with areas of 24.7, 23.6, and 26.8 ha, respectively. The site has a flat topography, with poorly drained hydric soils and a shallow water table. The control watershed (D1) was managed in conventional drainage mode during the 1988-2008 study period when the other two treatment watersheds (D2 and D3) went through various water and silvicultural treatments. Each of the three watersheds is drained by four 1.4 to 1.8 m deep lateral ditches spaced 100 m apart. Details of the study site are given elsewhere (Amatya et al., 1996; Amatya and Skaggs, 2011; Tian et al., 2012a).

Hydro-Meteorological Measurements

Santee SC Site

Daily precipitation and daily maximum and minimum temperature were manually measured at the weather station at the Santee Experimental Forest headquarters (SHQ) from 1946 to 1995 and automatically using a Campbell Scientific data logger thereafter. Climate parameters, including air temperature, relative humidity, wind speed, wind direction, vapor pressure, and solar and net radiation, were automatically measured using sensors at 30 min intervals since 2003. Three onsite weather stations (Met5 on WS77, Lotti adjacent to WS79, and Met25 on WS80) measure daily precipitation and air temperature. Continuous data measured at a recently installed weather station on a tower above the forest canopy on watershed WS80 were also used together with forest vegetation parameters (leaf area index (LAI) = 2.90 (±0.50) $m^2\ m^{-2}$ and maximum conductance = 90 mmoles $m^2\ s^{-1}$) to estimate PM-forest PET.

Streamflow rates at the outlets of WS77 and WS80 were measured based on stage-discharge relationships of compound V-notch weirs. Stages were measured at 10 min intervals at the flow gauging stations using data loggers since 1963. The streamflow rate was calculated using standard rating curve methods developed for these weirs, and the 10 min values were integrated into daily, monthly, and annual flows normalized to mm per day by dividing the watershed area to be comparable to daily precipitation (Amatya et al., 2006). Detailed information on instrumentation and data monitoring are given by Amatya and Trettin (2007).

Carteret NC Site

Rainfall was measured with a tipping-bucket rain gauge backed up by a manual rain gauge on the western side of the study watershed. Air temperature, relative humidity, wind speed, and solar and net radiation were continuously measured by an automatic weather station since 1988, as described by Amatya et al. (1996) and Amatya and Skaggs (2011).

A 120° V-notched weir with an automatic stage recorder, located in a water level control structure at a depth of about 0.3 m from the bottom of the outlet ditch, was used to measure continuous drainage outflow on the study watershed. The stage measured at 12 min intervals was used to estimate flow rates using the standard weir equations, and the flow rates were integrated to obtain daily, monthly, and annual flows. In 1990, a pump was installed downstream from all three watersheds in the roadside collector ditch to prevent weir submergence during larger events. An additional recorder was placed downstream from the weirs in May 2005 to determine if weir submergence occurred and to correct flows in that event. Details of the measurement protocols are given by Amatya et al. (1996) and Amatya and Skaggs (2011).

Estimations of Potential ET (PET)

Santee SC Site

The 30 min weather data collected at the weather station were used in earlier studies to estimate daily PET using the TH (Thornthwaite, 1948), PM (Monteith, 1965), and HS (Hargreaves and Samani, 1985) methods for a grass reference (Harder et al., 2007; Dai et al., 2010, 2013; Amatya et al., 2014). In this study, daily PET was estimated using the PM equation for a grass reference for the 2003-2008 period (Harder et al., 2007; Dai et al., 2010; Amoah et al., 2012) using observations of relative humidity, wind speed, vapor pressure, solar and net radiation that were not available for the earlier period. The Hargreaves equation (Gavilan et al., 2006; Sepaskhah and Razzaghi, 2009) based estimates of the daily HS PET were obtained from Dai et al. (2013) for the whole period from 1946 to 2008 for this site (table 1). The HS PET is generally higher than the value obtained from the standard PM method (Jensen et al., 1990; Amatya et al., 1995, 2014), so its daily values for 1946-2008 were adjusted using a calibration factor (0.68) obtained by using a regression model developed from the daily PET obtained by the PM and HS methods for the 2003-2008 data for the study site (table 1).

We estimated the monthly and annual PET for the 2011-2013 period using the PM and HS methods to test the hypothesis that grass-based PET is lower than the PM-forest PET (table 1) estimated using the above-canopy weather data together with vegetation characteristics, as reported by Amatya et al. (2014) for the adjacent forest on WS80. This allowed us to assess the accuracy of using the HS PET calibrated with the PM-grass PET in simulating long-term streamflow, as well as ET, for a second-order forest watershed (WS79) (that contains the WS80 forest) using a WBA model reported recently by Dai et al. (2013), as briefly described below.

Carteret NC Site

A complete weather station was located about 800 m away from the study site, where the wind speed was measured at a height of 10 m and all other parameters were measured at the standard 3 m height from 1988 to mid-1997. In September 1997, an on-site standard 3 m tall weather station was installed in a clearcut area adjacent to the study site, followed in late 2001 by a weather station on a tower to monitor weather variables above the forest canopy. The tower weather station was severely damaged by Hurricane Ophelia in September 2005, and all the weather data since then until 2008 were obtained from another nearby site at Sutton Farms in Vanceboro, North Carolina. Daily weather data averaged from the continuous hourly or half-hourly measurements of the weather variables at these nearby weather stations described above were used to estimate daily PET by using PM and REF-ET (FAO-PM) method (table 1).

Hydrologic Models for ET Estimation

Thornthwaite Water Balance (WBA)

ET for the watershed WS80 at the Santee SC site was estimated using the WBA model suggested by Ward (1972) and Flerchinger and Cooley (2000) and reported by Dai et al. (2013):

$$E = P - (Q + ET + \Delta S) \quad (1)$$

where E is the estimation error (assumed to be negligible), P is measured precipitation, Q is streamflow, ET is estimated evapotranspiration, and ΔS is water storage in the soils and aquifer. ET is derived from the PET, precipitation, soil moisture storage, and changes in soil moisture. Change in deep aquifer storage was assumed negligible. The ET was assumed to be equal to PET if $P_i \geq ET_i$. Otherwise, $ET_i = P_i + \Delta SM_i$ if $P_i < PET_i$, where ΔSM_i is the change in soil moisture between the current and previous month, and subscript *i* represents the month. Details of the calculation of the monthly soil moisture (a function of soil moisture capacity for a given soil depth), change in soil moisture, and ET are given by Dai et al. (2013). The soil moisture capacity, the only model input parameter, was estimated to be 150 mm and was obtained from a sensitivity analysis of various model parameters including field capacity in an earlier study testing the MIKESHE model on this watershed (Dai et al., 2010). Harder et al. (2006) reported this value to be 175 mm while calibrating DRAINMOD on this watershed. The monthly rainfall measured in watershed WS80 together with the monthly HS PET (table 1) estimated using the weather data measured at the weather station described above and the estimated soil moisture capacity for the site soil type were used to calculate the monthly streamflow (Q) in the water balance equation given above for the 1969-2008 period. The calculated streamflow was validated with the measured monthly flow for its reliability in predicting streamflow, as well as soil moisture and ET.

We chose the Thornthwaite WBA model for the SC site mainly due to the limitation of the data required to apply the process-based DRAINMOD-FOREST model (Tian et al., 2012a) discussed below for the NC site. Harder et al. (2006) found less satisfactory results when validating the model predictions of long-term monthly and annual streamflow with the measured data at this site, even when the standard DRAINMOD model (Skaggs, 1978) was applied, although DRAINMOD performed slightly better than the WBA model for a short 2.5-year period.

The validated WBA water balance model was then applied by Dai et al. (2013) for the second-order forested watershed (WS79) containing watershed WS80 to simulate its monthly and annual water balance. In this study, we used the results of simulated ET from the long-term (1946-2008) water balance for watershed WS79 to further analyze the mean annual ET, HS-PET, ET/HS-PET, and ET/P, where P is the annual precipitation, and the mean monthly ET/HS-PET factors.

DRAINMOD-FOREST Model

PM PET and ET at the NC site were estimated using DRAINMOD-FOREST, an integrated, process-based, and stand-level forest ecosystem model developed for simulating hydrological processes, soil C and N dynamics, and tree growth for natural and managed forests on poorly drained soils with shallow water tables (Tian et al., 2012a). DRAINMOD-FOREST integrates a physiology-based forest growth model with DRAINMOD (Skaggs, 1978, 1999) and DRAINMOD-N II (Youssef, 2003; Youssef et al., 2005). Simulated hydrological processes in lowland forest ecosystems include rainfall interception, throughfall, infiltration, ET, subsurface drainage, surface runoff, vertical and lateral seepage, water table fluctuation, and soil water distribution in the vadose zone. Specifically, DRAINMOD-FOREST internally calculates daily PET using the PM method with canopy conductance estimated as a function of climatologically regulated stomatal conductance and leaf area index (LAI) that is predicted by the forest growth model. As in DRAINMOD, ET is set equal to PM PET when the soil water in the root zone is larger than PM PET. Otherwise, ET is controlled by the water table and upward flux (Skaggs, 1978). The measured LAI and the maximum conductance used in this study were 4.29 (±1.20) $m^2\ m^{-2}$ and 103 mmoles $m^2\ s^{-1}$, respectively. A modified version of the Gash model (Gash et al., 1995) was used to estimate rainfall interception by the forest. The calculated ET was added to the rainfall interception to obtain the total forest ET. Therefore, the PM PET and ET values predicted by DRAINMOD-FOREST were used in the further analysis, including ET/PET ratios (table 1). A detailed model description is given by Tian et al. (2012a). The model has been tested and applied for simulating long-term hydrological processes, e.g., flow dynamics and water table depth fluctuations (Tian et al., 2012b, 2013). The model parameterization was based on a global sensitivity analysis of all input parameters reported by Tian et al. (2014). A recent study showed that DRAINMOD-FOREST accurately predicted ET dynamics measured by an eddy covariance (EC) method at the same NC EC pine forest site studied by Sun et al. (2010) after calibration and validation for various hydrologic variables, including drainage and water table depth (Tian et al., 2015).

Results and Discussion

Santee SC Site

The 63-year (1946-2008) long-term annual measured precipitation (P) for the Santee Experimental Forest headquarters weather station adjacent to the study site varied from as low as 835 mm in 1954 to as high as 2026 mm in 1994, with an average of 1372 mm (±244). Both the long-term average and the 21-year (1988-2008) average rainfall for the Santee SC site are about 10% lower than the 21-year average of 1517 mm measured at the Carteret NC site (Amatya and Skaggs, 2011). Similarly, the long-term annual grass PET estimated using the HS method (HS-grass) calibrated with the PM method varied from 970 to 1304 mm, with an average of 1136 mm (table 2).

Thus, the long-term average P was higher than the long-term HS PET, indicating that the SC forest system has possibly surplus moisture in general, similar to other lower coastal plain forests, including the NC study site, as will be shown below (Amatya et al., 2014; Amatya and Skaggs, 2011; Skaggs et al., 1994). This is also consistent with recent findings by Sun et al. (2011b), who reported PET/P values in the range of 0.76 to 1.25 for this site. However, our result of PET/P for the Santee SC site is based on the HS-grass PET, which was calibrated with a factor of 0.68 derived from the 2003-2008 PM PET for the grass reference (table 2). Similar calibration factors between 0.55 in December and 0.97 in July, with an average of 0.80, when HS was compared against the PM for two coastal sites in North Carolina, were reported by Amatya et al. (1995). This indicates that the HS PET is generally higher than the PM-grass PET, as shown below, and use of the HS PET in the PET/P ratio may suggest that the SC site is moisture limited.

Figure 2 shows a comparison of calculated monthly PET using the PM method for the grass reference (PM-grass), HS-grass, and PM PET for the forest canopy (PM-forest) on watershed WS80 (table 1). The results showed that the HS-grass PET was very close to PM-forest in 2011 and 2012 but was considerably higher in 2013 for June to December. The HS-grass PET was generally slightly higher than PM-forest during January to June in the three years. Standard t-tests showed that the three-year mean monthly HS-grass PET of 109.6 mm was significantly ($p < 0.00001$) higher than the PM-forest PET of 98.9 mm, but the PM-grass PET of 79.5 mm was significantly ($p < 0.00001$) lower than the PM-forest PET. The calculated annual HS-grass PET values of 1412, 1331, and 1202 mm for 2011, 2012, and 2013, respectively, were consistently higher than 1332, 1219, and 1011 mm calculated using PM-forest PET (table 2). The three-year mean annual HS-grass was also significantly ($p < 0.03$) higher and the PM-grass PET was significantly ($p < 0.03$) lower than the PM-forest PET. The HS-grass PET was higher than the PM-forest PET by 6% for 2011 and 19% for 2013, with an average of 11%. This year-to-year variation in HS-grass and PM-forest could be explained by the difference in local climate and its interaction with vegetation. The year 2011 had low rainfall with only 934 mm (approx. 40% lower than the long-term average), and 2013 was wet with 1433 mm (5.5% higher than the average). The monthly relationship between HS-grass

Table 2. Means (and ranges) of annual PET estimated or simulated by various methods, simulated annual mean ET, and mean ET/PET ratio for two study sites (value in parentheses for mean ET/PET ratio is the standard deviation).

	For ET Modeling					For PET Comparison			
Site	Model Used	Data Period	Estimated or Simulated PET (mm)	Simulated Forest ET (mm)	Mean ET/PET Ratio	Data Period	Estimated PM-Forest PET (mm)	Estimated HS-Grass PET (mm)	Estimated PM-Grass PET (mm)
Santee SC	Thornthwaite water balance (WBA)	1946 to 2008	1136 (970 to 1304), estimated by HS-grass	1043 (913 to 1200)	0.92 (±0.05)	2011 to 2013	1187 (1011 to 1332)	1315 (1202 to 1412)	954 (869 to 1007)
Carteret NC	DRAINMOD-FOREST	1988 to 2008	1146 (1014 to 1335), simulated by model for forest	1020 (853 to 1177)	0.89	1988 to 2008	None	None	1010 (782 to 1254)

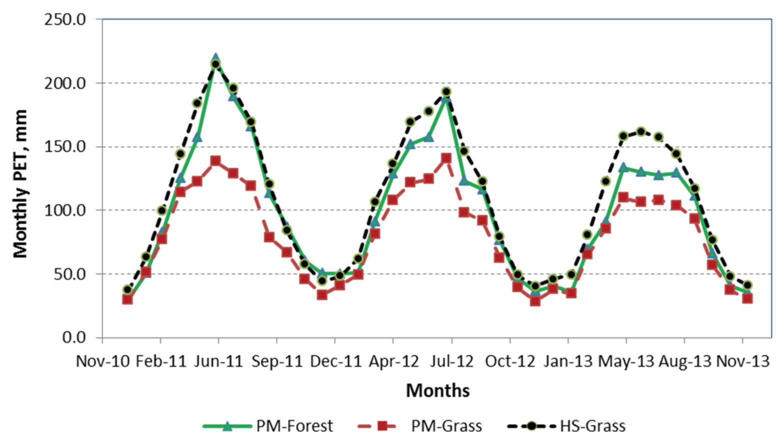

Figure 2. Comparison of calculated monthly PM PET for forest reference (PM-forest) on WS80 watershed with the PM-grass adjusted HS PET (HS-grass) for 2011-2013 period.

PET and PM-forest PET was strong (PM-forest = 0.907 × HS-grass; $R^2 = 0.97$, $p < 0.0001$), although there were some differences between them.

The three-year analysis indicates that the temperature-based HS method not adjusted with the PM-grass PET, as for the 1946-2008 period stated above, may potentially overestimate the PM-forest PET because the HS method does not take into account the effects of vapor pressure deficit (VPD) and net radiation (Mazur et al., 2014) during periods with high rainfall, in general. The largest difference in estimated PET between the two methods was observed in the wet year of 2013. In the relatively dry year with high temperature and net radiation, the HS method yielded similar PET as the PM method. Furthermore, the HS method also does not take into account the effects of VPD and stomatal control, which in turn interact with aerodynamic control (Brauman et al., 2012). This observation is critical because use of HS PET in a water balance, such as the WBA approach in this study and other modeling studies, may potentially overpredict ET and underpredict streamflow caused by the potential high PET estimated using HS-grass for relatively wet years. Thus, these results may have some implications in the analysis conducted below for the annual ET, ET/PET, and ET/P and the mean monthly ET/PET factors, particularly in wet years.

The results of validation of the WBA model using the measured monthly streamflow data obtained from Dai et al. (2013) are shown in figure 3. The model used the HS method for grass-based daily PET as input. Both the Nash-Sutcliffe coefficient (NSE) and R^2 were relatively high (0.83), indicating a reasonable performance of the model. However, the 1:1 line in the regression plot in figure 3 indicates an underprediction of monthly streamflow. The slope of 0.78 and intercept of 5.07 indicate that the monthly observed streamflow was underpredicted, possibly due to the overprediction of ET. Most of the higher flows may occur during the wet months from December to April due a low ET demand and also during some summer months with tropical storms (Harder et al., 2007) when moisture may not be limited. Accordingly, the HS PET values used in the model, even after adjustment with PM PET, possibly may

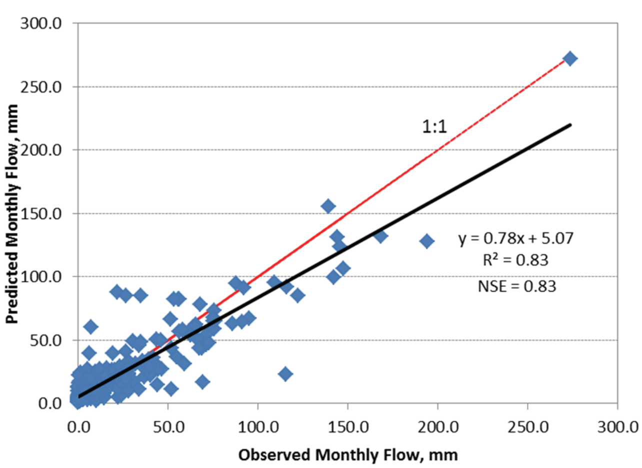

Figure 3. Measured and predicted monthly streamflow for watershed WS80, Santee Experimental Forest, SC (after Dai et al., 2013).

have been higher than the PM-forest PET, potentially contributing to higher ET and lower streamflows for these time periods.

Based on the long-term (1946-2008) simulation using the WBA model with the HS-grass PET method for the second-order forested watershed (WS79), Dai et al. (2013) obtained an average annual simulated ET of 1043 mm with a range of 913 to 1200 mm (table 2), which was lower than the estimated HS PET in this forest area. This indicates that soil moisture deficit can actually occur during low-precipitation periods, although surplus moisture was shown to exist at the site on a long-term basis. Interestingly, the estimated average annual ET was found to be within the error of eddy covariance-based measured annual average ET of 1038 (±112) mm reported by Sun et al. (2010) and Domec et al. (2012). This ET estimate of 1043 mm is also just 6% lower than the average annual estimate of 1107 mm obtained as a difference of annual rainfall and streamflow by Richter (1980) for the 160 ha treatment watershed (WS77) (Amatya et al., 2016) within this 500 ha second-order watershed (WS79). We believe that this 6% lower estimate of ET for watershed WS79 was possibly due to higher streamflows from this second-order watershed than from WS77 within it. Therefore, the simulated long-term monthly ET values from the WBA-based approach were further used to evaluate the influence of HS-grass PET on mean monthly and annual ET/HS PET ratios for this forest site.

Since the total ET for the forest is the sum of canopy evaporation (CE) and transpiration and soil/litter evaporation (TSE) (Amatya et al., 1996; Harder 2004; Tian et al., 2012a), as shown in figure 4, we assumed an 11% loss, on average, by CE for this study watershed, which was similar to the measured value obtained by Harder (2004) in his interception study on the control watershed (WS80) within watershed WS79. This 11% canopy interception loss for pine mixed hardwood forest is lower than the values (>15% loss) published for managed pine forests in the Atlantic coastal plain, including the NC site shown below (Amatya et al., 1996; Domec et al., 2012). Annual time series plots of estimated HS-grass PET, simulated ET, CE, and TSE, calculated as the difference of ET and CE, are shown in figure 4.

The simulated ET was equal to HS PET only in one year (1961) and was 99% of PET in three other years for this forest site using the PM-adjusted HS PET for grass. The CE, assumed the same as the canopy interception, varied from 93 to 132 mm, with an average of 115 mm. Similarly, the TSE component of ET varied from 751 to 1069 mm, with an average of 929 mm. Although these estimates of ET and its components are comparable to the NC site (table 2) and to similar managed pine forests in the Atlantic coastal plain obtained by eddy covariance-based ET flux measurements (Sun et al., 2010; Domec et al., 2012), additional validation using forest reference based PM-type PET and ET measurements using eddy flux systems is potentially warranted at this study site for an accurate water balance analysis.

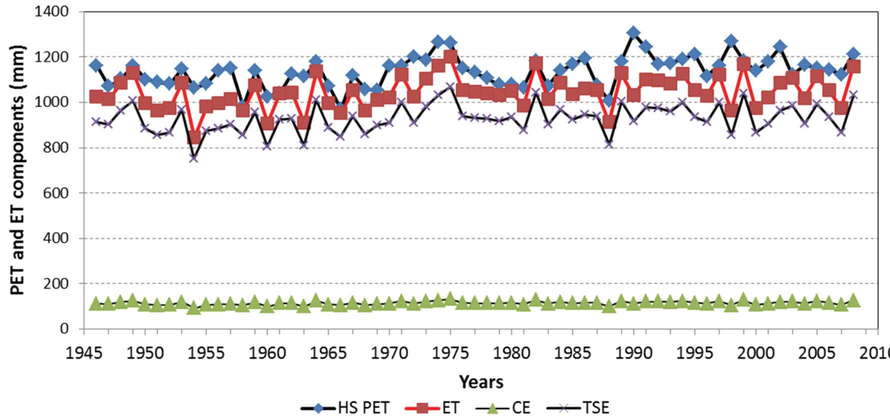

Figure 4. Long-term (1946-2008) annual estimated PM-adjusted HS PET, WBA-based simulated total ET, estimated canopy evaporation (CE), and transpiration and soil/litter evaporation (TSE) as the difference of ET and CE for the WS79 forest site.

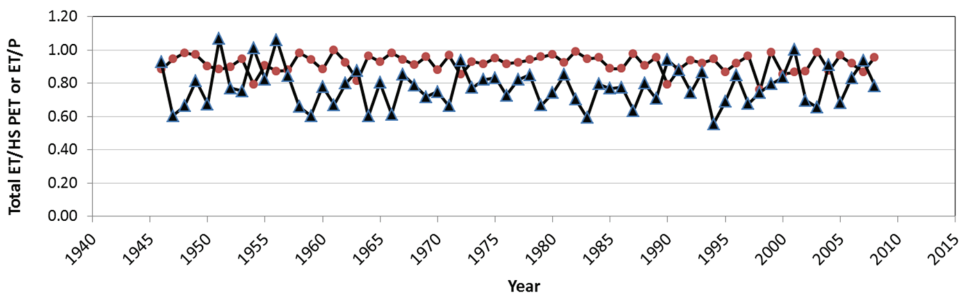

Figure 5. Simulated annual ET/HS PET for the forested watershed (WS79) at Santee SC site.

Figure 5 shows the long-term simulated annual ratios of ET/HS PET for the second-order forested watershed that contains the first-order watershed (WS80). The ET/HS PET varied from 0.76 to 1.00, with an average of 0.92 and a standard deviation (SD) of 0.05. Since the simulated ET cannot exceed the estimated PET even for unlimited soil moisture in the WBA model, no matter which method of PET is used, the ET/PET factor will never exceed unity, in contrast with the ratios reported by Sun et al. (2010), where the ratio of the pine forest ET flux measured by the eddy flux system to the FAO-Penman REF-ET (grass) was as high as 1.27, with a three-year average of 1.13. In this type of situation with unlimited soil moisture, if a method that generally overestimates PET for a given vegetation surface is used for a water balance, the maximum ET simulated by the water balance may also be overestimated, potentially underestimating the streamflow, and vice versa. On the other hand, the TH PET method, which generally underestimates the actual PM PET (Amatya et al., 1995), will likely overestimate the streamflows.

The annual ratios of simulated ET/P, defined as "evaporative index" (Creed et al., 2014), varied from 0.55 in the extremely wet year 1994 with the maximum rainfall of 2026 mm to 1.07 in the second driest year 1951 with only 900.7 mm of rainfall, with an average of 0.78 and SD of 0.12. The simulated minimum ratio of ET/P (0.55) in this simulation study is much smaller than the value (0.70) reported by Sun et al. (2010) in their limited three-year study, with a wider range of ratios between 0.70 to 1.13 and an average of 0.88 that is larger than the mean in this study. However, our mean value of 0.78 exceeds the range of 0.6 to 0.69 reported by Sanford and Selnick (2013), who developed an ET/P map for the conterminous U.S. using climatic data from 1970-2000 and a regression equation with land cover for 800 m grid cells.

The 63-year (1946-2008) long-term average monthly ET/HS PET ratios and SD values (vertical bars) based on the model simulation results for watershed WS79 are shown in figure 6. Although none of the mean monthly ratios exceeded unity, most of them were approximately or 0.90 or greater, except for April and May, and the mean value was smaller than 0.85 in May. This is because temperature, as well as PET, had increased since April, but precipitation did not increase with the increase in temperature in spring. The long-term monthly mean precipitation in April was the second lowest, 75.8 mm in the last 63 years, and only 8 mm higher

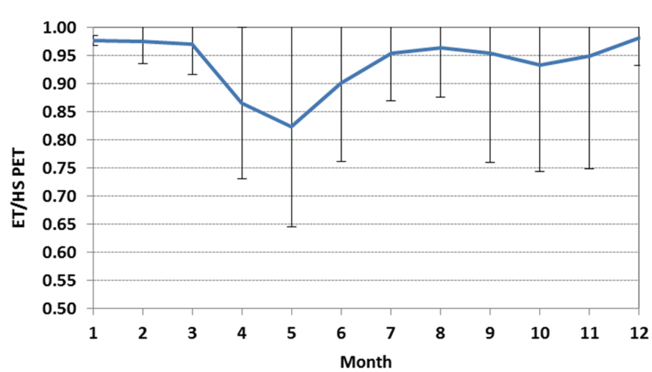

Figure 6. WBA model-simulated long-term (1946-2008) mean monthly ET/HS PET ratios (with standard deviations as vertical bars with positive values at unity). The monthly maximum never exceeded unity.

than the lowest mean in November (Dai et al., 2013). The ratio increased substantially after May due to an increase in precipitation, as well as soil moisture. Larger variations (SD) in mean values were also observed in April to June as well as September to November, when the soil moisture highly fluctuated due to variability in rainfall and higher PET. The fluctuation of the mean ET/PET ratio was relatively much smaller in wet winters (December to March) with potentially high soil moisture and low ET demands with a decrease in temperature.

Carteret NC Site

The long-term annual rainfall for the 1988-2008 period varied from 852 mm in 2001 to 2341 mm in 2003, with an average of 1517 mm (±300 mm) (Amatya and Skaggs, 2011). For the same period, the long-term REF-ET varied from 782 mm in 1992 to 1254 mm in 2007, with an average of 1010 mm, indicating that this site does also have excess moisture, on average, as was shown earlier for the SC site. Accordingly, the mean annual REF-ET/P value of 0.70 (±0.19) is also consistent with the range of 0.51 to 0.75 reported by Sun et al. (2011b) for the region where this site is located (fig. 1).

DRAINMOD-FOREST was applied for simulating long-term hydrological processes from the Carteret NC site. Results indicated that the model accurately predicted annual, monthly, and daily drainage, as indicated by NSE of 0.93, 0.87, and 0.75, respectively (Tian et al., 2012a). Figure 7 shows a comparison of model predictions and field measurements of monthly drainage. Monthly drainage predictions were very good (NSE > 0.75) for 18 of 21 years, acceptable (0.5 < NSE < 0.75) for two years, and unsatisfactory (NSE = 0.1) only for 2001. As suggested by these good model performance measures and the geological setting of the study site with minimal deep seepage (Amatya et al., 1996), the model should have accurately predicted ET, especially on a monthly and annual basis, consistent with a recent study by Tian et al. (2015).

Figure 8 shows the predicted annual dynamics of forest

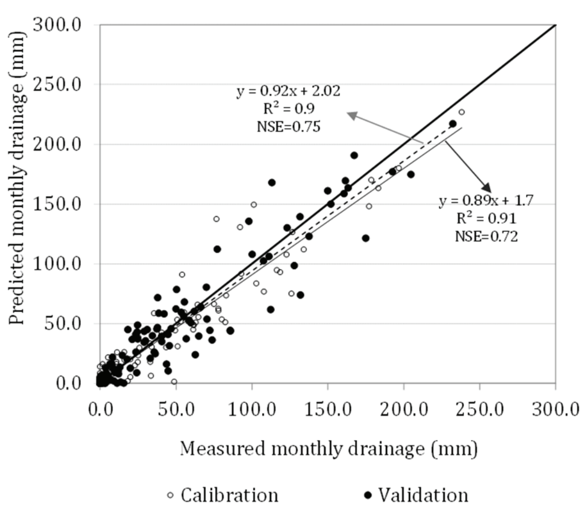

Figure 7. Comparison between DRAINMOD-FOREST predictions and field measurements of monthly drainage from the Carteret site during model calibration and validation (modified from Tian et al., (2012a).

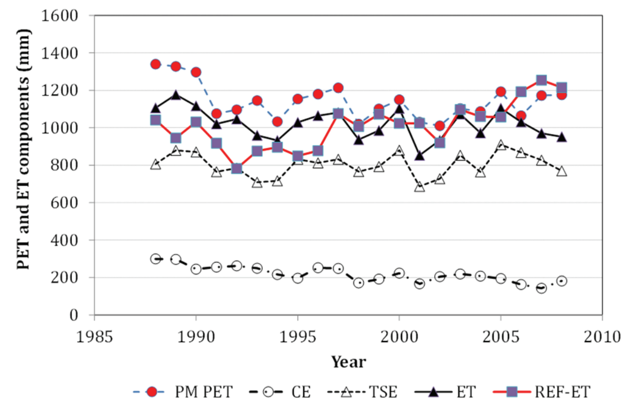

Figure 8. DRAINMOD-FOREST-predicted long-term (1988-2008) annual dynamics of pine PET using the PM method, REF-ET (Amatya and Skaggs, 2011), TSE, CE, and TET.

PET using the built-in PM method, outputs of CE from interception, and TSE, as well as total ET, which includes canopy interception. The simulated long-term mean annual forest PET of 1146 mm with a range of 1014 to 1335 mm was very close to the HS PET obtained for the SC site (table 2). This was also lower than the long-term rainfall and long-term REF-ET discussed above. In contrast, calculated annual REF-ET ranged from 782 to 1254 mm (table 2), with a long-term mean of only 1010 ±126 mm (Amatya and Skaggs, 2011). The DRAINMOD-FOREST-estimated PM PET is higher than the grass-based REF-ET during most years. On average, REF-ET is 14% lower than the PM PET simulated by DRAINMOD-FOREST. The simulated canopy interception is 223 ±40 mm year^{-1}, which is about 14% of precipitation.

The estimated canopy interception is comparable to field measurements from loblolly pine stands in eastern North Carolina (Domec et al., 2012; Sun et al., 2010) but slightly higher than at the Santee SC site (Harder, 2004), as expected. Simulated annual TSE for this pine forest ranged from 706 to 910 mm, with a long-term mean of 805 ±63 mm, which is continuously lower than the PM PET estimated by DRAINMOD-FOREST but higher than simulated grass-based PM PET for 18 of 21 years. The continuously lower TSE compared to the PM PET from DRAINMOD-FOREST is expected, since the model defines PET as the maximum water use for specific vegetation system under sufficient water supply. However, the simulated long-term mean annual ET of 1020 ±82 mm, which is about 3% higher than the estimated REF-ET, suggests some caution in using this relatively simple grass-based method for PET to estimate forest ET. This mean ET value is 2% lower than at the SC site (table 2) and 3% lower than that reported by Sun et al. (2010), who found the actual ET of a mid-rotation loblolly pine plantation to be about 13% higher, on average, than the REF-ET using a three-year limited dataset. Agricultural hydrological models use a two-step approach to compute ET, calculating REF-ET first and then reducing it with crop canopy resistance or soil moisture/water stress index (Katerji and Rana, 2011; Jovanovic and Israel, 2012). Other methods use field-measured crop coefficients to convert REF-ET to actual ET (Irmak et al., 2013).

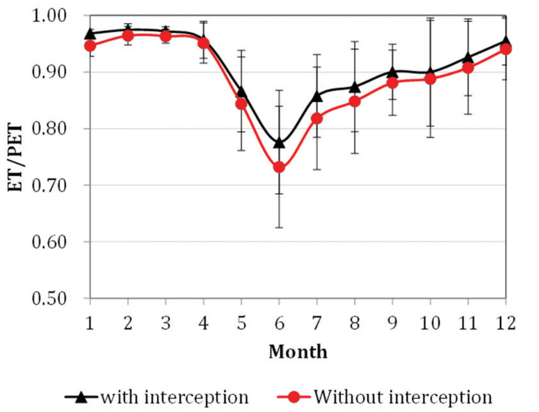

Figure 9. DRAINMOD-FOREST-predicted long-term mean monthly ratios (standard deviations as vertical bars) between ET with and without canopy interception and estimated PM-forest PET.

Figure 9 shows the long-term mean monthly ratios of predicted ET to estimated PET using DRAINMOD-FOREST with and without canopy interception (CE) and their variability, as shown by the vertical standard deviations. The predicted seasonal dynamics of the ET/PET ratio form a V-shaped curve, suggesting that the difference between water demand and water availability during summer is larger than during winter. Similar to the annual results, the monthly ratios are lower than unity. The ratio remained around 0.95 until April, followed by a quick decline, reached about 0.75 in June, and then slowly increased to around 0.95 by the end of the year. This seasonal variation of the mean ratios and their variability at this site are similar to the values calculated for the SC site, with the lowest ratio occurring in May instead of June (fig. 5). Although the ratios at both sites were larger than 0.90 in wet winter months (January to March) when the soil moisture is high at these sites, they were also larger than 0.90 in the summer to fall months (July to November) at the Santee SC site, indicating that the drained Carteret NC site may be more limited by soil moisture. However, the simulated seasonal dynamics of the ET/PET ratio based on DRAINMOD-FOREST at this site and at the Santee SC site are both in contrast with another study based on field-measured ET and grass REF-ET for a mid-rotation pine stand in eastern NC (Sun et al., 2010). Sun et al. (2010) showed a converse pattern of seasonal changes in ET/REF-ET, with low ratios (<1) during winter and high values (>1) during the growing season. The difference between this study for NC and SC sites and the study conducted by Sun et al. (2010) for another NC site was mainly caused by the inherent assumptions of the FAO-56 PM equation (also REF-ET) for grass. The FAO-56 PM method (Allen et al., 2005) implicitly assumes that the reference grass has static properties, with a canopy height of 0.12 m, a leaf area index of 2.8 m^2 m^{-2}, a bulk surface resistance of 70 s m^{-1}, and albedo of 0.23. These assumed static properties could potentially lead to overestimation of water demand during non-growing seasons and underestimation during growing seasons. Katerji and Rana (2011) noted the importance of canopy resistance dynamics in controlling seasonal ET variations, particularly in tall crops such as the forests in this study.

Given the simplicity of the grass REF-ET method, we examined its influence on simulated ET/PET ratios for the loblolly pine stand, as Sun et al. (2010) did. Due to the limitation of field measurements of actual ET, as for the SC site, we also assumed that predicted ET from DRAINMOD-FOREST is reasonably accurate based on the very good model performance (fig. 7) in simulating other hydrological variables (Tian et al., 2012a). Figure 10a shows a clearly declining ratio of annual total ET to grass-based REF-ET with stand age. The slope is significantly (p = 0.03) different from zero, although the rate of decline is small (0.02 per year). The ratio declined from 1.1 during the first five years (stand age between 15 and 20 years) to about 0.9 during the last five years (stand age of 30 to 35 years). The declining ratio of ET to REF-ET suggests that water use by this pine plantation decreased with time, as also reported by Delzon and Loustau (2005).

The mean ratio of total ET to REF-ET is 1.03 ±0.15, suggesting that the long-term mean annual ET is very close to the estimated REF-ET. However, at the Santee SC site, where the HS-grass PET, which was substantially higher than the PM PET, was used, the mean annual ET was only 0.92 of the HS PET. This information on widely varying

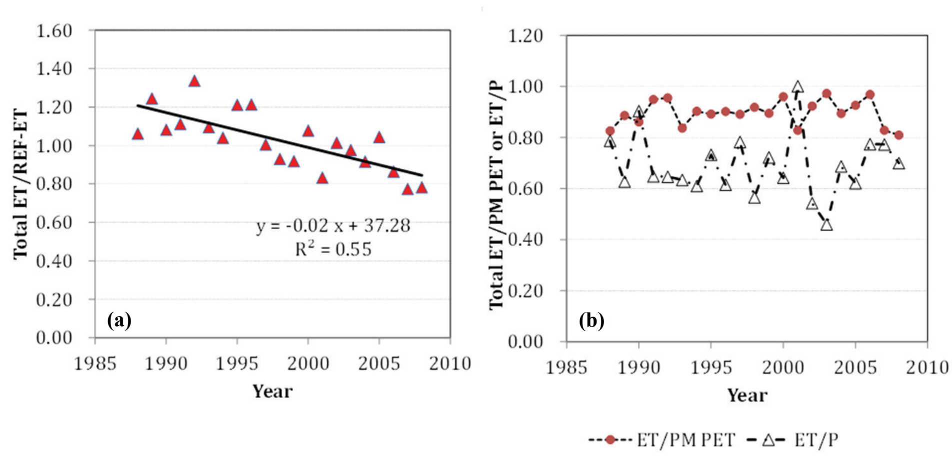

Figure 10. Inter-annual changes in (a) the ratio of annual total ET/REF-ET and (b) the ratio of annual total ET/PM PET and the ratio of annual total ET/P simulated by DRAINMOD-FOREST.

ET/PET values as influenced by PET method is critical for forest managers and planners to accurately estimate water use changes for natural and pine plantations, although more study is needed to verify the trends, magnitudes, and distribution of forest ET.

In contrast to the declining trend of the ratio of total ET to estimated grass REF-ET (fig. 10a), the ratio of ET to PM PET for forest and the evaporative index (ET/P) did not show a clear trend (fig. 10b). Specifically, the ET/PM PET changed from 0.81 in 2008 to 0.97 in 2003 (a wet year), with a mean of 0.89 and standard deviation of 0.05. The ratio suggests that the water supply can satisfy as least 80% of forest ET demand, which is expected given the site-specific climate conditions. However, annual ET/P changed from 0.46 in 2003 to 1.0 in 2001, with a mean of 0.69 and standard deviation of 0.12 (fig. 10b), which is lower than that for the SC site (table 2). Interestingly, this average value falls beyond the range of 0.5 to 0.59 reported by Sanford and Selnick (2013) for the lower coastal region of North Carolina where this site is located. The lowest ratio in 2003 within this study period was attributed to the wet weather during that year, while the highest ratio in 2001 was caused by the extreme drought during that year, with annual precipitation only 56% of the long-term mean.

PARKER TRACT NC SITE

The mean monthly ET/REF-ET ratios together with their standard deviations (vertical bars) obtained for a mature pine forest using measurements of ET flux above the forest canopy by the eddy covariance (EC) method for the 2005-2012 period at the Parker Tract site in coastal North Carolina (extension of data from Sun et al., 2010, and Domec et al., 2012) are plotted in figure 11. The ratios varied from 0.69 (±0.07) in March to 1.10 (±0.32) in November. Interestingly, the observed ratios equaled or exceeded the value of 1.0 from September to December for this pine forest site, indicating that monthly forest ET can exceed grass REF-ET. However, such was not the case for the ratios of ET and HS PET for grass at the SC site (fig. 5) to ET and PM PET for forest at the NC site (fig. 9), as expected, although only the ratio of ET to REF-ET on an annual basis

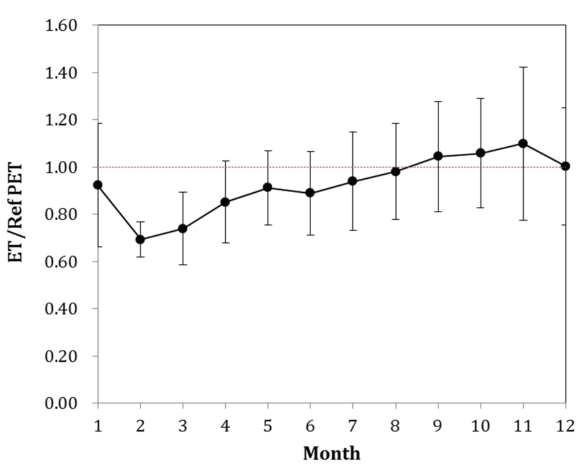

Figure 11. Mean monthly ratio between eddy covariance based measured ET and estimated PM PET for grass (or REF-ET) using 2005-2012 data for a mature pine forest site at the Parker Tract NC site.

exceeded unity during some years at the NC study site (fig. 10a). The simulated ET value for the SC site was limited by the PET obtained using the HS method for the grass reference in the WBA model, even when soil moisture was unlimited. We showed earlier (fig. 6) that HS PET for grass may overestimate PM PET for forest, resulting in ET/PET values lower than unity, as shown in figure 5. However, as shown in figure 6, PM PET for grass (or REF-ET) was lower than PM PET for forest, which may result in ET/REF-ET higher than unity, as shown by Sun et al. (2010) and in figure 11. When the soil moisture becomes abundant, ET may approach PET, resulting in ET/PET values close to unity. At the NC site, the transpiration portion of ET was limited by the potential transpiration simulated by the PM method within DRAINMOD-FOREST. Even when canopy interception was added to the transpiration component for total ET, the ratios increased, but still did not exceed unity for the NC site (fig. 9). The main reason for this was because the PM PET simulated for the forest was used in ET/PET ratios instead of the grass REF-ET used at the Parker Tract site shown in figure 11, which was about 14% lower than the PM-PET for the forest.

Although the low mean ratio of 0.69 at the Parker Tract NC site was similar to the low ratios of 0.75 for our pine and hardwood mixed forest in SC (fig. 5) and 0.72 for the pine forest in NC, the February timing when this occurred at the Parker Tract site was three to four months earlier than that predicted for our two study sites. This was mainly caused by the assumed constant magnitude of LAI, stomatal conductance, and aerodynamics conductance when estimating PET using the PM method for grass. This assumption simplified estimation but ignored seasonal variations and the interactions of important factors affecting PET. Thus, the PM PET for grass (REF-ET) may overestimate PET for a forest stand prior to the growing season and may not accurately represent the forest PET in other months.

Therefore, we believe that the PM method and other methods that account for the interactions and controls of biophysical properties of forest vegetation with the climate are a proper basis for estimating forest PET for further use in water balance and modeling approaches to simulate forest ET. Alternatively, methods that closely resemble PM-based forest PET in magnitude and seasonal variation may also be recommended when deriving ET/PET ratios and their application for forest vegetation. This is analogous to using REF-ET with crop coefficients to calculate actual crop ET in irrigation management.

SUMMARY AND CONCLUSIONS

Simulated long-term ET from earlier validated hydrologic modeling studies on two Atlantic coastal plain forest sites, a naturally drained matured pine mixed hardwood forest in South Carolina (SC) and a managed drained pine forest in North Carolina (NC), were used together with estimated and simulated PET to assess mean annual and monthly ET/PET ratios. We used estimated HS-grass PET adjusted with the PM-grass reference method for the SC site to simulate long-term (1946-2008) ET using the WBA model. However, PM PET for forest at the NC site was internally simulated to simulate actual forest ET using DRAINMOD-FOREST. The NC and SC study sites both yielded long-term mean annual PET close to 1140 mm and lower than the long-term average of rainfall (P), indicating that these coastal forests are generally wet and energy-limited systems. However, due to lower rainfall, mean annual ET/P was higher for the SC site (0.78) than for the NC site (0.69). The mean annual PET at both the sites was substantially higher than the REF-ET (1010 mm). However, the unadjusted HS-grass PET for the SC site was shown to be higher than the PM PET for the forest calculated using on-site above-canopy microclimate and resistance parameters. Although the magnitudes of mean monthly ET/PET ratios varied from 0.75 to 1.0, and their seasonal variations were somewhat similar at both sites, the ratios at the NC site were slightly lower, particularly in the summer-fall period, indicating that the artificial drainage at the NC site can reduce the soil moisture. Again, some of the discrepancies in the ratios were attributed to the use of two different PET methods for two reference vegetation types (grass for HS PET and forest for PM PET), as well as the climatic differences. The seasonal variations of ET/PET at the two sites in this study were different from the eddy covariance based ET/REF-ET reported by Sun et al. (2010) including longer-term data for another coastal forest in North Carolina. This was mainly attributed to the assumptions of static physical parameters (e.g., canopy resistance) in the P-M equation (REF-ET) for a standard grass reference. These results indicate uncertainties associated with the methods and their parameters used in estimating PET/ET for forest systems that need to be explored further.

Our study suggests that direct use of standard grass REF-ET (or FAO-Penman) to represent PET for forest vegetation without considering the appropriate vegetation and climatic factors could lead to underestimation of actual seasonal forest PET, potentially resulting in overestimation of actual ET during non-growing seasons and underestimation during growing seasons. The reason is that forests have higher LAI, lower albedo, and lower aerodynamic resistance than grass. Similarly, use of HS-grass PET for forests may overestimate ET, resulting in underestimation of streamflows, particularly in wet years. Future research should focus on modification of the standard REF-ET or FAO-Penman and/or simpler PET methods such as HS with appropriate factors for reliable estimates of forest PET. Additional studies are also warranted to quantify PM-type PET and ET/PM PET, as "crop coefficients" analogous to agricultural crops, for major forest types using recently available large global datasets of eddy flux-based measured ET to address ET and associated water yield for various forest types in ecohydrologic studies. This is particularly critical in the face of changing climate, as forest types can potentially influence the resilience of water yields, as was recently shown by Creed et al. (2014) using results from long-term experimental watersheds across North America.

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