Case Study

# Grass and Forest Potential Evapotranspiration Comparison Using Five Methods in the Atlantic Coastal Plain

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**Abstract:** Studies examining potential evapotranspiration (PET) for a mature forest reference compared with standard grass are limited in the current literature. Data from three long-term weather stations located within 10 km of each other in the USDA Forest Service Santee Experimental Forest (SEF) in coastal South Carolina were used to (1) evaluate monthly and annual PET estimates from five different methods with varying complexities [Penman-Monteith (P-M), Turc, Thornthwaite (Thorn), Priestley-Taylor (P-T), and Hargreaves-Samani (H-S)] at two grass reference sites; and (2) compare results for the grass sites with PET estimated using the P-M method for a forest reference site using measured daily climatic data for the 2011–2014 period. The grass reference sites are located at the SEF headquarters (SHQ) and in the Turkey Creek watershed (TC). The forest reference station is on a 27-m-tall tower above the canopy of a pine/mixed hardwood forest in watershed WS80 in the SEF. At the WS80 forest site, the highest annual PET (1,351 mm) was observed in 2011 with the lowest rainfall (934 mm), and the lowest PET (1,017 mm) was observed in 2013 with the highest rainfall (1,433 mm), which is consistent with the two grass sites. The temperature-based H-S method yielded estimated monthly and annual PETs that were in better agreement than those of another temperature-based Thorn method at both grass sites when compared against the P-M PET for the forest site. The P-M–based PET values estimated for the SHQ grass site were significantly lower ($\alpha = 0.05$) than those obtained at the TC grass site and the P-M PET values for the WS80 forest site. The solar radiation-based Turc and temperature-based Thorn PET estimates at both grass sites were significantly different ($\alpha = 0.05$) from the P-M PET estimates for the forest. These results for the grass sites demonstrate that PET estimates are sensitive to the method used, resulting in significantly different estimates using a single method even for nearby sites because of differences in the complexity of describing the PET process, climatic factors, and interaction with site vegetation types. When compared with the P-M PET for the forest site, the P-T method was in the closest agreement, with the highest $R^2$ of 0.96 and the least bias of 9.7% in mean monthly estimates, followed by the temperature-based H-S with an $R^2$ of 0.95 and a bias of 12.6% at the SHQ grass site. It is concluded that the simpler P-T and H-S methods appear to be adequate to estimate forest P-M PET and that their estimates are within the error bounds of the data-intensive P-M PET method for coastal forests. **DOI:** **10.1061/(ASCE)HE.1943-5584.0001341.** 

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## Introduction

Potential evapotranspiration (PET) is defined as the maximum amount of water that can be removed from a land surface through evapotranspiration (ET)—the sum of both evaporation and transpiration—given an unlimited supply of soil moisture. In other words, the removal of water by ET depends only on the available energy. PET is frequently used in many hydrologic applications, including water balance estimation, water resources development, reservoir planning and design, irrigation scheduling for crop water management, and wetland hydrology restoration, and in land use and climate change studies that use hydrologic modeling (Allen et al. 1998; Dai et al. 2013, 2010; Federer et al. 1996; Fisher et al. 2005; Harder et al. 2007; Kim et al. 2013; McKinney and Rosenberg 1993; Nghi et al. 2008; Prudhomme and Williamson 2013; Tian et al. 2015). Recent studies (Tegos et al. 2015; Rao et al. 2011; Valipour 2015a, b, c; Valipour and Eslamian 2014) found that more than 50 mathematical models are currently available to estimate PET, varying from simple temperature-based to radiation/energy balance–based to physically based process models that have been applied to various types of land covers from soil surface to crop, water, and vegetation (Alexandris et al. 2008; Allen et al. 1998; Amatya et al. 1995; Archibald and Walter 2014; Brauman et al. 2012; Douglas et al. 2009; Federer et al. 1996; Fisher et al. 2005).

Widely used PET models include Hargreaves-Samani (H-S) (1985), Penman-Monteith (P-M) (Monteith 1965), Priestley and Taylor (P-T) (1972), Thornthwaite (Thorn) (1948), Turc (1961), and others evaluated by several studies (Amatya et al. 1995; Lu et al. 2005; Alexandris et al. 2008; Douglas et al. 2009; Rao et al. 2011; Valipour 2015b). Most of these PET models were developed for a well-watered uniform grass cover. In their comprehensive review of PET estimation methods, Douglas et al. (2009) stated that the selection of one method from the many is primarily dependent on the objectives of a given study and the type of data available. In recent years, several studies have shown that the physically based P-M method (Monteith 1965), which considers both climatic factors and their interaction with surface vegetation characteristics, is the

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most accurate for estimating PET for a grass reference termed a REF-ET (Allen et al. 1998; Jensen et al. 1990; Prudhomme and Williamson 2013). The recent FAO-56 P-M model (Irmak et al. 2013), a slight modification of the original P-M method, represents a standard REF-ET ($ET_0$) for a grass reference to compare the PET of all other crops (Allen et al. 1998). As the indicator of atmospheric evaporative demand over a hypothetical reference surface, $ET_0$ is an important input to hydrologic models (Wang et al. 2015). Although it is customary to use $ET_0$ for estimating crop water requirements (McMahon et al. 2013), it is also widely used by watershed modelers as a precursor to estimating actual ET based on leaf area index (LAI), rooting depth, and soil moisture (Archibald and Walter 2014).

The calculation of water balance, including hydrologic impacts due to land use change, climate variability, and change in a watershed, is dependent on estimating actual ET (Andreassean et al. 2012; Arnold et al. 1998; Dai et al. 2010, 2013; Harder et al. 2007; Kim et al. 2013; Nghi et al. 2008; Tian et al. 2015; Prudhomme and Williamson 2013; Wang et al. 2015). At the same time, several studies have shown the sensitivity of predicted streamflows to of PET methods in hydrologic models (Harder et al. 2007; Kim et al. 2013; Liciardello et al. 2011; Wang et al. 2006). As a result, there has been a growing concern among ecohydrologists about the selection of PET methods when assessing watersheds with varied or nongrass land cover (Douglas et al. 2009; Rao et al. 2011). The major concern is the potentially different vegetation surface characteristics such as LAI, stomatal conductance ($g_s$), and canopy conductance ($G_s$), besides forest vegetation height, which likely affects plant-specific stomatal and aerodynamic control of vapor transfer differently from grass (Amatya et al. 2015; Brauman et al. 2012; Fisher et al. 2005; McKinney and Rosenberg 1993; Mohamed et al. 2012; Rao et al. 2011; Douglas et al. 2009; Federer et al. 1996). Sun et al. (2010, 2011) showed that actual ET from a pine plantation forest was substantially higher than the PET estimated by a common PET method, such as the FAO-56 grass reference ET method. However, there are only a limited number of studies on estimating forest vegetation PET (Douglas et al. 2009; Fisher et al. 2005; Rao et al. 2011) and even fewer focusing on humid coastal plain landscapes (Brauman et al. 2012).

Therefore, the main objectives of this study are (1) to assess the microclimatic characteristics of three weather stations located within a 10-km distance of each other; (2) to evaluate monthly and annual PET using the P-M, P-T, Turc, H-S, and (Thorn) methods for two nearby grass reference sites that have been widely used in coastal hydrologic studies (Amatya et al. 2015; Dai et al. 2013; Harder et al. 2007); and (3) to compare the results against those computed by the P-M method on a forest reference at an adjacent site in coastal South Carolina, allowing assessment of the reliability of each method to predict forest PET. The P-M method, which includes variable LAI effects on canopy resistance and vegetation height on a surface roughness parameter, has been shown to have significantly improved accuracy for estimating PET over a wide variety of climates and locations (Jensen et al. 1990; Brauman et al. 2012; McMahon et al. 2013).

## Materials and Methods

### Site Description

The Santee Experimental Forest (SEF) is located in the Francis Marion National Forest near Cordesville, South Carolina (Fig. 1). Weather data (initially daily precipitation and maximum/minimum air temperature) have been collected at the Santee headquarters (SHQ) station since 1946. An automatic Omnidata system (Omnidata International, Logan, Utah) measured the weather variables from 1992 until 2000. A standard 3-m weather station with a Campbell Scientific CR10X data logger (Campbell Scientific, Logan, Utah) and weather sensors (U.S. Weather Bureau) was installed on a grass surface there in August 2001. Monitoring of a standard Class-A evaporation pan was initiated in 1964, discontinued in 1968, and resumed in 2003. The predominant forest cover types in WS78 are pine and mixed hardwoods. In October 2005, a 3-m-tall weather station (TC) with a Campbell Scientific CR10X data logger and sensors was installed in the forest on a much more open grass site than the opening at the SHQ site. Finally, a Campbell Scientific CR1000 data logger (Campbell Scientific, Logan, Utah) and weather sensors were installed in WS80 above the forest canopy on a 27-m-tall tower in March 2010. The dominant vegetation around the tower is a pine/mixed hardwood stand with <25 m height.

### Potential Evapotranspiration (PET) Methods

This study used the physically based P-M method (Monteith 1965) with net radiation, vapor pressure, and aerodynamic and vegetation control; the energy-balance–based P-T (1972) and Turc (1961) methods; and the temperature-based H-S (1985) and Thorn (1948) methods to estimate daily, monthly, and annual PET at two grass reference sites (SHQ and TC). Only the P-M method, which takes climate and vegetation interaction into account, was used on the forest site (WS80).

**P-M Method**

$$LE = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e)/r_a}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad (1)$$

where $LE$ = daily PET (mm day$^{-1}$); $\Delta$ = slope of the saturation water vapor pressure at air temperature $T$ (kPa °C$^{-1}$); $R_n$ = net radiation (MJm$^{-2}$ day$^{-1}$); $G$ = soil heat flux (MJm$^{-2}$ day$^{-1}$); $\rho_a$ = dry air density (kg m$^{-3}$); $c_p$ = specific heat capacity of air (kJ kg$^{-1}$ °C$^{-1}$); $e_s$ = saturation vapor pressure (kPa); $e$ = actual vapor pressure (kPa); $\gamma$ = psychrometric constant (kPa °C$^{-1}$); $r_a$ = air resistance (s m$^{-1}$); and $r_s$ = stomatal resistance (s m$^{-1}$).

**P-T Method**

$$LE = 1.26 \frac{\Delta(R_n - G)}{\Delta + \gamma} \quad (2)$$

where $LE$ = daily PET (mm day$^{-1}$); = slope of the saturation water vapor pressure at air temperature $T$ (kPa °C$^{-1}$); $\gamma$ = psychrometric constant (kPa °C$^{-1}$); $R_n$ = net radiation (MJm$^{-2}$ day$^{-1}$); and $G$ = soil heat flux (MJm$^{-2}$ day$^{-1}$).

**Turc Method**

$$E = 0.013\left(\frac{T}{T+15}\right)(23.89R_s + 50)\left[1 + \frac{(50 - RH)}{70}\right] \quad \text{for RH} < 50\% \quad (3a)$$

and

$$E = 0.013\left(\frac{T}{T+15}\right)(23.89R_s + 50) \quad \text{for RH} > 50\% \quad (3b)$$

where $E$ = daily PET (mm day$^{-1}$); $T$ = mean air temperature (°C); $RH$ = mean relative humidity (%); and $R_s$ = daily solar radiation (MJm$^{-2}$ day$^{-1}$).

**H-S Method**

$$E = 0.408 \times 0.0023 \times Ra \times (T_{av} + 17.8) \times (T_{\max} - T_{\min})^{0.5} \quad (4)$$

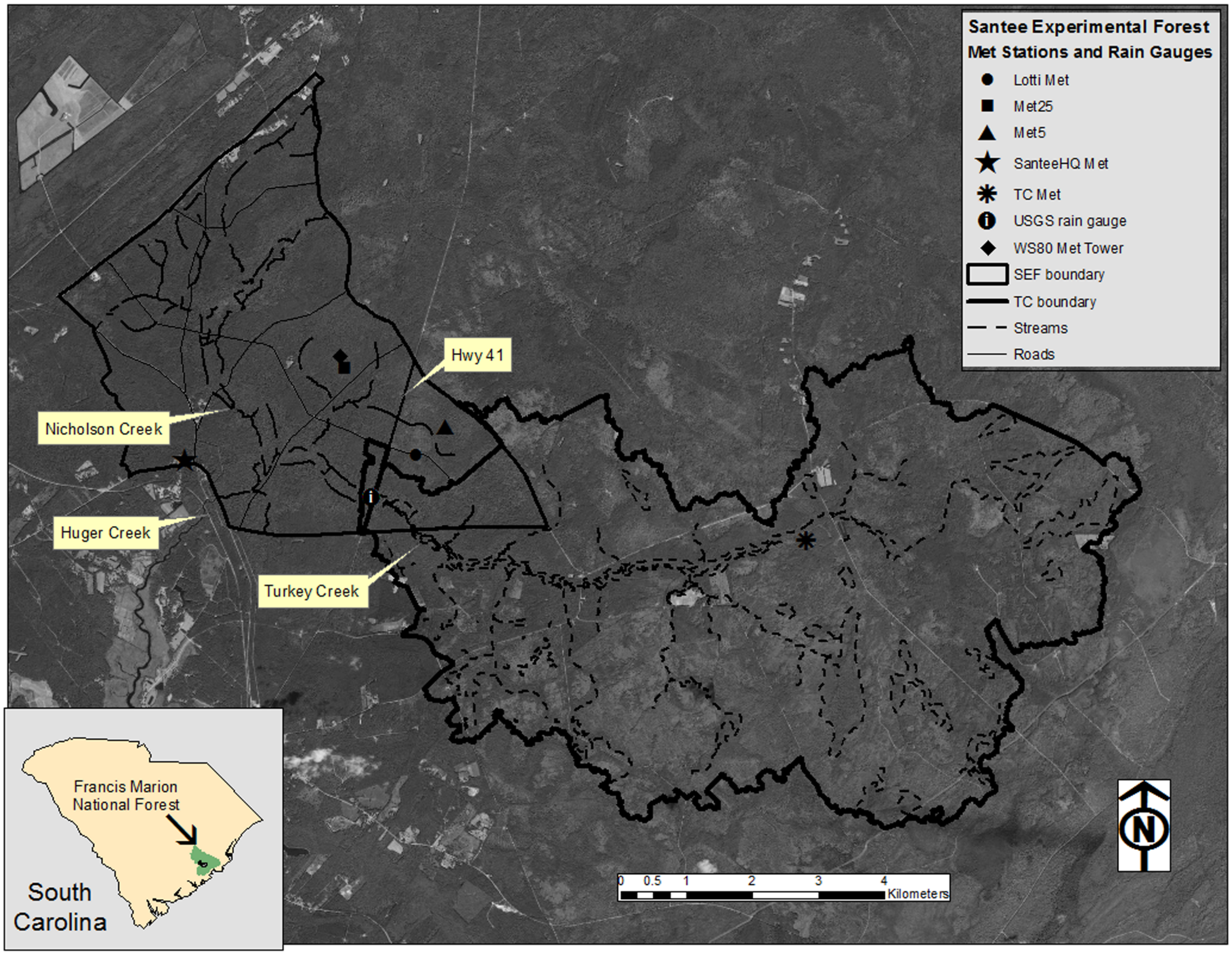


**Fig. 1.** Weather stations on or near the Santee Experimental Forest (SEF), Cordesville, South Carolina (sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGP, swisstopo, and the GIS User Community)

where $E$ = daily PET (mm day$^{-1}$); $T_{av}$ = daily average temperature (°C); $T_{\max}$ = daily maximum temperature (°C); $T_{\min}$ = daily minimum temperature (°C); $Ra$ = extraterrestrial radiation (MJm$^{-2}$ day$^{-1}$); and 0.408 = conversion factor to mm day$^{-1}$.

**Thorn Method**

$$E = 16 \times L_d \times \left(10 \times \frac{T_c}{I}\right)^a \quad (5a)$$

where $E$ = daily PET (mm day$^{-1}$); $L_d$ = mean daytime length (time from sunrise to sunset in multiples of 12 h); and $T_c$ = monthly mean air temperature (°C).

$$a = 6.75 \times 10^{-7} \times I^3 - 7.71 \times 10^{-5} \times I^2 + 0.01792 \times I + 0.49239 \quad (5b)$$

Where $I$ = annual heat index, computed from monthly heat indices.

Detailed descriptions of parameters in each of the five methods are given elsewhere (Monteith 1965; Priest-Taylor 1972; Turc 1961; Hargreaves-Samani 1985; Thornthwaite 1948; Jensen et al. 1990; Amatya et al. 1995). The original coefficient of 0.0023 in the H-S method [Eq. (4)] was substituted by 0.0020, which was found by calibration for coastal North Carolina forest conditions (Amatya et al. 2000).

### Weather Parameter Measurements

CR10X data loggers at the SHQ and TC standard weather station sites on grass, and a CR1000 data logger at the WS80 tower site on forest, were linked to various sensors at each station. Air temperature ($T$) and relative humidity ($RH$) were measured by CS500 (Campbell Scientific, Logan, Utah) and HMP45C (Vaisala, Helsinki, Finland) sensors; net radiation ($R_n$), by Q-7.1 (Radiation and Energy Balance Systems, Bellevue, Washington) and NR-LITE (Kipp & Zonen B.V., Delft, Netherlands) sensors at the SHQ and the WS80 sites, respectively; solar radiation ($R_s$), by LI-200X (LI-COR, Lincoln, Nebraska) sensors initially, which were replaced later by Apogee SP-110 (Apogee Instruments, Logan, Utah) at all sites; and wind speed ($U$) and wind direction, by MetOne 034A and MetOne 034B sensors (Met One Instruments, Grants Pass, Oregon) at the SHQ, TC, and WS80 sites, respectively. All weather parameter measurements by the sensors were made at 30-s intervals, and averages were logged for each parameter at 30-min intervals at the SHQ and TC sites and at 15-min intervals at the WS80 site. These 30- and 15-min records were integrated to obtain the daily average weather parameters for

PET estimates, except as noted, for the study period, as suggested by McMahon et al. (2013). Occasional data losses occurred when sensors malfunctioned or were periodically calibrated as recommended, as shown later. All downloaded data were checked for consistencies and completeness.

### Parameter Estimation

Because the TC weather station at the grass site lacked a net radiometer, $R_n$ data were estimated by a regression relationship ($R_n = 0.71 \times R_s - 0.77$; $R^2 = 0.89$, $P < 0.0001$) developed using daily average $R_n$ and $R_s$ at the SHQ station at the grass site for the 2003–2009 period with its measured daily $R_s$. Also, inconsistencies in and/or missing daily average $T$ data at the SHQ and TC stations were corrected and/or predicted using regressions developed between manual maximum and minimum thermometer readings at SHQ and the corresponding sensor data. All of these long-term climatic data are available at the Santee Experimental Forest online database (http://www.srs.fs.usda.gov/charleston/santee/data.html).

For the P-M method [Eq. (1)], vapor pressure deficit ($e_s$–$e$) was calculated using the FAO (1992) method. Aerodynamic resistance ($r_a$) for the 24-m-tall forest stand was calculated using that method also. Soil heat flux ($G$) for the P-M and P-T methods [Eqs. (1) and (2)] was assumed negligible for the monthly PET estimates in this study (FAO 1992).

A fixed canopy resistance ($r_s$) value of 70 $sm^{-1}$ was used for the standard 12-cm-highgrass for the P-M method (Jensen et al. 1990; Sumner and Jacobs 2005; Rao et al. 2011). A variable canopy resistance $r_s$ was calculated as an inverse of the product of a fixed maximum stomatal conductance ($g_{smax}$) and the variable leaf area index (*LAI*) for the forest canopy at the WS80 site (Lindroth 1985). Stomatal conductance ($g_s$) is a critical but complex tree physiological parameter that controls water balance through transpiration and is dependent on vegetation, soil moisture, and climatic parameters, primarily the vapor pressure deficit (VPD) and net radiation (Ambrose et al. 2010; Amatya and Skaggs 2001; Amatya et al. 1996; Tian et al. 2012, 2014). An average $g_{smax}$ value of 91 mmoles $m^2\,s^{-1}$ (0.002 $ms^{-1}$) weighted by 66% pine mixed with approximately 33% hardwood forest was estimated based on limited field measurements by a LiCOR-1600 porometer (LI-COR, Lincoln, Nebraska) on pine and hardwood species at two plots at the WS80 forest site from March through June of 2014. This value was consistent with that in other studies conducted in pine or mixed forests in the North Carolina coastal plain: ~85 mmole $m^2\,s^{-1}$ reported by Maier and Teskey (1992) for eastern white pine (*Pinus strobus*) in western North Carolina; and 80 mmoles $m^2\,s^{-1}$ reported by Amatya et al. (1996) for a loblolly pine forest in coastal North Carolina, which was the same as the value found by Laviner (1997) for loblolly pine in the upper North Carolina coastal plain. A $g_{smax}$ of 103 mmoles $m^2\,s^{-1}$ was used recently for simulating the long-term transpiration of the same forest by Tian et al. (2012), who reported $g_{smax}$ as one of the most sensitive parameters to pine forest ET. The weighted conductance values measured at the site varied from 74 on May 15, 2014, to 124 mmoles $m^2\,s^{-1}$ on October 2, 2014, and the VPDs measured at the canopy on both days were within 1.0–1.1 kPa recommended as a reference for $g_{smax}$ (Ambrose et al. 2010).

A sensitivity analysis was also conducted to examine the effects of $g_{smax}$ on mean annual PET obtained from total annual PET in each year with varying climatic patterns using the minimum (74 mmoles $m^2\,s^{-1}$) and maximum (124 mmoles $m^2\,s^{-1}$) observed values, which were coincidentally very close to the range recently reported by Albaugh et al. (2014) for a pine stand in eastern North Carolina. The monthly LAI values measured at the same plots during the 2008–2009 period varied from 1.7 to 4.0 $m^2\,m^{-2}$, with an average of 2.90 $m^2\,m^{-2}$ (Dai et al. 2010). This yielded a mean canopy resistance of $170 \pm 47$ $sm^{-1}$, which was consistent with values reported in the literature (Douglas et al. 2009; Zhou et al. 2006; Lhomme et al. 1998).

### Data and Statistical Analysis

Annual rainfall and daily mean weather parameters (temperature, wind speed, vapor pressure deficit, and net radiation) for each year were computed and compared among each of the sites (Table 1). Monthly mean weather variables for the 4-year (2011–2014) period were plotted to examine the observed microclimatic conditions at those three stations; next, linear regression and Z-tests were performed using Microsoft Excel for means of the daily weather variables between the two closest SHQ grass and WS80 forest reference sites to assess the observed differences, if any, that may have potentially affected the respective PET estimates. These regressions, and the regression between the two grass sites (SHQ and TC), were also used to fill in the missing data at each station, including in periods when the sensors were out. F-tests were first conducted between annual ($n = 4$) PET calculated by each of the grass methods (P-M, P-T, Turc, H-S, and Thorn) compared with the P-M PET for the forest reference at the SHQ and TC sites to examine the equality of variances. Student t-tests also using Microsoft *Excel* were then conducted comparing the annual PET for each grass method with the P-M PET for the forest for testing significance at $\alpha = 0.05$ using equal or unequal variances between the pair based on the F-test results. The same procedure was repeated for testing the significance of mean monthly PET for the 4-year (2011–2014) period and also for the TC site. linear regressions were conducted between each of the five methods for the grass PET compared with that of the P-M PET for the WS80 forest site to examine the best grass PET method for predicting the P-M PET for the forest reference. Mean monthly prediction error (%) was calculated as the difference between the monthly P-M PET for the forest and the PET calculated by each grass method divided by the P-M PET for the forest to evaluate the prediction bias of each method at both sites.

**Table 1.** Annual Rainfall ($P$) and Mean Daily Temperature ($T$), Wind Speed ($U$), Vapor Pressure Deficit (VPD), and Net Radiation ($R_n$) at the Three Sites for 2011–2014

| | SHQ | | | | | TC | | | | | WS80 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | $P$ (mm) | $T$ (°C) | $U$ ($ms^{-1}$) | $VPD$ (kPa) | $R_n$ ($MJm^{-2}\,d^{-1}$) | $P$ (mm) | $T$ (°C) | $U$ ($ms^{-1}$) | $VPD$ (kPA) | $R_n$ ($MJm^{-2}\,d^{-1}$) | $P$ (mm) | $T$ (°C) | $U$ ($ms^{-1}$) | $VPD$ (kPa) | $R_n$ ($MJm^{-2}\,d^{-1}$) |
| 2011 | 962.8 | 18.6 | 0.42 | 1.01 | 8.85 | 1,043.2 | 17.8 | 0.79 | 0.93 | 10.6 | 934.2 | 18.2 | 1.25 | 1.03 | 10 |
| 2012 | 1,193.8 | 17.8 | 0.47 | 0.96 | 8.65 | 1,117.2 | 17.8 | 0.74 | 0.84 | 10.3 | 1,174.4 | 18.2 | 1.17 | 0.85 | 9.74 |
| 2013 | 1,464.8 | 16.9 | 0.38 | 0.76 | 8.1 | 1,545.8 | 17 | 0.77 | 0.67 | 9.65 | 1,433.3 | 17.3 | 1.04 | 0.72 | 9.1 |
| 2014 | 1,429.6 | 16.8 | 0.33 | 0.84 | 8.0 | 1,428.8 | 16.8 | 0.77 | 0.77 | 10.1 | 1,375.1 | 17.1 | 1.19 | 0.81 | 9.1 |

## Results

Annual rainfall ($P$) varied widely, with the highest in 2013 and the lowest in 2011 at all three sites (Table 1). The highest mean daily temperature ($T$), $VPD$, and net radiation ($R_n$) were observed in the year 2011, with the lowest $P$ at all sites. Mean daily temperatures were lower during the wet years of 2013 and 2014, resulting in their lower summer peak monthly means [Fig. 2(a)]. Monthly mean temperature ($T$) was highest in July 2011 and lowest in January 2014. Monthly mean $RH$ showed an increasing trend from 2011 to 2014, varying between 65 and 90% at all sites, with the consistently lowest values at the WS80 forest [Fig. 2(b)]. Mean daily wind speed ($U$) at the WS80 canopy was almost three times and approximately 50% higher than at the SHQ and TC grass sites, respectively, in all four years (Table 1), which was consistent with the mean monthly values in Fig. 2(c). Monthly mean wind speed ($U$) generally peaked between January and April with low humidity, and the lowest values usually occurred between July and October, generally with high humidity [Fig. 2(c)]. Mean monthly $VPD$ was highest at all sites in 2011 as a result of lower humidity than in other years [Fig. 2(d)]. It was generally higher from May to August and lower from December to February in all years, with the highest value at the SHQ site and the lowest at the TC site, resulting in a significant difference.

Monthly mean solar radiation at the TC grass site was similar to that observed at the forest canopy (WS80), but for unknown reasons the SHQ site recorded lower values from July 2011 until approximately June 2013 [Fig. 2(e)]. Mean daily $R_n$ was higher at the forest canopy (WS80) than at the SHQ grass site in all years (Table 1), which was consistent with the mean monthly data shown in Fig. 2(f). Soon after the month of April, the $R_n$ measured above the canopy (WS80) increased much more rapidly than the grass $R_n$, with peaks from May to July. Both the monthly mean $R_s$ and the net radiation ($R_n$) values followed the pattern of temperature, with the highest in the driest summer of 2011 and the lowest in the wettest year of 2013. However, the $R_n$ at the TC grass site was extrapolated using the regression at the SHQ site.

There was no difference between the mean daily $T$ among the two nearby SHQs and the WS80 forest sites, with a regression $R^2$ of 0.99 and a slope of 0.96 [Fig. 3(a)]. However, the WS80 mean daily $T$ was different ($\alpha = 0.05$) from the temperature at the farthest station at the TC grass site (Table 1). The plot of daily $RH$ values in Fig. 3(b) showed lower but significant ($\alpha = 0.05$) values at the forest canopy site than at the grass sites for $RH < 97\%$, which occurred most of the time, as is also evident from Fig. 2(c). Daily $U$ at the TC site was almost twice that at the SHQ site, and above-forest canopy (WS80) $U$ was almost three times higher than $U$ at the SHQ grass site, with a slope of 1.65 but a $R^2$ of only 0.64 [Fig. 3(c)], both of which were statistically significant ($\alpha = 0.05$). However, the mean daily $VPD$ above the forest canopy was not different from the mean daily $VPD$ at either the SHQ grass site [high $R^2$ of 0.96, slope of 0.98; Fig. 3(d)] or TC grass site. Mean daily solar radiation at the SHQ site was also highly correlated ($R^2 = 0.95$) with a slope of 1.02 [Fig. 3(e)], but was significantly lower than that at the WS80 site. There was strong correlation ($R^2 = 0.96$) for daily $R_n$ between the SHQ grass and WS80 forest sites, with a mean daily forest $R_n \sim$ 13% higher ($\alpha = 0.05$) than that for the SHQ grass site [Fig. 3(f)]. All regression models and their parameters for the daily weather variables were also statistically significant ($\alpha = 0.05$).

The annual PET for the 2011–2014 period varied widely among the five grass-based methods at both the SHQ and the TC site, with the highest estimates consistently estimated by the H-S method except in 2014 at the TC site, and the lowest estimates estimated by the Thorn method (Table 2). This resulted in the mean annual PET varying from 903 mm for the Thorn method to 1,307 mm for the H-S method at the SHQ site, and from 892 mm for the former to 1,300 mm for the latter at the TC site. Both methods are temperature-based and yielded values not significantly different ($\alpha = 0.05$) between these sites. This was expected because the temperature was similar at both [Fig. 2(a)]. However, the mean annual PETs of 1,127, 1,043, and 1,266 mm estimated by the P-M, Turc, and P-T methods, respectively, at the TC site (Table 2) were significantly higher than the values of 935, 949, and 1,067 mm for those methods at the SHQ grass site (Table 2) located approximately 10 km away.

When compared with the mean annual PET for the WS80 forest reference, the mean annual PETs estimated by the P-M, Turc, and Thorn methods were significantly different, but not those estimated by the P-T and H-S methods, which underestimated and overestimated the forest P-M PET, respectively, at the SHQ site (Table 2). However, except for the Thorn method, there was no significant difference between the grass PET methods and the P-M PET for the WS80 forest at the TC site (Table 2).

The monthly P-M PET for the forest at the WS80 site varied from 222.8 mm (7.4 $mm\,d^{-1}$), the highest value of all the methods in the very warm June of 2011, to 29.8 mm (0.96 $mm\,d^{-1}$) in December 2014 [Fig. 4(a)]. However, in 2013, with relatively wet months, the P-M forest PET in summer did not exceed 134 mm (4.3 $mm\,d^{-1}$). The monthly H-S PET for the grass consistently yielded the highest values for all months of the 4-year period except June 2011 and July 2012, when the P-M PETs for the WS80 forest yielded the highest (shown by the slopes of 0.91, significant at $\alpha = 0.05$, above the 1:1 line for both the SHQ and the TC sites in Figs. 5 and 6). Visual observations of monthly PET in Figs. 4(a and b) and slopes of regression lines of monthly PET compared with the 1:1 line for the P-M forest PET in those figures show that both the H-S and P-T monthly PETs more closely followed the forest P-M PET than did the other three grass PET methods, with the H-S PET staying closer to the P-M PET for most months except in the summer of 2013 and 2014, when it overpredicted the P-M forest PET [Figs. 4(a and b)]. The P-T PET seems to have performed better at the TC site [Fig. 4(b)] than at the SHQ site [Fig. 4(a)], where it underestimated PET in all summer months except in 2013, as shown in Fig. 5.

The monthly P-M PET for the TC grass site followed the P-M PET for the forest site more closely than did the monthly P-M PET for the SHQ grass site [Figs. 4(a and b)], resulting in a mean monthly TC grass PET (94 mm), which was much closer than the SHQ grass P-M PET (only 78 mm) to the P-M forest PET (99 mm). The Thorn method yielded the lowest values in the winter at both the SHQ and TC sites [Figs. 4(a and b)]; it yielded values higher than those estimated by the P-M, Turc, and P-T methods at the SHQ site, and values higher only than those estimated by the Turc method at the TC site during the peak summer months. Accordingly, the Thorn regression line slopes with the P-M forest PET were below the 1:1 line (Figs. 5 and 6).

Regression plots of monthly PET estimated by each of the five grass-based PET methods against the monthly P-M PET for the WS80 forest site indicated that both the P-T and the H-S method were in better agreement ($R^2 = 0.95$–$0.96$) with the P-M forest PET than were the other three methods, including the grass P-M PET at both the SHQ and the TC site when compared with the 1:1 line (Figs. 5 and 6). Both methods also yielded an intercept that was insignificant at the SHQ site but significant for the P-T PET at the TC site. However, the slope of 0.91 for the H-S PET at both sites indicated a bias with an overestimate of the forest P-M PET; the slope of 1.11 at the SHQ site and 1.15 at the TC site for the P-T method indicated a bias with an underestimate. When evaluated

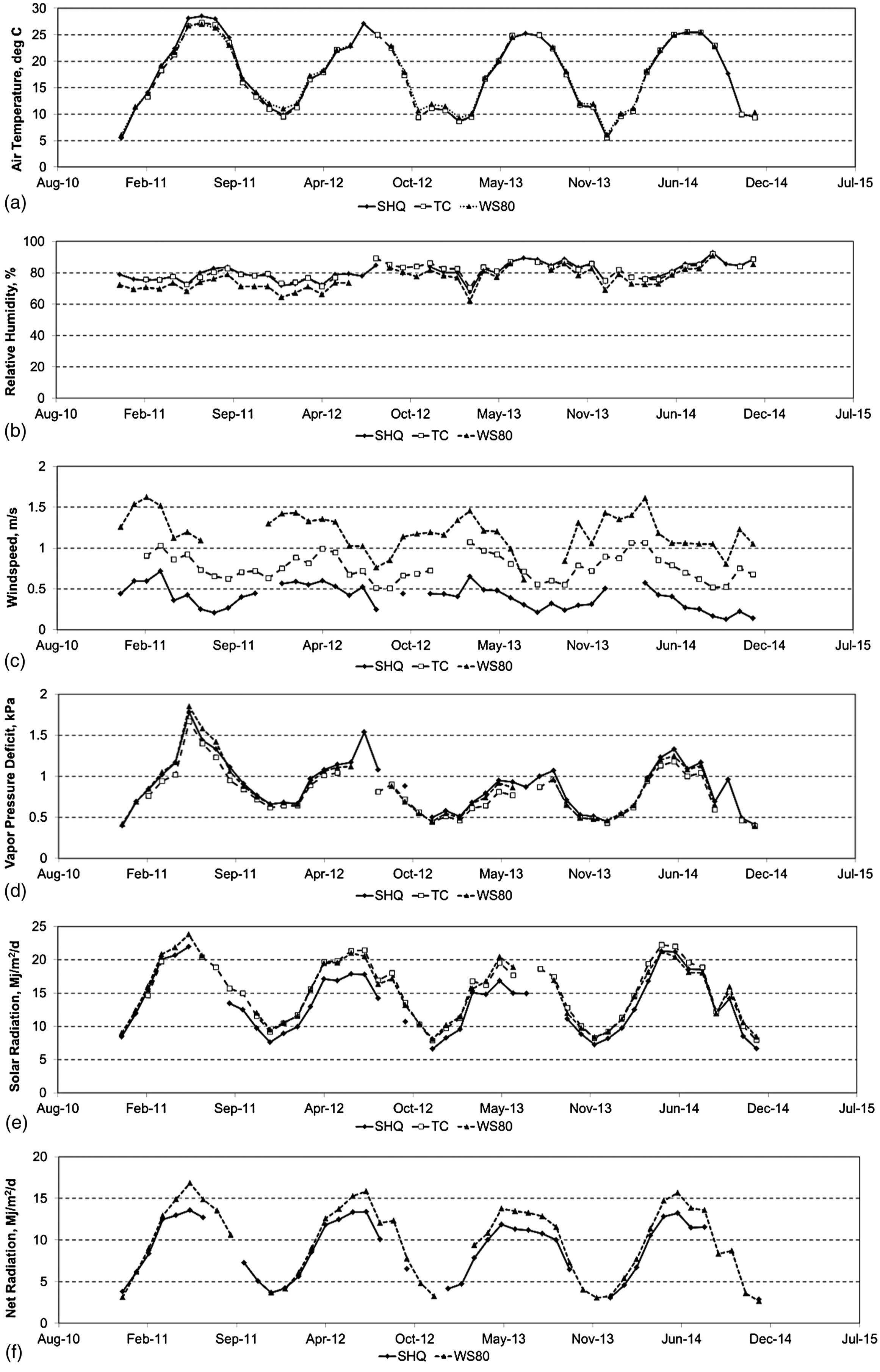


**Fig. 2.** Monthly mean: (a) temperature; (b) relative humidity; (c) wind speed; (d) vapor pressure deficit; (e) solar radiation; and (f) net radiation at the SHQ, TC, and WS80 weather stations

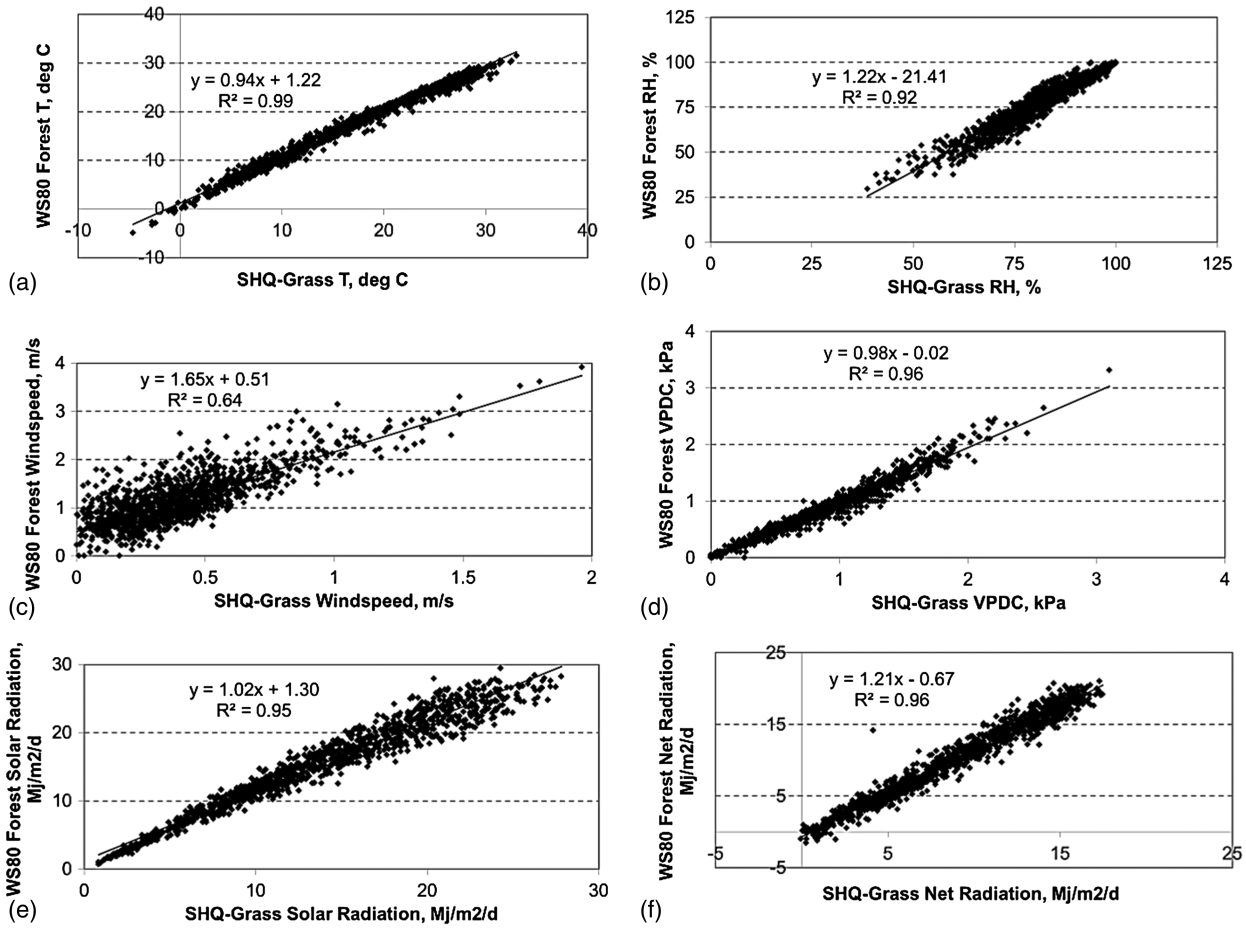


**Fig. 3.** Regression of measured daily mean weather parameters ($T$, $RH$, $U$, $VPDC$, $R_s$, and $R_n$) between the forest canopy (WS80) and the grass vegetation (SHQ) sites

**Table 2.** Estimated Annual PET by Five Methods for Grass Reference Compared with the P-M PET Method for the Forest Reference

| | SHQ grass site | | | | | TC grass site | | | | | Forest reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | P-M (mm) | Turc (mm) | Thorn (mm) | P-T (mm) | H-S (mm) | P-M (mm) | Turc (mm) | Thorn (mm) | P-T (mm) | H-S (mm) | P-M (mm) |
| 2011 | 1,006 | 1,049 | 1,032 | 1,146 | 1,412 | 1,194 | 1,084 | 940 | 1,336 | 1,373 | 1,351 |
| 2012 | 987 | 922 | 893 | 1,105 | 1,331 | 1,164 | 1,087 | 929 | 1,295 | 1,376 | 1,239 |
| 2013 | 869 | 864 | 828 | 1,005 | 1,236 | 1,040 | 980 | 838 | 1,183 | 1,211 | 1,017 |
| 2014 | 876 | 959 | 859 | 1,014 | 1,248 | 1,110 | 1,022 | 860 | 1,250 | 1,238 | 1,123 |
| Mean annual[a] | 935[b] | 949[b] | 903[b] | 1,067[a] | 1,307[a] | 1,127[a] | 1,043[a] | 892[b] | 1,266[a] | 1,300[a] | 1,182[a] |
| Standard deviation | 72 | 77 | 90 | 69 | 82 | 67 | 52 | 51 | 65 | 87 | 144 |
| Mean monthly[b] | 78[b] | 79[b] | 75[b] | 89[a] | 109[a] | 94[a] | 87[a] | 74[b] | 106[a] | 108[a] | 99[a] |
| Standard deviation | 37 | 36 | 54 | 46 | 54 | 37 | 39 | 52 | 45 | 55 | 52 |

[a]Mean annual PET values with the same superscripts for each of the grass sites at SHQ and TC are not significantly ($\alpha = 0.05$) different from the PET value for the WS80 forest reference.

[b]Mean monthly PET values with the same superscripts for each of the grass sites at SHQ and TC are not significantly ($\alpha = 0.05$) different from the PET value for the WS80 forest reference.

using the statistics of mean monthly error (MME) for the bias, the P-T method yielded 9.7% compared with 12.6% for the H-S method. Clearly, the Thorn PET method with significant slopes of 0.91 at SHQ and 0.93 at TC consistently underestimated the forest-based P-M PET based on the large significant intercept of approximately 30 mm, yielding the poorest values of $R^2$ (0.88 or less) and an MME of > 31% at both sites. The Turc method, with an MME of 8%, performed better at the TC site than at the SHQ site, with an MME of 16.7%, when compared with the P-M forest PET at the WS80 site.

The computed energy [first term in the P-M method in Eq. (1)] and the aerodynamic (aero) [second term in the P-M method in Eq. (1)] components of the monthly P-M PET were compared with the total PET at the SHQ grass site and that from the WS80 forest site in Fig. 7 for 2011–2014. The data in Fig. 7 show that the energy component of the SHQ grass site PET was consistently higher than the energy component of the WS80 forest PET. However, the aero component of the tall forest PET was significantly higher than the aero component of the grass PET except in some winter months (December–February), resulting in significantly higher monthly

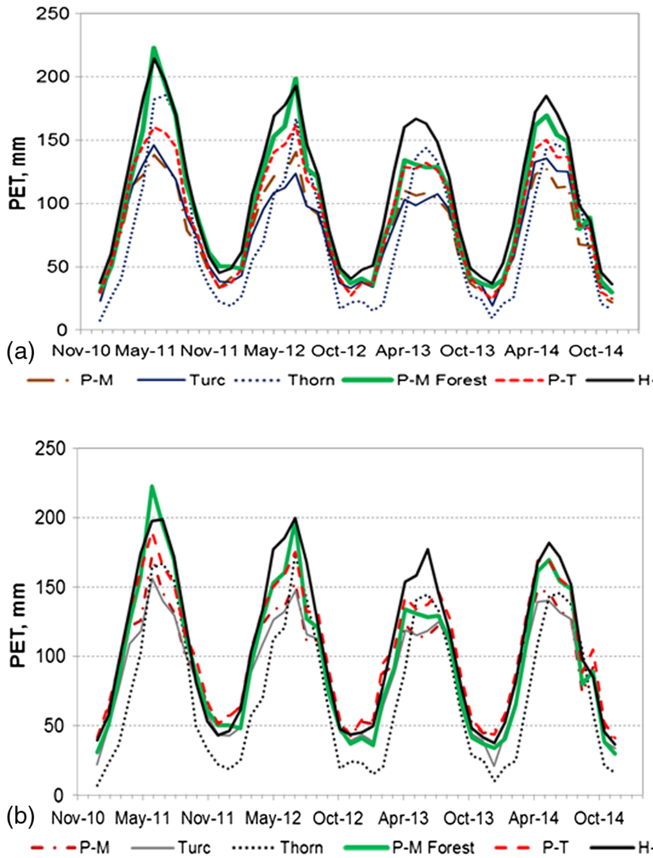


**Fig. 4.** Estimated monthly PET by five methods (P-M, Turc, Thorn, P-T, and H-S) compared with the P-M PET for the WS80 forest at (a) SHQ site; and (b) TC site for 2011–2014

and annual PET than at the grass site (Table 2). The mean monthly aero component of 10 mm was only 12.8% of the mean monthly PET of 77.9 mm at the grass site compared with 57.5% (56.7 mm) calculated for the mean monthly PET of 98.6 mm at the forest site. Whereas the mean monthly energy component substantially dominated the aero component at the grass site, it was slightly lower than the aero component at the tall forest, which exceeded the energy component of the grass PET in June 2011. Both the energy and aero components of the P-M PET were found to be higher at the TC site than at the SHQ site (not shown) because the net radiation was not measured at the TC site but estimated using a regression with the solar radiation.

When the monthly PET for the WS80 forest was examined in the context of the monthly LAI (1.85–4.0), which influences both the energy and aerodynamic components of the P-M PET (Fig. 7) through canopy resistance, $r_s$, as stated earlier, the peak monthly PET generally occurred in June or July (Fig. 7), when both the energy component and the LAI peaked and the $r_s$ value was at minimum (not shown). However, this did not hold true in 2013, when the peak monthly PET occurred in the month of May and the peak LAI occurred in July.

The sensitivity of maximum stomatal conductance ($g_{s\max}$) in the P-M method [Eq. (1)] was tested by varying its assumed base value of 90 mmoles $m^2$ $s^{-1}$ from a minimum of 74 to a maximum of 124, which was equivalent to 18% lower to 38% higher than the base line value. This was done to examine $g_{s\max}$'s effects on estimated mean total PET for the tall forest canopy at the WS80 site. Analysis showed that an 18% decrease in $g_{s\max}$ resulted in an 8.9% decrease in annual PET in the wet year (highest rainfall) of 2013 to an 9.8% decrease in PET in the dry year (lowest rainfall) of 2011, with an average annual decrease of 9.5% in PET. Similarly, a 38% increase in $g_{s\max}$ resulted in an increase of 14.4% in PET in the wet year of 2013 to 16.1% in the dry year of 2011, with an average annual PET increase of 15.5%. The sensitivity of the percentage change in annual PET to the percentage change in $g_{s\max}$ was nonlinear, as expected (not shown). The range of $g_{s\max}$ values (stated previously) yielded uncertainty in the mean annual PET varying between 1,070 mm for the lower range of $g_{s\max}$ to 1,368 mm for the higher range for the 2011–2014 period. The mean annual values of 1,067 and 1,307 mm for the P-T and the H-S methods, respectively, at the SHQ grass site and the mean values of 1,127, 1, 266, and 1,300 mm for the P-M, P-T, and H-S methods, respectively, at the TC grass site were well within the bounds of uncertainty for the P-M PET at the WS80 forest site (because of its uncertainty in $g_{s\max}$ value). The mean annual PET obtained from the Turc and Thorn methods for both grass sites was outside the bounds.

## Discussion

Although some differences in PET estimates by various methods at the same site were expected based on several studies (Amatya et al. 1995; Douglas et al. 2009; Federer et al. 1996; Jensen et al. 1990; Rao et al. 2011; Wang et al. 2015; Valipour 2015a, b), significant differences ($\alpha = 0.05$) in PET estimates were also found using the same method at sites located < 10 km from one another because of site characteristics that influenced the local microclimate. For example, observed wind speed ($U$) at the TC grass site was almost double that observed at the SHQ grass site and about three times higher at the WS80 forest canopy than at the SHQ site [Fig. 2(c), Table 1). An analysis conducted to compare relationships for SHQ wind speed ($U_{\text{SHQ}}$) versus that for above-canopy WS80 ($U_{WS80}$) for wind speed <1 m/s ($U_{WS80} = 1.63U_{\text{SHQ}} + 0.51$, $R^2 = 0.53$; $N =$ 1,256) and wind speed >1 m/s ($U_{WS80} = 1.64\, U_{\text{SHQ}} + 0.54$, $R^2 =$ 0.63, $N = 45$) observed at the SHQ site indicated no difference, although $U_{WS80}$ for the latter yielded slightly higher values than $U_{\text{SHQ}}$ for the former. Both equations were statistically significant. Overall, the relationships for both cases were also not different from the relationship $U_{WS80} = 1.65\, U_{\text{SHQ}} + 0.51$, $R^2 = 0.64$ using all of the data shown in Fig. 3(c). A possible reason for the lowest wind speed at the SHQ grass site may be the much smaller opening at the weather station with its distance from the nearest obstruction (e.g. 15–16-m-tall trees) less than the usually recommended 100 m for wind measurements (ASAE 2004) in contrast with the wide open TC grass site.

The significantly higher annual P-M PET at the TC grass site than at the SHQ grass site is attributed to significantly higher $U$ ($\alpha = 0.05$) at the TC site than at the SHQ site and also somewhat higher $R_n$, resulting in higher energy and aero components at the former than at the latter (not shown). However, the use of regression-based net radiation ($R_n$) using measured solar radiation ($R_s$) at the TC site may also have been an influencing factor, especially in the estimates produced by the radiation only–based P-T method. However, a sensor defect at the SHQ site in 2012 and early 2013 resulted in lower values of the $R_s$-based Turc PET compared with the TC site PET [Figs. 4(a and b)]. Except in 2011, the temperature-based Thorn and H-S methods produced very similar results (with H-S higher than Thorn) for monthly and annual PET at both sites (Table 2), as expected , with a slightly higher PET for both methods at the SHQ site due to that site's somewhat higher temperatures (Table 1).

The 14% higher $R_n$ values observed at the forest canopy (WS80) than those at the grass site (SHQ) were consistent with

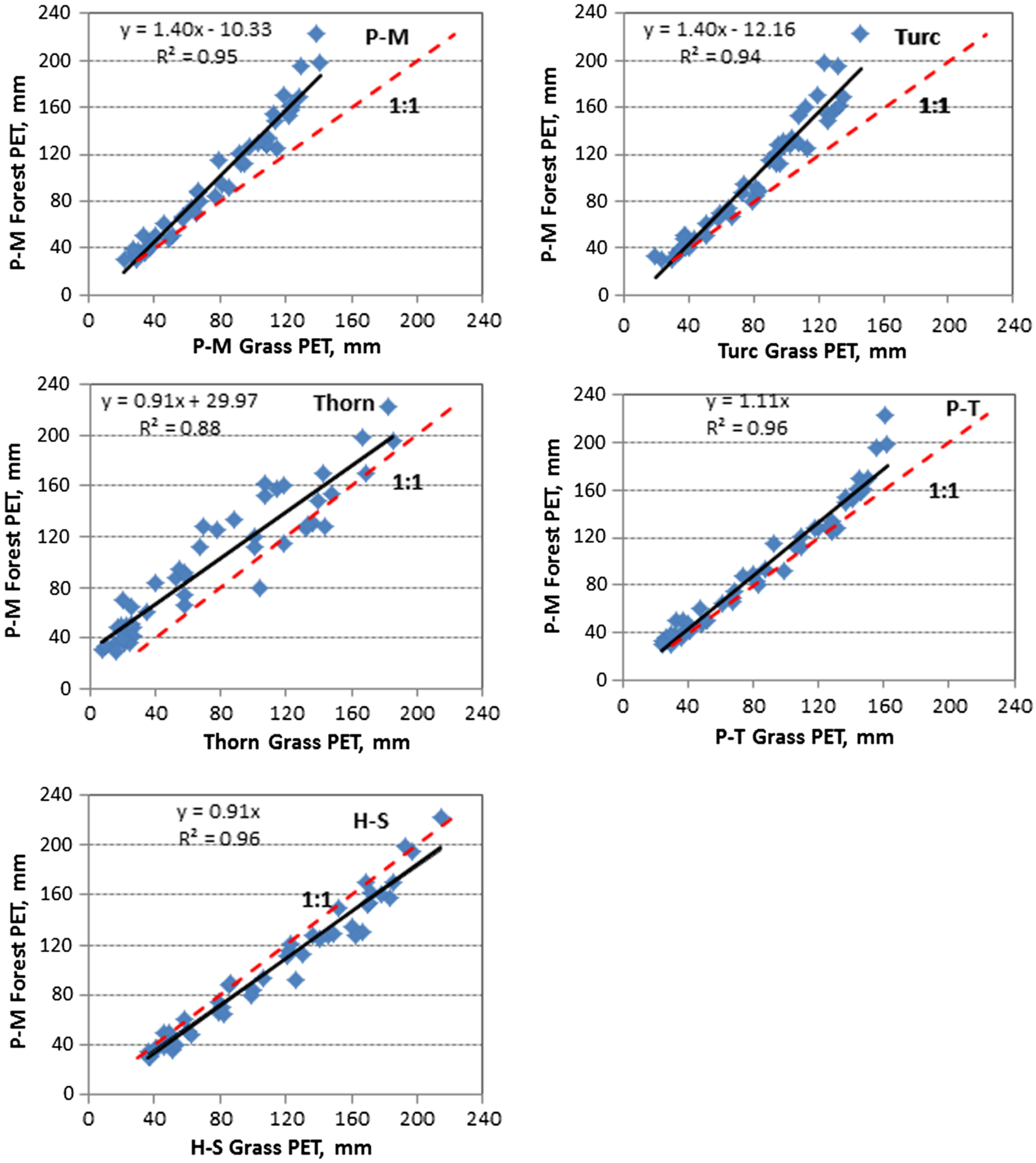


**Fig. 5.** Regression of estimated monthly PET by five methods (P-M, Turc, Thorn, P-T, and H-S) compared with the P-M PET for the WS80 forest at the SHQ site for 2011–2014

results from other coastal studies (Rao et al. 2011; Sun et al. 2010; Douglas et al. 2009). They were due to the grass surface's higher albedo (0.23) than the forest canopy's albedo (0.17) (Amatya et al. 2000; Jensen et al. 1990; Nghi et al. 2008; Sun et al. 2010). As expected, higher VPD resulted from relatively lower humidity and higher wind speeds at the forest canopy. Both of these contributed to the increased aerodynamic component in the P-M PET for the forest, as shown in two plots in Fig. 4. Similarly, as shown in Table 1 and Figs. 2(c, d, and f), both the difference in climatic parameters (wind speed, possibly VPD, and net radiation) and that in vegetation characteristics (LAI and canopy resistance) between the short grass and the tall forest canopy might have also influenced the PET estimates by the P-M method for the grass and forest reference sites, as noted in the past studies (Amatya et al. 2015; Brauman et al. 2012; Douglas et al. 2009; Fisher et al. 2005; Federer et al. 1996; Lhomme et al. 1998; McKinney and Rosenberg 1993). Douglas et al. (2009) found that literature values for the P-M method underestimated the observed daily ET at forested sites and that the use of at-site values of surface resistance greatly improved P-M mean daily ET values, suggesting that existing surface resistance parameters for trees are not reliable for all forest communities in Florida. Fisher et al. (2005) found that uncertainty in canopy resistance contributed to 53% of the total uncertainty in the Shuttleworth-Wallace model, a modified version of the P-M method (Federer et al. 1996; Zhou et al. 2006).

The energy component of the P-M PET for the forest site was consistently lower than that for the grass site, despite the 14% more net radiation received by the forest canopy. Still, the total PET for the forest reference was significantly higher than that for the grass, primarily because of its significantly higher aero component (mainly due to much higher wind speed) compared with the grass aero component (Fig. 7). The higher aerodynamic contribution was due to the interaction of the canopy and aerodynamic resistance controls in the P-M PET [Eq. (1)] in conjunction with climatic factors characterized by high wind speed and low VPD. Although a fixed canopy resistance of 69 $s\,m^{-1}$ was used in the P-M PET for

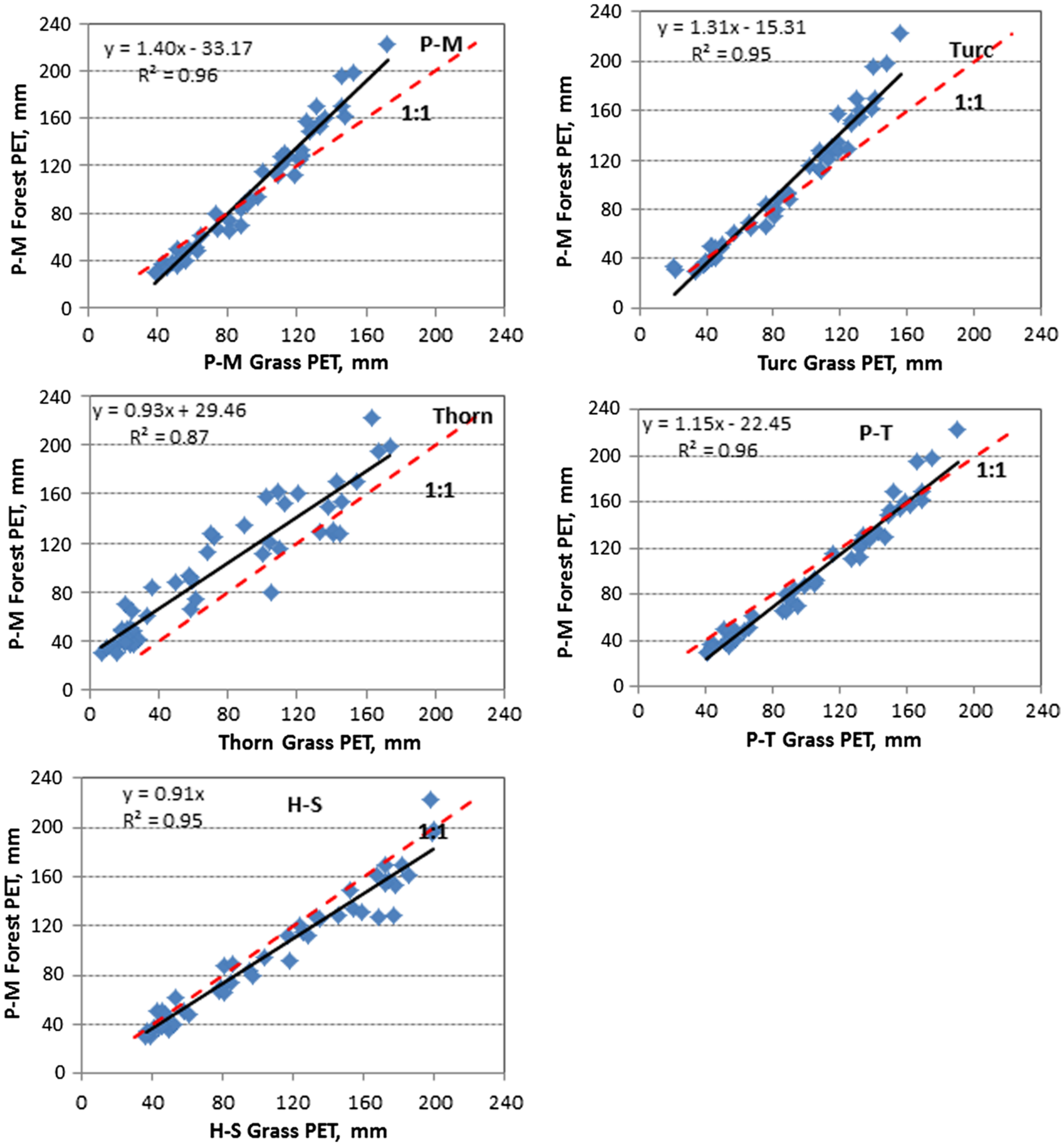


**Fig. 6.** Regression of estimated monthly PET by five methods (P-M, Turc, Thorn, P-T, and H-S) compared with the P-M PET for the WS80 forest at the TC site for 2011–2014

the grass, the canopy resistance for the forest varied 112–267 $s\,m^{-1}$ (the result of variable LAI for the maximum stomatal conductance of 90 $mmoles\,m^{-2}\,s^{-1}$), with an average of 171 $s\,m^{-1}$, which was 2.5 times higher than the grass canopy resistance. Conversely, the annual daily mean aerodynamic resistance for the forest canopy during the 2011–2014 period varied only 43–67 $s\,m^{-1}$ (average 51 $s\,m^{-1}$); in comparison, the annual daily mean aerodynamic resistance for grass varied 402–634 $s\,m^{-1}$ (average 480 $s\,m^{-1}$), which was almost an order of magnitude higher. The much smaller aerodynamic resistance and higher VPD for the forest compared with the grass (Table 1; Fig. 3) yielded a much higher aerodynamic component contribution to the forest P-M PET, resulting in a higher total forest P-M PET for most months in the 4-year period. However, in a recent study on a humid Hawaiian island, Brauman et al. (2012) unexpectedly found that modeled PET from a pasture was higher than that from a forest when ET was low, primarily because of a significantly different balance between aerodynamically and stomatally controlled ET between the two vegetation types.

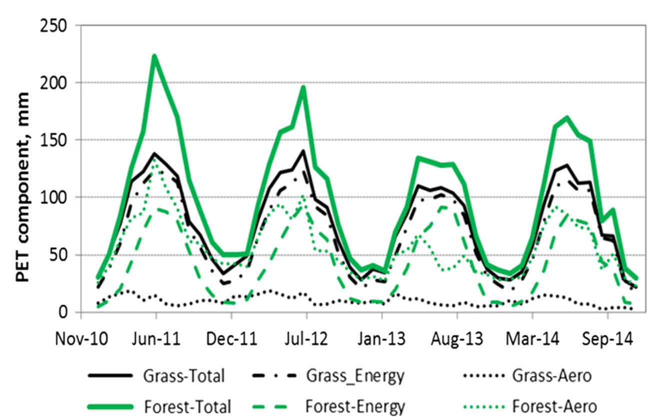


**Fig. 7.** Comparison of estimated monthly total P-M PET and its energy and aero components for the SHQ grass and WS80 forest reference sites for 2011–2014

The control of canopy resistance in both energy and aerodynamic components of the P-M PET method for the WS80 forest might have also affected the timing of its peak monthly PET, which generally occurred in June–July (Fig. 7), when the net radiation (Fig. 2) and LAI also peaked and the canopy resistance was at the minimum (not shown). Only in 2013 did the PET peak, in the month of May, which was the result of relatively lower components of canopy and aerodynamic resistance due to higher wind speed and VPD (Fig. 2) in May than in June and July. This clearly demonstrates the importance of (1) considering vegetation interaction with climatic control when selecting a PET method, and (2) interpreting the results in hydrologic and water balance studies. The latter consideration is especially true for forested sites with much taller vegetation than seen in grassland, which is assumed in most PET methods in the literature, including REF-ET (PET for a 12-cm standard grass reference) (Allen et al. 1998). In a recent related study, Amatya et al. (2015) cautioned about the use of ET/REF-ET ratios, depending on the PET or REF-ET method employed, for estimating ET in forested conditions, unlike agricultural croplands, where ET/REF-ET is widely used with a monthly crop factor to estimate monthly crop ET (Irmak et al. 2013).

Although the 1,115-mm PET obtained by the Thorn method for the limited 2-year (1964–1965) average reported by Young (1968) fell within the range of this study's 4-year mean annual P-M PET of 1,182 mm ($\pm$144) for the forest reference, it was in contrast with this study's results for the Thorn method. However, the average P-M PET of 940 mm reported by Harder et al. (2007)—using data for 2003–2004 and 945 mm obtained for the most recent 7-year (2006–2012) period (unpublished data) for the SHQ grass site—was significantly lower compared with the P-M PET for the forest reference at the WS80 site, which was consistent with this study's results. In their long-term (1946–2008) study at this experimental forest, Dai et al. (2013) obtained annual PET ranging 970–1,304 mm (average 1,137 mm), as estimated by the H-S (1985) method adjusted using 6-year (2003–2008) P-M PET estimates. These estimates were within the error bound of the 4-year mean annual P-M PET of 1,182 mm for the forest in this study. Similarly, this study's 4-year P-M forest PET results for this pine/mixed hardwood forest were also comparable with simulated results, ranging 1,014–1,335 mm/year with a long-term mean of 1,146 $\pm$ 87 mm/year, obtained by the P-M method in DRAINMOD-FOREST for a managed pine forest in coastal North Carolina (Tian et al. 2012).

Some of the results for the forest PET may have been affected by the extrapolation of missing weather data when the sensors malfunctioned or were out for factory calibration. More reliable PET estimates by any method depend on regular calibration and maintenance of weather sensors and quality control for data accuracy (Jensen et al. 1990). Similarly, estimates of canopy conductance and LAI from limited field measurements for the heterogeneous pine/mixed hardwood forest in this study may have contributed some uncertainty to the P-M PET estimate for the forest reference, although the results of a simple sensitivity test of maximum conductance were used to estimate the range of annual PET estimates and compare them with other grass-based PET methods. Furthermore, the assumption of a negligible soil heat flux in the energy term of both the P-M and P-T methods may have introduced some minor discrepancies. A new measurement of soil heat flux at the WS80 site is under way.

The results from the study's analysis indicate that the P-T method was the best predictor of the forest reference PET at the study site, and they are consistent with results from other studies in the region (Rao et al. 2011; Fisher et al. 2005; Douglas et al. 2009; Sumner and Jacobs 2005). Rao et al. (2011) reported that the P-T method gave the most reasonable estimates of forest PET when correlated with actual ET obtained from the water balance, as compared with estimates from the FAO-56 Penman method (which is the same as the P-M PET method in this study) and the Hamon method for the grass reference for two upland forest watersheds in western North Carolina. Similarly, Fisher et al. (2005) found that the P-T method, with a well-defined $\alpha$ value, performed remarkably well compared with five other physical methods for a ponderosa forest Ameriflux site in northern California.

## Summary and Conclusions

Observed local microclimatic parameters used to estimate PET can vary significantly based on site characteristics across weather stations located as close to each other as 10 km. As a result, the PET calculated by the P-M method differed significantly between the two grass reference sites. Similarly, the P-M PET for the forest was significantly higher ($\alpha = 0.05$) than the P-M PET for a nearby grass site, indicating the potential effects of site factors on P-M-based PET estimates that take vegetation-specific stomatal and aerodynamic control of vapor transfer into account. The net radiation–based P-T PET method was found to be the best predictor of monthly P-M PET for the forest reference site, followed by the temperature-based H-S method, which also takes radiation into account in addition to temperature, unlike the solely temperature-based Thorn method. The remaining three methods for grass reference, including P-M PET (at the SHQ site), yielded significantly different compared with the mean monthly PET of the P-M forest site. Additional studies are needed to understand the LAI and the canopy conductance dynamics of various forest vegetation types along with the effects of soil heat flux as it relates to the energy and aerodynamic terms of the PET by the P-M method in this low-gradient, matured natural forest. Future studies may also consider comparing mass transfer–based PET methods against the P-M-based forest PET method.

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