**Spatiotemporal variations of T/ET (the ratio of transpiration to
evapotranspiration) in three forests of Eastern China**

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Abstract

Evapotranspiration (ET), which is comprised by evaporation from soil surface (E), transpiration (T) and evaporation from the intercepted water by canopy (EI), plays an important role in maintaining global energy balance and regulating climate. Quantifying the spatiotemporal variation of T/ET (the ratio of T to ET) can improve our understandings on the role of vegetation ecophysiological processes in climate regulation. Using eddy covariance measurements at three forest ecosystems (Changbaishan temperate broad-leaved Korean pine mixed forest (CBS), Qianyanzhou subtropical coniferous plantation (QYZ) and Dinghushan subtropical evergreen mixed forest (DHS)) in north–south transect of Eastern China (NSTEC), we run the revised Shuttleworth-Wallace model (S-W model), validated its performance with the water vapor fluxes measured at two layers, and quantified the spatiotemporal variations of T/ET. The S-W model performed well in simulating ET and T/ET. The mean value of annual T/ET at three forests during the observation period all exceeded 0.6. The diurnal variation of canopy stomatal conductance (G_c) dominated that of T/ET. The seasonal dynamics of T/ET was mainly shaped by that of leaf area index (LAI), vapor pressure deficit (VPD) and air temperature (T_a) through altering G_c and the portion that the energy absorbed by canopy (P_{EC}) at temperate forest (CBS), while the seasonal dynamics of T/ET at subtropical forests (QYZ and DHS) were mainly affected by T_a , net radiation, VPD, and soil water content through altering G_c and soil surface conductance (G_s). The variation of mean annual G_c governed the interannual variation and spatial variation of T/ET. Therefore, forests in Eastern China played an

important role in regulating climate through T and G_c primarily affected the spatial and temporal variations of the role of forest T in regulating climate.

Key-words: eddy covariance; Shuttleworth-Wallace model; evapotranspiration; the ratio of transpiration to evapotranspiration (T/ET); forest

1 Introduction

Forest, occupying 31% of the land surface, plays an important role in global mass cycles and energy flows (FAO, 2010). Evapotranspiration (ET) of forest, an important component sustaining the forest water and energy balance (Falge et al., 2005), affects the global energy partition and then climate, whereas ET is comprised by multiple source water vapor fluxes such as evaporation from soil surface (E), transpiration by plant (T) and evaporation from the intercepted water by canopy (EI) (Kool et al., 2014), which are controlled by different biotic and physical processes (Scanlon and Kustas, 2012). Therefore, to fully clarify the role of each process in forest ET and then in regulating climate, it is critical to quantify the portion of ET components in ET and reveal factors controlling these portions (Hu et al., 2009; Lawrence et al., 2007).

The ratio of T to ET (T/ET), the key parameter for productivity and water use efficiency (Hu et al., 2008; Schlesinger and Jasechko, 2014), reflects the role of vegetation ecophysiological processes in water loss through ET (Hu et al., 2009), which is also a parameter indicating the role of plant ecophysiological processes in regulating climate. The variation of T/ET and its affecting factors have been extensively investigated (Hu et al., 2009; Kato et al., 2004), while most studies about the variation of T/ET are conducted in croplands or grasslands (Hu et al., 2009; Kato

et al., 2004; Liu et al., 2002), it is still unclear what dominated the spatiotemporal variation of T/ET in forests.

Meanwhile, quantifying T/ET should base on ET partition, which can be fulfilled through various measurements and models (Blyth and Harding, 2011; Kool et al., 2014). Shuttleworth-Wallace model (S-W model) is the first model designed for ET partition, which is a physically-based combination model based on Penman-Monteith equation (Shuttleworth and Wallace, 1985). S-W model has also been regarded as an accurate model and the foundation of other ET partition models, which provides a validation for other models (Kool et al., 2014) and has been widely used (Hu et al., 2009; Iritz et al., 2001; Kato et al., 2004), while there have been no attempt in using S-W model to partition ET into its components at forests of China, which occupied an important portion in global forests (FAO, 2010)

China has conducted eddy covariance measurements since 2003 at three forests along the north-south transect of Eastern China (NSTEC), which experiences apparent decreasing temperature and precipitation gradients with the increasing latitude (Yu et al., 2008). The continuous flux measurements at three forests along NSTEC, which helps us understand the effects of environmental factors along climate gradients, provides a valuable platform for analyzing the variation of T/ET among different spatiotemporal scales. Using measurements from three forests along NSTEC, we run the S-W model to partition ET into its components and analyzed the variations of T/ET. The specific objectives were: (1) validate the performances of S-W model at forests, (2) quantify the importance of T in ET at forests, (3) reveal factors affecting

the spatiotemporal variations of T/ET, and (4) clarify the difference in the effects of various factors on the spatiotemporal variations of T/ET along climate gradients.

2 Material and methods

2.1 Site description and measurements

2.1.1 Site descriptions

We collected data from three ChinaFLUX sites: Changbaishan temperate broad-leaved Korean pine mixed forest (CBS), Qianyanzhou subtropical coniferous plantation (QYZ) and Dinghushan subtropical evergreen mixed forest (DHS). Brief descriptions about these three sites were listed in Table 1. Detailed information can be found in our previous works (Wen et al., 2010; Yan et al., 2013; Yu et al., 2008; Zhang et al., 2006).

Table 1 Site descriptions

Sites	CBS	QYZ	DHS
Latitude (° N)	42.4025	26.7330	23.1670
Longitude (° E)	128.0928	115.05	112.5330
Elevation (m.a.s.l)	738	100	300
Mean annual temperature (°C) ^a	3.6	17.9	21.0
Mean annual precipitation (mm) ^a	696	1485	1956
Stand age (years)	~ 200	~ 23	~ 100
Dominated species	<i>Pinus koraiensis</i> , <i>Tilia amurensis</i> , <i>Acer mono</i> , <i>Fraxinus mandshurica</i> , <i>Quercus mongolica</i>	<i>Pinus elliotii</i> , <i>Pinus massoniana</i> , <i>Cunninghamia lanceolata</i>	<i>Castanopsis chinensis</i> , <i>Schima superba</i> , <i>Cryptocarya chinensis</i> , <i>Cryptocarya concinna</i> , <i>Machilus chinensis</i>
Canopy height (m)	26	12	22

Mean diameters at breast height (cm)	~ 23	14.6	7.06
Maximum leaf area index ($\text{m}^2 \text{m}^{-2}$)	6.1	5.6	5.6
Sapwood area ($\text{m}^2 \text{hm}^{-2}$)	47.88	30.92	36.30
Total biomass (tC hm^{-2})	175	106	130
Mean annual total gross primary productivity ($\text{gC m}^{-2} \text{yr}^{-1}$) ^b	1338.84	1798.74	1367.26
Mean annual total ecosystem respiration ($\text{gC m}^{-2} \text{yr}^{-1}$) ^b	1036.51	1311.22	971.31
Mean annual total net ecosystem productivity ($\text{gC m}^{-2} \text{yr}^{-1}$) ^b	302.33	487.51	395.95
Mean annual total evapotranspiration ($\text{kgH}_2\text{O m}^{-2} \text{yr}^{-1}$) ^c	522.35	761.57	706.20

Note: a, values are the averages from 1985 to 2005 according to Yu et al. (2008); b, values are the averages from 2003 to 2008 according to Yu et al. (2013); c, values are the averages from 2003 to 2008 according to ChinaFLUX dataset.

2.1.2 Measurement and instruments

At three forests, ecosystem CO_2 and H_2O flux data were determined from the open-path eddy covariance system (OPEC) above the canopy with a sampling frequency of 10 Hz and block averaging over 30 minutes. The OPEC was consisted of an open-path infrared gas analysers (Model LI-7500; Licor Inc., Lincoln, NB, USA), a 3-D sonic anemometer (Model CSAT3; Campbell Scientific Inc., Logan, UT, USA), and a datalogger (Model CR5000; Campbell Scientific Inc.). The measuring height of ecosystem CO_2 and H_2O fluxes for CBS, QYZ and DHS were 40 m, 39 m and 27 m, respectively. In addition, another OPEC was installed below the canopy and the measuring height were all around 2.5 m for these three forests.

Routine meteorological variables were measured simultaneously with CO_2 and H_2O fluxes. Global radiation (R_g) and net radiation (R_n) above the canopy were

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5 118 measured with radiometers (Model CM11 and Model CNR-1, Kipp & Zonnen, Delft,
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7 119 Netherlands). Photosynthetic active radiation (PAR) above the canopy was measured
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10 120 with a quantum sensor (Model LI190SB, LICOR Inc.), whereas that below the canopy
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12 121 was measured by five quantum sensors (Model LQS7010-SUN, APOGEE, Logan, UT,
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15 122 USA). Air temperature (Ta) and relative humidity (RH) at different heights above and
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17 123 within canopy were measured with shielded and aspirated probes (Model HMP45C,
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19 124 Campbell Scientific Inc.). Precipitation was recorded with a rain gauge (Model 52203,
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22 125 Rm Young, Traverse City, MI, USA) above the canopy. Soil temperature (Ts) and soil
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24 126 water content (Swc) were measured using thermocouple probes (Model 105T,
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26 127 Campbell Scientific Inc.) and water content reflectometers (Model CS616, Campbell
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28 128 Scientific Inc.), respectively. Soil heat flux (G) was measured with two flux plates
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31 129 (Model HFP01SC, Campbell Scientific Inc.) at the depth of 5 cm. All
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34 130 micrometeorological measurements were recorded at 30-min intervals with
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36 131 dataloggers (Model CR10X & CR23X, Campbell Scientific Inc.). The detailed
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38 132 equipment descriptions were also described by previous works (Wen et al., 2010; Yan
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40 133 et al., 2013; Yu et al., 2008; Zhang et al., 2006).

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46 134 Leaf area index (LAI) was measured at two-week intervals or a longer period
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48 135 during the growing seasons from 2003 to 2005 using an canopy analyzer (Model
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51 137 **2.2 Data preparing**

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56 138 Flux data measured by eddy covariance technique in two layers (above and
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three-dimensional rotation (Aubinet et al., 2000), WPL (Webb, Pearman and Leuning) correction (Webb et al., 1980), storage calculation (Hollinger et al., 1994), and spurious data removal caused by rainfall, water condensation, system failure, low turbulence and so on. The u^* threshold for determining the low turbulence fluxes was calculated following Reichstein et al. (2005) for two layer fluxes based on u^* , CO_2 fluxes, and T_a . Following Menzel et al. (2003), we determined the start and the end of growing-season based on daily T_a . Negative CO_2 fluxes at nighttime (when the solar elevation angle was lower than 0°) and at non-growing season were then also removed. After data quality control, the average data coverage during 2003 to 2009 were 54%, 46%, and 43% for CBS, QYZ, and DHS, respectively, while that at daytime were 73%, 77%, and 64%, respectively.

For CO_2 fluxes measured above and below the canopy, if data gaps were less than 2 hours, they were linearly interpolated. For other gaps, the missing daytime CO_2 fluxes were interpolated using the Michaelis-Menten equation with PAR (Falge et al., 2001b), whereas the missing nighttime CO_2 fluxes were filled using the Lloyd - Taylor model with T_s at 5 cm depth following previous studies (Gao et al., 2014; Reichstein et al., 2005). Daytime ecosystem respiration (R_e) was calculated with the trained Lloyd - Taylor model at nighttime having T_s at 5 cm depth as the input variable (Gao et al., 2014; Reichstein et al., 2005). Half-hourly gross primary productivity (GPP) values were obtained based on the calculated daytime R_e and the filled half-hourly daytime CO_2 fluxes. For the two layer H_2O fluxes, data gaps were filled by the look-up table method (Falge et al., 2001a; Reichstein et al., 2005) based

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5 162 on Ta, vapor pressure deficit (VPD), and R_n .
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7 163 Data gaps of meteorological variables (including R_n , Ta, Swc, and so on) were
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9 164 filled with the mean diurnal variation (MDV) method for longer periods but using the
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11 165 linear interpolation for gaps of less than 2 hours (Falge et al., 2001b). Based on the
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22 169 absorbed PAR. Daily LAI was estimated from integrating the absorbed PAR with the
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24 170 relationship between the absorbed PAR and LAI, which was established by the
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26 171 absorbed PAR at 12:00 pm and the measured LAI (Beer et al., 2009; Gower et al.,
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28 172 1999; Law et al., 2001).
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33 173 **2.3 Model description and parameterizations**

34 174 **2.3.1 Model descriptions**

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36 175 S-W model was firstly developed based on the Penman – Monteith model and
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38 176 regarded ET as the sum of two water vapor fluxes from separate sources: evaporation
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40 177 from the soil surface (E) and transpiration from the canopy (T) (Shuttleworth and
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42 178 Wallace, 1985). Five resistances were explored in S-W model with units of $s\ m^{-1}$ (Fig.
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44 179 1): the soil surface resistance (r_{ss}), the aerodynamic resistance from the soil surface to
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46 180 the canopy (r_{as}), the canopy stomatal resistance (r_{sT}), the bulk boundary layer
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48 181 resistance (r_{ac}) and aerodynamic resistance from the canopy to the reference height
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50 182 (r_{aa}).
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57 183 In S-W model, T and E was calculated as:
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$$ET = C_c PM_c + C_s PM_s \quad (1a)$$

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$$PM_c = \frac{\Delta(R_n - G) + (\rho C_p VPD - \Delta r_{ac}(R_{ns} - G)) / (r_{aa} + r_{ac})}{\Delta + \gamma(1 + r_{sT} / (r_{aa} + r_{ac}))} \quad (1b)$$

$$PM_s = \frac{\Delta(R_n - G) + (\rho C_p VPD - \Delta r_{as}(R_n - R_{ns})) / (r_{aa} + r_{as})}{\Delta + \gamma(1 + r_{ss} / (r_{aa} + r_{as}))} \quad (1c)$$

Where PM_c and PM_s were terms describing T and E, respectively, whereas C_c and C_s were the resistance coefficient for canopy and soil surface, respectively. Δ was the slope of the saturation vapor pressure versus temperature curve ($kPa K^{-1}$). R_n and R_{ns} ($W m^{-2}$) were the net radiation arriving at the canopy and the soil surface, respectively. G was the soil heat fluxes ($W m^{-2}$). ρ was the air density ($1.293 kg m^{-3}$) and C_p was the specific heat at constant pressure ($1012 J kg^{-1} K^{-1}$). VPD was the abbreviation of vapor pressure deficit (kPa) and γ was the psychrometric constant ($0.067 kPa K^{-1}$). r_{ac} was the bulk boundary layer resistance and r_{aa} was aerodynamic resistance from the canopy to the reference height. r_{ss} was the soil surface resistance and r_{as} was the aerodynamic resistance from the soil surface to the canopy. r_{sT} was the canopy stomatal resistance.

C_c and C_s can be drawn as:

$$C_c = \left[1 + \frac{R_c R_a}{R_s (R_c + R_a)} \right]^{-1} \quad (2a)$$

$$C_s = \left[1 + \frac{R_c R_a}{R_c (R_s + R_a)} \right]^{-1} \quad (2b)$$

Where R_c , R_a and R_s were given as:

$$\begin{aligned} R_a &= (\Delta + \gamma) r_{aa} \\ R_s &= (\Delta + \gamma) r_{as} + \gamma \\ R_c &= (\Delta + \gamma) r_{ac} + \gamma r_{sT} \end{aligned} \quad (3)$$

R_{ns} was estimated through Beer's law using LAI as:

$$R_{ns}=R_n \exp(-k \times LAI) \quad (4)$$

Where k was extinction coefficient, which was set to 0.5 in this study according to previous study (Beer et al., 2009) as the forests were needle forest or mixed forest.

The calculations of each resistances were described in the previous study (Shuttleworth and Wallace, 1985) in detail. In a recent study, Hu et al. (2009) revised the expressions of soil surface resistance (r_{ss}) and the canopy stomatal resistance (r_{sT}). r_{ss} was calculated as the function of soil water content (Swc):

$$r_{ss} = b_1 \left(\frac{Sws}{Swc} \right)^{b_2} + b_3 \quad (5)$$

where Sws was the saturated water content in the surface soil ($m^3 m^{-3}$), which was set to 0.48, 0.42, and 0.54 for CBS, QYZ, and DHS, respectively. b_1 , b_2 , b_3 were empirical constants.

r_{sT} was calculated using a modified Ball - Berry model (Hu et al., 2009; Wang and Leuning, 1998) as:

$$r_{sT} = \frac{1}{g_0 + a_1 \times f(Swc) \times GPP \times RH / C_a} \quad (6a)$$

$$f(Sw) = \frac{Swc - Sw_n}{Sw_m - Sw_n} \quad (6b)$$

where g_0 and a_1 were empirical parameters, and g_0 was set to 0.00001 following Hu et al. (2009). Swm and Swn were the surface soil water content at field capacity and the wilting point, which was set to the observed maximum and the minimum Sw, respectively. C_a was leaf surface CO_2 content, which was calculated from the LI-7500 measurements.

In this study, we run the S-W model following Hu et al. (2009). Moreover, to make the revised S-W model by Hu et al. (2009) more suitable for forests, we revised

the calculation of roughness length (z_0) and displacement height (d), which were used for calculating the aerodynamic resistances, following the previous study (Shi et al., 2008b) as:

$$z_0 = 0.075 \times h \quad (7a)$$

$$d = 0.75 \times h \quad (7b)$$

Where h was the canopy height.

Fig. 1 Evapotranspiration components and their experiencing resistances. T and E were the abbreviations of transpiration and evaporation from the soil surface, respectively. The resistances included: the soil surface resistance (r_{ss}), the aerodynamic resistance from the soil surface to the canopy (r_{as}), the canopy stomatal resistance (r_{sT}), the bulk boundary layer resistance (r_{ac}) and aerodynamic resistance from the canopy to the reference height (r_{aa}).

2.3.2 Model parameterization

The surface resistances, i.e., r_{ss} and r_{sT} , were calculated with Eqs (5), (6a) and

(6b). The empirical parameters (b_1 , b_2 , b_3 , and a_1) in Eqs. (5) and (6a) were estimated using the Monte Carlo method in each year and each site following Hu et al. (2009). In each site and each year, 273 days (about 75% of the whole year data) were randomly selected to estimate the empirical parameters. In the selected days, only data having high confidence according to Reichstein et al. (2005) were used for training the empirical parameters.

2.4 Data analysis

In this study, we run the S-W model with the trained empirical parameters and validated its performance (including its performances on simulating ET and T/ET) using the independent datasets. The model outputs were then used to analyze the spatiotemporal variations of T/ET.

2.4.1 Model validation

Excluding the 273 days data used for training the model, we selected the remaining 92 (or 93 in 2004 and 2008) day data as the validation dataset to validate the performances of the model, which was validated in two aspects: its performance on simulating ET and that on simulating T/ET.

We validated the performance of S-W model on simulating ET at three scales: half-hour scale, daily scale and annual scale. At half-hour scale, the simulated half-hour ET was validated with the high confidence data (Reichstein et al., 2005) in the validation dataset. At daily scale, the validation was conducted at three scenarios. The simulated daily ET was firstly validated with the daily ET in validation dataset after gap-filling. Days in validation dataset having more than 15 high confidence

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5 264 half-hour data at daytime were then selected to validate the simulated corresponding
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7 265 daily ET, which may prevent the effects of gap-fillings. In addition, S-W model was
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10 266 also validated in no rain days to exclude the effects of precipitation on the
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12 267 performance of S-W model. At annual scale, we validated our simulated annual total
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18 269 We validated the performance of S-W model on simulating T/ET through
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20 270 integrating two layer H₂O fluxes measured by eddy covariance: above and below the
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22 271 canopy. H₂O fluxes from the eddy covariance system below canopy can be regarded
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25 272 as E (Wilson et al., 2001). T can therefore be obtained from the difference between
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28 273 H₂O fluxes obtained by two layer eddy covariance measurements. The performance of
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30 274 T/ET was validated at daily and annual scale. The validation of T/ET at daily scale
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33 275 was conducted by grouping ET with the bin width of 0.1 kgH₂O m⁻² d⁻¹ to prevent the
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36 276 effects of random errors in measurements.
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38 277 **2.4.2 Model output analysis**

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41 278 With model outputs of T and ET at half hour scale, we calculated the daily and
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43 279 annual total values. Then T/ET values at half-hour scale, daily scale and annual scale,
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46 280 which were used to analyze the spatiotemporal variations of T/ET, were calculated
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49 281 with T and ET at the corresponding scales.
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51 282 With model outputs of the canopy stomatal resistance (r_{sT}) and the soil surface
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53 283 resistance (r_{ss}), we calculated canopy stomatal conductance (G_c) and the soil surface
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56 284 conductance (G_s) as the reciprocal of r_{sT} and r_{ss} , respectively. The annual mean G_c (MG_c)
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59 285 was calculated as the mean daytime G_c .
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To illustrate the way that various factors affecting the variation of T/ET, we also calculated the portion that the energy absorbed by canopy (P_{EC}), which was calculated as the ratio of the energy absorbed by canopy (R_c) to that arrived at the canopy (R_n) from Eq. (4) and can be regarded as the function of LAI:

$$P_{EC}=R_c/R_n=(R_n-R_{ns})/R_n=1-\exp(-0.5 \times LAI) \quad (8)$$

2.5 Statistical analysis

We processed data and run the model with MATLAB software (Math Works Inc., Natick, MA). Under Matlab 7.7, we used the generalized linear model (GLM) of regstats to conduct the regression analysis between simulated and measured values to validate the model performances. With paired-sample T-test, the significance test on the difference between simulated and measured annual T/ET was conducted ($\alpha=0.05$). We employed the path-analysis to evaluate the dependence of the seasonal dynamics of T/ET on various factors. Then the multivariable regression were conducted to build the equation describing the seasonal dynamics of T/ET. The regressions between T/ET and various factors were also completed with the generalized linear model (GLM) of regstats or nonlinear regressions.

3 Results

3.1 Performances of S-W model

3.1.1 Performance of S-W model on simulating ET

At half-hour scale, the simulated ET by S-W model was well consistent with the measurements, which was the high confidence data in the validation dataset, in three forests (Fig. 2). The slope of the simulated ET: the measured ET were all around 1.

The R^2 of the regression between measurements and the simulated ET ranged from 0.59 to 0.72, all of which were significant in statistics.

Fig. 2 The performance of Shuttleworth-Wallace model (S-W model) on simulating half-hour evapotranspiration (ET) at CBS (a), QYZ (b), and DHS (c). Measured ET was the high confidence data in the validation dataset, while the Simulated ET was the corresponding ET generated by S-W model. The solid line was the regression line between simulated and measured ET while the dash line was the 1:1 line.

At daily scale, S-W model performed well on simulating ET both in the direction and in the magnitude (Fig. 3). In all three scenarios, the simulated ET was positively correlated with measurements, which were the daily ET at validation dataset, and the R^2 of the regression between the simulated ET and the measurements increased from all validation days to no rain days. The simulated ET agreed well with the measured values in days in validation dataset, which was calculated after gap-filling (Fig. 3 a-c).

However, in days having more than 15 half-hour high confidence data at daytime and no rain days, the simulated ET slightly overestimated the measurements (Fig. 3 d-i).

Fig. 3 The performance of Shuttleworth-Wallace model (S-W model) on simulating daily evapotranspiration (ET) at three forests. Measured ET was the measured daily ET at the validation dataset, while the Simulated ET was the corresponding ET simulated by our S-W model. a-c were the performance at CBS, QYZ, and DHS, respectively. d-f were the performance at CBS, QYZ and DHS in days in validation dataset having more than 15 half-hour high confidence data at daytime, respectively. g-i were the performance at these three sites in no rain days. The solid line was the regression line while the dash line was the 1:1 line.

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336 The high consistent between the simulated ET and the measured ones was also
 337 found at annual scale. The simulated annual total ET postively correlated with the
 338 measured ET and the values were also comparable (Fig. 4).

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341 Fig. 4 The performance of Shuttleworth-Wallace model (S-W model) on simulating annual
 342 evapotranspiration (ET) at three forests. The solid line was the regression line among site-year
 343 data while the dash line was the 1:1 line. The thin solid line was the regression line among years
 344 within the same ecosystem.

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346 3.1.2 Performance of S-W model on simulating T/ET

347 At daily scale, S-W model performed well on simulating T/ET. The simulated
 348 T/ET agreed well with the measured ones (Fig. 5 a-c), with the R^2 between simulated
 349 and measured T/ET ranging from 0.36 to 0.76. While the value of our simulated
 350 T/ET differed from that of measured T/ET. At CBS, our simulated T/ET was larger
 351 than the measured ones when T/ET was lower than 0.5 but it was in reverse when
 352 T/ET were larger than 0.5. At subtropical forests (QYZ and DHS), most simulated

T/ET were both lower than the measured values. After excluding the effects of precipitation, we found an improved relationship between simulated and measured T/ET at CBS and QYZ, which was indicated by an improved R^2 (Fig. 5 d-e). The relationship between simulated and measured T/ET got worse at DHS, whereas most data distributed around the 1:1 line (Fig. 5f).

Fig. 5 The performance of Shuttleworth-Wallace model (S-W model) on simulating the ratio of transpiration to evapotranspiration (T/ET) at three forests. a-c were the performance at CBS, QYZ, and DHS, respectively. d-f were the performance at CBS, QYZ, and DHS after excluding data from rainy days, respectively. Data were binned with the measured ET with the bin width of 0.1 kgH₂O m⁻² d⁻¹. Errorbars were the standard deviation of T/ET within each group. The solid line was the regression line while the dash line was the 1:1 line.

At annual scale, there were obvious difference between our simulated T/ET and the measured values (Table 2). At CBS, our simulated T/ET (0.68 ± 0.07) was significantly higher than the measured T/ET (0.56 ± 0.03). While at subtropical forests (QYZ and DHS), the simulated T/ET were both lower than the measured T/ET in values, though the difference between two T/ET was not significant in statsics ($p > 0.05$). In addition, our simulated T/ET were comparable with published results in temperate and subtropical forests (Granier et al., 2000; Schlesinger and Jasechko, 2014; Stoy et al., 2006).

Table 2 The measured and simulated annual ratio of transpiration to evapotranspiration (T/ET) at three forest ecosystems

Ecosystem	Year	Measured T/ET	Simulated T/ET
CBS	2003	0.56	0.67
	2004	0.59	0.69
	2005	0.52	0.68
	2006	0.55	0.78
	2007	0.53	0.55
	2008	0.60	0.68
	2009	0.59	0.73
	Mean(std)	0.56(0.03)b	0.68(0.07)a
QYZ	2004	0.85	0.70
	2005	0.69	0.40
	2006	0.77	0.82
	Mean(std)	0.77(0.08)a	0.64(0.22)a
DHS	2003	0.73	0.73
	2004	0.73	0.56
	2005	0.70	0.54
	2006	0.72	0.54
	Mean(std)	0.72(0.01)a	0.68(0.11)a

Note: Measured T/ET were calculated from two layer eddy covariance measured water vapor fluxes. Simulated T/ET were obtained from the revised Shuttleworth-Wallace model (S-W model) following Hu et al. (2009). Different lowercase letters between the Measured T/ET and Simulated

T/ET indicates a significant difference at $\alpha = 0.05$ in the same site.

3.2 Spatiotemporal variations of T/ET

3.2.1 Diurnal variation

With data obtained from the S-W model at August, 2003, we investigated the diurnal variation of T/ET in three forests. T/ET all showed an single-peak diurnal pattern, with the nearly constant T/ET in the daytime while nearly zero in nighttime (Fig. 6), which was also found in other months and years (data were not shown).

Fig. 6 The diurnal variation of the ratio of transpiration to evapotranspiration (T/ET) at CBS (a), QYZ (b) and DHS (c). Data were collected during August, 2003 from Shuttleworth-Wallace model outputs. Errorbars were the standard deviation of T/ET in the same local time.

The diurnal variation of T/ET was primarily affected by that of canopy stomatal conductance (G_c) (Fig. 7). With the increasing G_c , T/ET showed an obvious increasing trend. The power function based on G_c explained over 90% of variation in T/ET.

Fig. 7 The effect of canopy stomatal conductance (G_c) on the diurnal variation of the ratio of transpiration to evapotranspiration (T/ET) at CBS (a), QYZ (b) and DHS (c), respectively. Data were obtained from Shuttleworth-Wallace model during August, 2003. Each points indicates the mean value of T/ET at each half-hour and errorbars were the standard deviation of T/ET in each half-hour.

3.2.2 Seasonal variation

With data obtained from the S-W model, we found that T/ET exhibited obvious seasonal variations, while the seasonal variation of T/ET differed among forests (Fig. 8). At CBS, T/ET exhibited an single-peak variation and reached its peak value around July, with the value ranging from 0 to 0.85. At QYZ, T/ET also showed an single-peak variation but the range of T/ET obviously narrowed, which only ranged from 0.3 to 0.8 in most years. At DHS, T/ET exhibited an obvious single-peak pattern in most years but the range of T/ET further narrowed.

Fig. 8 Seasonal dynamics of the ratio of transpiration to evapotranspiration (T/ET) at CBS (a), QYZ (b) and DHS (c). Lines are 10-d running average.

The seasonal variation of T/ET was shaped by multi-factors through their direct or indirect effects. The direct factors affecting the seasonal dynamics of T/ET differed among forests (Fig. 9). At CBS, the seasonal dynamics of T/ET was mainly affected by the direct effect of T_a , VPD , and LAI . The increases in T_a and LAI directly enhanced T/ET while the increasing VPD exerted a reverse role (Fig. 9a). However, at subtropical forests (QYZ and DHS), LAI played no direct effects on the seasonal variation of T/ET , whereas T_a , Swc , R_n and VPD directly affected the seasonal

dynamics of T/ET. With the increasing R_n and T_a , T/ET showed obvious increasing trends, while the increasing Swc and VPD decreased T/ET (Fig. 9b and 9c).

Fig. 9 Path diagram of factors affecting the seasonal dynamics of the ratio of transpiration to evapotranspiration (T/ET) at CBS (a), QYZ (b) and DHS (c). The abbreviation of factors were as follows: air temperature (T_a), net radiation (R_n), soil water content (Swc), vapor pressure deficit (VPD), leaf area index (LAI).

With the direct factors affecting the seasonal dynamics of T/ET, we drew equations describing the seasonal dynamics of T/ET as follows:

CBS: $T/ET = 0.017T_a - 0.17VPD + 0.13LAI - 0.01$, $R^2 = 0.87$, $RMSE = 0.13$, $n = 2557$ (9a)

435 QYZ: $T/ET=0.02T_a-0.20VPD-0.85S_{wc}+0.02R_n+0.38$, $R^2=0.52$, $RMSE=0.16$, $n=2557$

436 (9b)

437 DHS: $T/ET=0.02T_a-0.12VPD-0.44S_{wc}+0.01R_n+0.36$, $R^2=0.45$, $RMSE=0.13$, $n=2557$

438 (9c)

439 3.2.3 Interannual and spatial variations

440 Data from S-W model suggest that annual total T occupied a large portion of
441 annual water loss as ET at three forests. During the measuring period, the mean
442 annual value of T/ET for CBS, QYZ and DHS were 0.68 ± 0.07 , 0.65 ± 0.13 and 0.68
443 ± 0.07 , respectively. Therefore, vegetation at NSTEC played an important role in
444 regulating the climate, which should be paid more attention in the future.

445 T/ET showed obvious interannual variations but was not directly affected by
446 climate and biotic factors such as mean annual air temperature (MAT), mean annual
447 precipitation (MAP) and mean leaf area index (LAI). With the increasing MAT, MAP
448 and LAI, T/ET showed no obvious trend among years (Fig. 10). However, mean
449 canopy stomatal conductance (MG_c) did affect the interannual variation of T/ET. With
450 the increasing MG_c , T/ET exhibited an obvious increasing trend, which was found at
451 all three forests (Fig. 11).

452 T/ET also exhibited some differences among forests. T/ET in the temperate
453 forest (CBS) was comparable with that at DHS but was slightly higher than that at
454 QYZ. Though T/ET showed a slight decreasing trend with the increasing MAT, MAP
455 and LAI, the relationship between T/ET and factors (i.e., MAT, MAP and LAI) was

not significant in statistics (Fig. 10). However, with the increasing MG_c , T/ET significantly increased among ecosystems (Fig. 11).

Fig. 10 Factors affecting the ratio of annual total transpiration to annual total evapotranspiration (T/ET) at each site. MAT, MAP and LAI were the abbreviation of mean annual air temperature, mean annual precipitation and mean leaf area index, respectively.

Fig. 11 The relationship between mean annual canopy stomatal conductance (MG_c) and annual T/ET. T/ET was the ratio of the simulated annual total transpiration (T) to the annual total evapotranspiration (ET). The dash lines were the interannual variation of T/ET at each forest,

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5 468 while the solid line was the regression line between MG_c and T/ET among forests.
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10 470 **4 Discussion**

11 471 **4.1 Model performances and uncertainties**

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15 472 Results from model validations suggest that S-W model performed well on
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17 473 simulating the variation trend of ET and T/ET (Fig. 2 – Fig. 5), while the simulated
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20 474 ET and T/ET differed from the measured ones in values, which can be attributed to
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23 475 the uncertainties in measurements and simulations.
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25 476 The uncertainties in measurements included the following aspects. First, due to
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28 477 the effects of gap-filling in rainy days (Kang et al., 2012), dews (Maestre-Valero et
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30 478 al., 2012) and fogs (Beiderwieden et al., 2008; Eugster et al., 2006), the measured ET
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33 479 may be underestimated. Second, the underestimated ET caused by gap-filling in rainy
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36 480 days (Kang et al., 2012), dews (Maestre-Valero et al., 2012) and fogs (Beiderwieden
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38 481 et al., 2008; Eugster et al., 2006) may overestimate T/ET. Third, during days with
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41 482 open canopy, the low temperature (Shi et al., 2008a) caused small measured water
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44 483 vapor fluxes below the canopy, which made the measured T (the difference between
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46 484 two layers water vapor fluxes) and T/ET overestimated. Four, during days having
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49 485 close canopy, water vapor fluxes measured below the canopy may contribute to T,
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51 486 which made the measured T and T/ET underestimated.
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54 487 The uncertainties in simulations primarily sourced from the lackage of EI session
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56 488 in S-W model. During the period when the measured ET were directly measured by
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59 489 eddy covariance and had high confidence, EI scarcely occurred. The simulated ET and
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490 T/ET therefore fully reflected their real values. However, during rainy days or days
 491 having much low confidence data, EI appeared but was not simulated by S-W model.
 492 The simulation would underestimate the real ET but may overestimate the real T/ET.
 493 The consistent high confidence in simulations and measurements made the values
 494 of simulated ET agree well with the measured ones at half-hour scale (Fig. 2). The
 495 consistent underestimation in simulations and measurements also made the simulated
 496 ET agree well with the measured ones at daily and annual scale (Fig. 3 a-c and Fig. 4),
 497 while during days having more than 15 half-hour high confidence data at daytime and
 498 no rain days, the single underestimation in the measured ET made the simulated ET
 499 higher than the simulated values (Fig. 3 d-i). At the temperate forest (CBS) which
 500 experienced obvious canopy developments, during days with the open canopy, the
 501 overestimation in measured T/ET made the simulated T/ET lower than the measured
 502 ones, while the underestimation in measured T/ET primarily accounted for the higher
 503 simulated T/ET (Fig. 4a and 4d) during days with the close canopy. The
 504 overwhelming portion of growing-season ET in annual total ET (Shi et al., 2008b)
 505 also made the simulated annual T/ET higher than the measured ones (Table 2). At
 506 subtropical forests, the consistent overestimation in simulations and measurements
 507 made the simulated annual T/ET be comparable with the measured values (Table 2).
 508 Though there were some uncertainties in the simulated T/ET due to the lackage of
 509 EI session in S-W model, EI occupied no more than 20% of ET in these three forests.
 510 For example, the portion of EI in ET in temperate forest in a forest in Finland (Ge et
 511 al., 2011) and Sweden (Iritz et al., 2001) was around 10%, which had similar climate

and vegetation status as CBS, while EI occupied about 15.79% of ET at a tropical rainforest (Kume et al., 2011), which had more precipitation than the two subtropical forests but similar vegetation status. In addition, the simulated T/ET were comparable with the measured ones (Fig. 5 and Table 2) and those published in literatures. We can therefore conservatively conclude that the overestimation in T/ET was relatively small at these three forests. However, to make S-W model more feasible for its application in forests and accurately quantify the portion of each ET components, intergrating an EI session to the S-W model should be paid much attention in the future.

4.2 Factors affecting the variation of T/ET

The variation of T/ET, including the diurnal variation, seasonal variation and so on, can be fulfilled through changing the canopy stomatal conductance (G_c), the soil surface conductance (G_s , the reciprocal of r_{ss} in Eq. (5)) and the portion that the energy absorbed by canopy (P_{EC} , Eq. (8)) (Hu et al., 2009).

The dinural variation of T/ET was mainly affected by that of G_c as little variation in G_s and P_{EC} during the same day. The variation of G_s and P_{EC} were primarily affected by that of Swc (Eq. (5)) and LAI (Eq. (4)), which showed little variation in the same day, while PAR had obvious dinural dynamics, which made G_c vary substaintially (Stoy et al., 2008) and then the variation of T/ET. Our results were also consistent with the previous study (Hu et al., 2009).

The seasonal variation of T/ET was jointly affected by that of G_c , G_s or P_{EC} but the joint effects differed among ecosystems. The seasonal dynamics of G_c was affected by PAR, VPD, and LAI (Stoy et al., 2008), while that of G_s and P_{EC} were

534 affected by Swc (Eq.5) and LAI (Eq. 4), respectively. At CBS, Ta , and LAI
 535 experienced obvious seasonal dynamics (Shi et al., 2008a; Zhu et al., 2014), which
 536 made G_c and P_{EC} vary substantially among seasons thus hid the effects of G_s on the
 537 variation of T/ET . The seasonal dynamics of T/ET was therefore jointly affected by
 538 that of G_c and P_{EC} through the direct effects of Ta , VPD , and LAI , which was
 539 consistent with previous studies (Hu et al., 2009; Huang et al., 2010; Zhu et al., 2014).
 540 At subtropical forests (QYZ and DHS), LAI did not exhibit obvious seasonal variation
 541 (Zhu et al., 2014), and the seasonal dynamics of PAR was accompanied with that of
 542 Ta , VPD , and R_n , which made G_c vary obviously but P_{EC} vary little. In addition, the
 543 seasonal variation of G_s induced by Swc also plays an important role in the seasonal
 544 dynamics of T/ET as little variation in LAI thus G_c and P_{EC} . Therefore, the seasonal
 545 dynamics of T/ET was jointly affected by that of G_c and G_s through the direct effects
 546 of Ta , VPD , R_n , and SW , which differed from previous studies at temperate
 547 ecosystems (Hu et al., 2009; Huang et al., 2010; Zhu et al., 2014).

548 At annual scale, T/ET of these three forests were higher than that of grasslands
 549 (Hu et al., 2009; Lauenroth and Bradford, 2006) and croplands (Kato et al., 2004),
 550 which resulted from the higher LAI (Huxman et al., 2005). The interannual variation
 551 and the spatial variation of T/ET were governed by mean annual G_c (MG_c) (Fig. 10).

552 Therefore, G_c strongly affected the spatial and temporal variations of T/ET in
 553 three forest ecosystems of China, including the diurnal variation, the seasonal
 554 variation and the interannual variation, while the seasonal variation of T/ET was also
 555 affected by P_{EC} at temperate forest and G_s at subtropical forests.

566 **5 Conclusions**

567 Based on eddy covariance measurements at three forests of ChinaFLUX situated
568 in NSTEC, we run the S-W model, validated its performance with two layer eddy
569 covariance measurements and analyzed the spatiotemporal variations of T/ET. The
570 S-W model performed well in simulating ET and T/ET but some improvements should
571 be needed in adding EI session in the future. At three forests, T/ET all exceeded 0.6,
572 indicating that vegetation played an important role in regulating the climate, which
573 should be highly emphasized in the future. The spatial and temporeal variations of
574 T/ET, including the diurnal variation, the seasonal variation and the interannual
575 variation, were mainly affected by the canopy stomatal conductance, while soil water
576 content played an important role through altering the soil surface conductance in
577 regulating the seasonal dynamics of T/ET at subtropical forests.

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744 Table 1 Site descriptions

Sites	CBS	QYZ	DHS
Latitude (° N)	42.4025	26.7330	23.1670
Longitude (° E)	128.0928	115.05	112.5330
Elevation (m.a.s.l)	738	100	300
Mean annual temperature (°C) ^a	3.6	17.9	21.0
Mean annual precipitation (mm) ^a	696	1485	1956
Stand age (years)	~ 200	~ 23	~ 100
Dominated species	<i>Pinus koraiensis</i> , <i>Tilia amurensis</i> , <i>Acer mono</i> , <i>Fraxinus mandshurica</i> , <i>Quercus mongolica</i>	<i>Pinus elliotii</i> , <i>Pinus massoniana</i> , <i>Cunninghamia lanceolata</i>	<i>Castanopsis chinensis</i> , <i>Schima superba</i> , <i>Cryptocarya chinensis</i> , <i>Cryptocarya concinna</i> , <i>Machilus chinensis</i>
Canopy height (m)	26	12	22
Mean diameters at breast height (cm)	~ 23	14.6	7.06
Maximum leaf area index (m ² m ⁻²)	6.1	5.6	5.6
Sapwood area (m ² hm ⁻²)	47.88	30.92	36.30
Total biomass (tC hm ⁻²)	175	106	130
Mean annual total gross primary productivity (gC m ⁻² yr ⁻¹) ^b	1338.84	1798.74	1367.26
Mean annual total ecosystem respiration (gC m ⁻² yr ⁻¹) ^b	1036.51	1311.22	971.31
Mean annual total net ecosystem productivity (gC m ⁻² yr ⁻¹) ^b	302.33	487.51	395.95
Mean annual total evapotranspiration (kgH ₂ O m ⁻² yr ⁻¹) ^c	522.35	761.57	706.20

745 Note: a, values are the averages from 1985 to 2005 according to Yu et al. (2008);

746 b, values are the averages from 2003 to 2008 according to Yu et al. (2013); c, values

747 are the averages from 2003 to 2008 according to ChinaFLUX dataset.

Table 2 The measured and simulated annual ratio of transpiration to evapotranspiration (T/ET) at three forest ecosystems

Ecosystem	Year	Measured T/ET	Simulated T/ET
CBS	2003	0.56	0.67
	2004	0.59	0.69
	2005	0.52	0.68
	2006	0.55	0.78
	2007	0.53	0.55
	2008	0.60	0.68
	2009	0.59	0.73
	Mean(std)	0.56(0.03)b	0.68(0.07)a
QYZ	2004	0.85	0.70
	2005	0.69	0.40
	2006	0.77	0.82
	Mean(std)	0.77(0.08)a	0.64(0.22)a
DHS	2003	0.73	0.73
	2004	0.73	0.56
	2005	0.70	0.54
	2006	0.72	0.54
	Mean(std)	0.72(0.01)a	0.68(0.11)a

Note: Measured T/ET were calculated from two layer eddy covariance measured water vapor fluxes. Simulated T/ET were obtained from the revised Shuttleworth-Wallace model (S-W model) following Hu et al. (2009). Different lowercase letters between the Measured T/ET and Simulated T/ET indicates a significant difference at $\alpha = 0.05$ in the same site.

Legends

Fig. 1 Evapotranspiration components and their experiencing resistances. T and E were the abbreviations of transpiration and evaporation from the soil surface, respectively. The resistances included: the soil surface resistance (r_{ss}), the aerodynamic resistance from the soil surface to the canopy (r_{as}), the canopy stomatal resistance (r_{sT}), the bulk boundary layer resistance (r_{ac}) and aerodynamic resistance from the canopy to the reference height (r_{aa}).

Fig. 2 The performance of Shuttleworth-Wallace model (S-W model) on simulating half-hour evapotranspiration (ET) at CBS (a), QYZ (b), and DHS (c). Measured ET was the high confidence data in the validation dataset, while the Simulated ET was the corresponding ET generated by S-W model. The solid line was the regression line between simulated and measured ET while the dash line was the 1:1 line.

Fig. 3 The performance of Shuttleworth-Wallace model (S-W model) on simulating daily evapotranspiration (ET) at three forests. Measured ET was the measured daily ET at the validation dataset, while the Simulated ET was the corresponding ET simulated by our S-W model. a-c were the performance at CBS, QYZ, and DHS, respectively. d-f were the performance at CBS, QYZ and DHS in days in validation dataset having more than 15 half-hour high confidence data at daytime, respectively. g-i were the performance at these three sites in no rain days. The solid line was the regression line while the dash line was the 1:1 line.

Fig. 4 The performance of Shuttleworth-Wallace model (S-W model) on simulating annual

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5 777 evapotranspiration (ET) at three forests. The solid line was the regression line among site-year
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7 778 data while the dash line was the 1:1 line. The thin solid line was the regression line among years
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10 779 within the same ecosystem.

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15 781 Fig. 5 The performance of Shuttleworth-Wallace model (S-W model) on simulating the ratio of
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17 782 transpiration to evapotranspiration (T/ET) at three forests. a-c were the performance at CBS, QYZ,
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19 783 and DHS, respectively. d-f were the performance at CBS, QYZ, and DHS after excluding data
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21 784 from rainy days, respectively. Data were binned with the measured ET with the bin width of 0.1
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23 785 $\text{kgH}_2\text{O m}^{-2} \text{ d}^{-1}$. Errorbars were the standard deviation of T/ET within each group. The solid line
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25 786 was the regression line while the dash line was the 1:1 line.

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33 788 Fig. 6 The diurnal variation of the ratio of transpiration to evapotranspiration (T/ET) at CBS (a),
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35 789 QYZ (b) and DHS (c). Data were collected during August, 2003 from Shuttleworth-Wallace model
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37 790 outputs. Errorbars were the standard deviation of T/ET in the same local time.

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43 792 Fig. 7 The effect of canopy stomatal conductance (G_c) on the diurnal variation of the ratio of
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45 793 transpiration to evapotranspiration (T/ET) at CBS (a), QYZ (b) and DHS (c), respectively. Data
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47 794 were obtained from Shuttleworth-Wallace model during August, 2003. Each points indicates the
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49 795 mean value of T/ET at each half-hour and errorbars were the standard deviation of T/ET in each
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51 796 half-hour.

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59 798 Fig. 8 Seasonal dynamics of the ratio of transpiration to evapotranspiration (T/ET) at CBS (a),
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799 QYZ (b) and DHS (c). Lines are 10-d running average.

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801 Fig. 9 Path diagram of factors affecting the seasonal dynamics of the ratio of transpiration to
802 evapotranspiration (T/ET) at CBS (a), QYZ (b) and DHS (c). The abbreviation of factors were as
803 follows: air temperature (T_a), net radiation (R_n), soil water content (Swc), vapor pressure deficit
804 (VPD), leaf area index (LAI).

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806 Fig. 10 Factors affecting the ratio of annual total transpiration to annual total evapotranspiration
807 (T/ET) at each site. MAT, MAP and LAI were the abbreviation of mean annual air temperature,
808 mean annual precipitation and mean leaf area index, respectively.

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810 Fig. 11 The relationship between mean annual canopy stomatal conductance (MG_c) and annual
811 T/ET. T/ET was the ratio of the simulated annual total transpiration (T) to the annual total
812 evapotranspiration (ET). The dash lines were the interannual variation of T/ET at each forest,
813 while the solid line was the regression line between MG_c and T/ET among forests.

Evapotranspiration (ET)

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