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Comparing different methods for determining forest evapotranspiration and its components at multiple temporal scales

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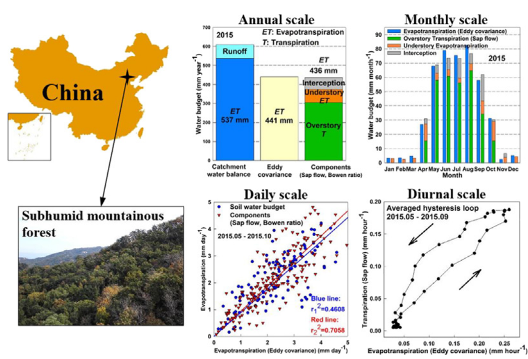
HIGHLIGHTS

- Forest evapotranspiration (*ET*) is important for ecosystem-atmosphere water exchange.
- Methods for determining *ET* and its components were compared at four temporal scales.
- Sap flow-based *ET* estimate well agrees with eddy covariance-based estimate.
- Catchment water balance method may probably overestimate annual *ET*.
- Diurnal time lag effects exist between sap flow and eddy covariance-based estimates.

GRAPHICAL ABSTRACT



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ABSTRACT

Accurately estimating forest evapotranspiration and its components is of great importance for hydrology, ecology, and meteorology. In this study, a comparison of methods for determining forest evapotranspiration and its components at annual, monthly, daily, and diurnal scales was conducted based on in situ measurements in the subhumid mountainous forest of North China. The goal of the study was to evaluate the accuracies and reliabilities of the different methods. The results indicate the following: (1) The sap flow upscaling procedure, taking into account diversities in forest types and tree species, produced component-based forest evapotranspiration estimate that agreed with eddy covariance-based estimate at the temporal scales of year, month, and day, while soil water budget-based forest evapotranspiration estimate was also qualitatively consistent with eddy covariance-based estimate at the daily scale; (2) At the annual scale, catchment water balance-based forest evapotranspiration estimate was significantly higher than eddy covariance-based estimate, which might probably result from non-negligible subsurface runoff caused by the widely distributed regolith and fractured bedrock under the ground; (3) At the sub-daily scale, the diurnal course of sap flow based-canopy transpiration estimate lagged significantly behind eddy covariance-based forest evapotranspiration estimate, which might physiologically be due to stem water storage and stem hydraulic conductivity. The results in this region may have much referential significance for forest evapotranspiration estimation and method evaluation in regions with similar environmental conditions.

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Abbreviations

D	discharge, m^3 $time^{-1}$
DBH	tree diameter at breast height, cm
DH	diameter of heartwood, cm
DS	outer diameter of sapwood, cm
e	vapor pressure, kPa
E_u	evapotranspiration from the understory vegetation, including soil evaporation and the transpiration of the understory vegetation, mm $time^{-1}$
E_{u_b}	E_u estimated from the Bowen ratio-energy balance method, mm $time^{-1}$
ET	evapotranspiration from the entire ecosystem, mm $time^{-1}$
ET_{com}	ET estimated as the sum of three evapotranspiration components ($E_{u\_b} + T_{o\_s} + I_d$), mm $time^{-1}$
ET_{cwb}	ET estimated by the catchment water balance method, mm $time^{-1}$
ET_{ec}	ET estimated by the eddy covariance method, mm $time^{-1}$
ET_{swb}	ET estimated by the soil water budget method, mm $time^{-1}$
G	ground heat flux, measured at a depth of 5 cm in the soil, W m^{-2}
H	sensible heat flux estimated by the eddy covariance method, W m^{-2}
I	interception loss of the overstory canopy, mm $time^{-1}$
I_d	I estimated as the difference between precipitation and throughfall, mm $time^{-1}$
LAI	leaf area index, obtained from a MODIS product (MCD15A3), m^2 m^{-2}
P	precipitation, mm $time^{-1}$
P_t	throughfall, mm $time^{-1}$
PAR	photosynthetically active radiation, (μ)mol m^{-2} $time^{-1}$
Q_p	energy flux associated with carbon dioxide flux (through photosynthesis and respiration), W m^{-2}
Q	runoff, mm $year^{-1}$
R_n	net radiation, W m^{-2}
RFA	ratio of forest area to catchment area, km^2 km^{-2}
RFA_b	RFA of broad-leaved forest, km^2 km^{-2}
RFA_m	RFA of coniferous and broad-leaved mixed forest, km^2 km^{-2}
S	rate of change in total heat storage of the forest air, water vapor, and biomass, W m^{-2}
S_a	rate of change in heat storage forced by change in canopy air temperature, W m^{-2}
S_b	rate of change in heat storage associated with the above-ground biomass, W m^{-2}
S_w	rate of change in heat storage forced by change in canopy specific humidity, W m^{-2}
SA	sapwood area, cm^2
SAI	sapwood area index (ratio of sapwood area to ground area), cm^2 m^{-2}
SAI_{a_b}	SAI of aspen (*Populus davidiana*) in broad-leaved forest, cm^2 m^{-2}
SAI_{a_m}	SAI of aspen in coniferous and broad-leaved mixed forest, cm^2 m^{-2}
SAI_{l_m}	SAI of larch (*Larix gmelinii*) in coniferous and broad-leaved mixed forest, cm^2 m^{-2}
SFD	sap flux density, g cm^{-2} s^{-1}
SFD_a	SA-weighted average SFD of all the experimental aspen trees, g cm^{-2} s^{-1}
SFD_l	SA-weighted average SFD of all the experimental larch trees, g cm^{-2} s^{-1}
SWS	soil water storage of the 0–850 mm soil layer, mm^3 mm^{-2}
T_a	air temperature, °C
T_o	transpiration from the overstory canopy, mm $time^{-1}$
T_{o_s}	T_o upscaled from sap flow measurement, mm $time^{-1}$
VPD	vapor pressure deficit, kPa
β	Bowen ratio
γ	psychrometric constant, kPa $°C^{-1}$
λE	latent heat flux estimated by the eddy covariance method, W m^{-2}

1. Introduction

Forest evapotranspiration is one of the most significant factors influencing the terrestrial hydrological cycle (Jasechko et al., 2013; Oki and Kanae, 2006; Shimizu et al., 2015), and it is a major process that regulates water exchange between the forest ecosystem and the atmosphere (Cristiano et al., 2015). As the forest ecosystem generally consists of the overstory canopy and the understory vegetation, the evapotranspiration from the entire forest ecosystem (ET) is composed of three main components: the evapotranspiration from the understory vegetation (E_u), the transpiration from the overstory canopy (T_o), and the interception loss of the overstory canopy that is evaporated from the leaf surface (I), i.e.:

$$ET = E_u + T_o + I \tag{1}$$

Accurately estimating forest evapotranspiration and its components is of great importance for a wide range of disciplines, including hydrology, ecology, and meteorology, and is essential for understanding the links between the hydrological and ecologic systems of a forest (Good et al., 2015; Thompson et al., 2011a; Wei et al., 2017; Wilson et al., 2001). Several methods have been developed to estimate forest evapotranspiration and its components, and the corresponding spatial and temporal scales, and the estimated forest evapotranspiration components of the methods are quite different (Ford et al., 2007; Kosugi and Katsuyama, 2007; Oishi et al., 2008; Shimizu et al., 2015; Wilson et al., 2001; Yaseef et al., 2010). Generally, the catchment water balance method estimates catchment-scale $E_u + T_o + I$, and the sap flow method estimates individual tree-level T_o, and the soil water budget method estimates point-level $E_u + T_o$. In addition, the point-level I can be estimated individually from the difference between precipitation and throughfall (with the assumption of negligible stemflow). The spatial scales and the estimated components of the eddy covariance method and the Bowen ratio-energy balance method vary with the heights of the observation systems. When the observation systems are placed above the overstory canopy, regional-scale $E_u + T_o + I$ is estimated, and when the observation systems are placed under the overstory canopy but above the understory vegetation, small plot-scale E_u is estimated individually. The temporal scales of these methods are usually daily or sub-daily, while the catchment water balance method is generally only applied at the temporal scales longer than the annual cycle.

The spatial and temporal scale dependencies of the methods are significant, and each method is subject to certain limitations in applicability and accuracy (Thompson et al., 2011b; Wilson et al., 2001). The catchment water balance method generally provides no information on evapotranspiration processes at temporal scales shorter than the