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Estimation of annual forest evapotranspiration from a coniferous plantation watershed in Japan (1): Water use components in Japanese cedar stands

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SUMMARY

To increase the ability to control forest ecosystem water and carbon cycles using forest management, we estimated watershed-scale evapotranspiration (*ET*) and its components, i.e., upper-canopy stand transpiration (E_{UC}), sub-canopy vegetation transpiration (E_{SC}), and canopy interception (I_C), in a Japanese cedar (*Cryptomeria japonica* D. Don.) plantation over a whole year. For E_{UC}, xylem sap flux density was measured in three plots: an upper (UP) and lower (LP) plot on a northeast-facing, and one on a south-facing slope (SP). Mean stand sap flux density (J_S) in the UP, LP, and SP was similar despite differences among plots in tree density and size, implying that J_S measured in a partial stand within the watershed is a reasonable estimator of the values of other stands, and that stand sapwood area is a strong determinant of the E_{UC}. Prior information on annual variations in *ET* and its components was insufficient and urgently needed in Japan. Using a combination of observations and modeling, we obtained reliable estimations of E_{SC} and I_C, and thus, of annual variations in *ET* and its components (911.4, 359.3, 126.9, and 425.2 mm/year for *ET*, E_{UC}, E_{SC} and I_C, respectively). We found a conservative ratio of I_C to rainfall (*P*) (I_C/P) throughout the year, a significant contribution of I_C/P to the ratio of *ET* to *P* (*ET*/*P*) during heavy rainfall conditions, and an increase in I_C and E_{SC} when E_{UC} was decreasing, resulting in a constant monthly *ET*/*P* in the growing season and winter. These support the idea of the conservative process of forest water use in that *P* mainly controls *ET* on a monthly and longer time scale.

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1. Introduction

Forests cover 66% of the total land area in Japan, with plantation forests constituting 41% of the forested area. This is a result of extensive reforestation following deforestation in World War II. Forty-three percent of Japan's plantation forest area comprises a single tree species: Japanese cedar (*Cryptomeria japonica* D. Don) (Japan Forest Agency, 2011). Although Japanese cedar is the most popular wood material in Japan and extensive research has been conducted on its wood quality, information on the use of this species for environmental benefits is scarce (Kumagai et al., 2007, 2008). Currently, Japan imports large amounts of timber and forest products, and environmental roles of forests are gaining precedence over that of timber production (Fujimori, 2000).

Japan has relatively little area that is level and lowland, and mountainous watersheds supply almost all of the water resources to the lowlands. The majority of the forests are situated in mountain regions, and mountains tend to receive higher precipitation (Sawano et al., 2005). On an annual basis, subtracting forest water use from precipitation denotes the upper limit of available water (see Komatsu et al., 2008b). Therefore, forest management such as thinning and forest conversions has been expected to alter forest water use components, such as upper- and sub-canopy transpiration and interception, and improve the ability of forests to control water yield, especially in plantation forests (see Komatsu et al., 2008a).

Many of the forest water use theories assume larger evaporative demand than annual precipitation (i.e., $E_{eq} \geqslant P$, where E_{eq} is equilibrium evaporation and P is precipitation) and an evenly

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distributed P throughout the year or a large P in winter (see Komatsu et al., 2007, 2008b). Scientists from the US and UK devised these theories for application to their familiar hydrologic environment, thus, detailed information of forest water use when $E_{eq} \ll P$ and when there is a large P in summer conditions, as in most East Asian countries, should be more important locally and globally.

The goal of this study was to obtain quantitative and process information on forest water use in a typical Japanese cedar watershed, which is also the typical forest watershed in moist East Asian regions. Questions to be addressed were: (1) how the evapotranspiration (*ET*) is assigned to the water use components such as overstory and understory vegetation transpiration and canopy interception; (2) what the spatial variation of *ET* in a watershed is; and (3) what biological and/or environmental factors determine the spatial variation (see Ford et al., 2007; Baldocchi and Ryu, 2011). These are especially important in hilly regions of Japan, where topographical gradients have a strong influence on plant–soil systems. To achieve this goal, we conducted stand-level sap flow measurements at different elevations on northeast- and south-facing slopes, and combined canopy interception measurements and their model estimates using biometric data from several plots, and model estimates of transpiration from sub-canopy vegetation using individual-leaf level ecophysiological traits; further, we examined the observation strategies for estimating forest water use at our study site. Finally, we validated forest water use estimated in this study using eddy covariance water vapor flux and catchment water balance measurements at this site, and reported in earlier publications in Japan (see Komatsu et al., 2008b).

2. Materials and methods

2.1. Study site and meteorological measurements

The experiments were carried out in the Kahoku Experimental Watershed (KHEW), a 2.63 ha evergreen coniferous plantation on the island of Kyushu, Japan (33°08′N, 130°43′E, 150–220 m a.s.l.). The watershed is underlain by crystalline schist and the slopes on both sides of the valley are steep (20–40°). The mean annual precipitation for the period 2000–2008 was 2138 mm, with rainy season from mid-June to early July. The mean annual temperature was 15.3 °C with a minimum mean monthly of about 4 °C in January–February and a maximum mean monthly of about 26 °C in August.

The forest in the watershed consists mainly of even-aged 50-year-old (in 2007) *C. japonica* stands, and to a lesser degree, *Chamaecyparis obtusa* Endl. (Japanese cypress) stands ranging in age from 30 to 50 years old (in 2007). Although the planting areas of these species are almost equal, half of the Japanese cypress trees in KHEW are comparatively young and small. In ≈20% of KHEW, broadleaf trees species compete with the planted conifers, forming a patchy forest watershed. Understory vegetation is dense and consists of various species of evergreen trees such as *Quercus glauca* Thunb., *Castanopsis sieboldii* Hatsusima ex Yamazaki et Mashiba., and *Eurya japonica* Thunb. For the sap flow measurements in this study, we sampled three plots within the Japanese cedar stand: an upper-slope plot (UP) and a lower-slope plot (LP), located less than 100 m from each other on a 20° northeast-facing slope, and a middle-slope plot on a 25° south-facing slope (SP) (see Table 1). Although the plots were of the same age, tree densities increased in the order UP > SP > LP, and the stand basal area and individual tree sizes varied in the order LP > SP > UP (Table 1). It should be noted that the frequency distributions of diameter at breast height (DBH) in the LP was different to those of the UP and SP, which were similar to each other. The silhouette area index of leaves plus stems and branches (plant area index; PAI) including that of understory vegetation was measured every month in the period 2005–2006 around three basic PAI observation points in the watershed using a plant canopy analyzer (LAI-2000, Li-Cor, Lincoln, NE). The PAI ranged from 4.4 to 5.7 $m^2 m^{-2}$ and from 3.6 to 5.9 $m^2 m^{-2}$ in the LP and SP, respectively, implying minor seasonal variation.

Table 1
Stand characteristics of the three study plots. UP and LP (upper and lower slope plots on a northeast-facing slope, respectively), and SP (middle slope plot on a south-facing slope).

Characteristic	UP	LP	SP
Plot area (m^2)	318	321	203
Age (years in 2007)	50	50	50
Density (trees ha^{-1})	1575	904	1330
PAI[a] ($m^2 m^{-2}$)	3.2–5.4[b]	4.4–5.7	3.6–5.9
Mean DBH (cm)	23.8	40.3	26.6
Range DBH (cm)	12.5–30.8	23.7–53.3	14.3–33.7
Basal area ($m^2 ha^{-1}$)	71.7	118.7	76.3
Sapwood area[c] ($m^2 ha^{-1}$)	36.3	46.0	37.3
Mean height (m)	22	32	22[b]
Sap flux measurements (trees)	23	15	19

[a] PAI was measured from 2004 to 2005, and ranges of values denote seasonal variations.
[b] Measured at other slope positions with similar characteristics to the study plot.
[c] Sapwood area was estimated for each study plot based on allometric relationships.

Micrometeorological conditions and eddy-covariance fluxes were measured at the top of the canopy using a 50-m-tall canopy tower located at the center of the watershed. Wind speeds and gas concentration time series at a height of 51 m were all sampled at 10 Hz using a three-dimensional sonic anemometer (DA600-3T, Kaijo, Tokyo, Japan) co-located with a gas-inlet leading to a closed-path CO_2/H_2O analyzer (Li-7000, Li-Cor). All variances and covariances required for eddy-covariance flux estimates were computed over a 30-min averaging interval. According to the species distribution and topography map, wind directions were categorized so that each of them could be related to the fluxes from specific vegetation surfaces. If a wind direction was out of the appropriate categorization, the fluxes were interpolated with a generic multiple imputation method (see Hui et al., 2004). Furthermore, it was assumed that the eddy fluxes were underestimated by ≈25% (the energy imbalance ratio observed in this site) and the flux values were divided by this value. The resultant eddy water vapor flux was considered to be the whole-ecosystem *ET*, i.e., the total of wet and dry canopy evaporation and sub-canopy evaporation.

A solar radiometer (CM14B, Kipp & Zonen, Delft, Netherlands), a net radiometer (CNR4, Kipp & Zonen) and a ventilated psychrometer (NH020L, EKO, Tokyo, Japan) were installed at a height of 47, 50.5 and 42 m, respectively. Note that the UP and LP are on the highest and the lowest elevations in the studied plots, respectively. While the ground level is 20–30 m higher in the UP than in the LP, the canopy height in the UP is around 10 m lower than in the LP (see Table 1). In short, the canopy surfaces of all plots are somewhat even. Samples were taken every 30 s for solar radiation (R_s; W m^{-2}) and net radiation (R_n; W m^{-2}), and every 1 min for air temperature (T_a; °C) and relative humidity (*RH*; %), and averaged over 30 min intervals (CR10X, Campbell Scientific, Logan, UT). In an open field located approximately 100 m from the watershed, a tipping bucket rain gauge (RT-5, Ikeda Keiki, Tokyo, Japan) was placed on a waist-height bench. Discharges from the study watershed and a neighboring one were also measured using weirs. Further details of the experimental setup and data processing for the eddy flux and discharge are presented elsewhere (Shimizu et al., submitted for publication, hereinafter referred to as submitted manuscript, 2013).

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