

Reproducing monthly evapotranspiration from a coniferous plantation watershed in Japan

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ABSTRACT

A hydrological process model that takes into account the effects of the forest status on the water yield is a powerful tool for the effective management of forest and water resources. Evapotranspiration (ET), that is, interception (IC) plus transpiration (TR), uses water from forest water resources, and thus ET changes resulting from forest practices, mainly thinning, should form a submodel for use with hydrological process models. In this study, first we derived the monthly ET and TR in a coniferous plantation watershed using the short-term water budget (STWB) method with an eight-year hydrological record. Next, we determined the canopy stomatal responses to environmental factors, enabling us to model the TR. As a result, correcting errors in the STWB estimation, we quantified ET, IC, and TR at the study site and formulated an ET submodel whose main driver is the stand density resulting from forest thinning. We found that IC, which is amenable to thinning, formed a major component of ET in the forest we studied, implying that forest management plays an important role in the conservation of water resources.

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Introduction

In Japan, there have recently been increasing calls for forest management to conserve water resources from forested mountain watersheds in terms of both water quality and quantity (Forestry Agency 2018). Successful forest and water resources management (FWM) particularly requires quantitative information on the relationships between the forest status resulting from forest management and runoff and groundwater supplies (Komatsu et al. 2008a). Hydrological process models that take into account the effect of the forest status on the water yield should be one of the most promising and powerful tools for FWM planning (Vertessy et al. 1996; Sun et al. 2006).

A major FWM treatment in Japan is forest thinning (Forestry Agency 2018), and its effects on the watershed hydrology would be changes in evapotranspiration (ET) (cf. Komatsu et al. 2007) and soil physics related to the water holding capacity and conductivity (cf. Zhang et al. 2016). Changes in ET are induced by alterations to the forest canopy-atmosphere process, significantly more rapidly due to forest thinning than to changes in soil physics. It is noteworthy that ET changes immediately after thinning are drastic but the change becomes smaller over time as the forest status becomes stable. Thus, we focus on prediction of ET change of a stable forest as applicable to the hydrological process model.

Some hydrological process models that can reflect runoff affected by the forest status have been proposed (e.g. Yokoo and Sivapalan 2011). However, because of insufficient data on ET alterations caused by forest thinning (see Sun et al. 2014), or any forestry practice for that matter, to our knowledge, no models have attempted to evaluate and optimize FWM. The goals of this study are to suggest an ET-forest thinning submodel, with parameterization, and to verify its performance. Therefore, we

sought to eliminate errors in observation based-ET for the better ET estimation.

Materials and methods

Site description and the data

The experiments were carried out in the Oborasawa Experimental Watershed (OEW), a 49.5 ha coniferous plantation in the Kanto region of Japan (35°28'N, 139°12'E, 430–880 m a.s.l.). The watershed is located in a steep mountainous area with a slope of $34.9^\circ \pm 9.0^\circ$ and is underlain by tuff and tuff breccia of Neogene age. The soil is classified as Cambisol, and the average soil depth is 1.64 m. The mean annual precipitation and temperature for the period 2010–2017 were 2952.6 mm and 12.3°C, respectively. The forest in the OEW consists mainly of *Cryptomeria japonica* D. Don stands and, to a lesser extent, *Chamaecyparis obtusa* Endl. stands. The averaged stand density and plant area index over the watershed were estimated to be 1280 trees ha⁻¹ and 3.8, respectively.

Discharge (Q) and meteorological variables (e.g. precipitation (P_r), solar radiation (R_s), air temperature (T), and humidity) were observed in the OEW, and daily values of the data in the period 2010–2017 were used for this study. Note that although measurement of snowfall amount is important in this study, the rain gauge equipped in the watershed is not heater-installed, thereby causing an underestimation of the P_r during mid-winter. Further description is presented elsewhere (Oda et al. 2013).

Short-term water budget method

Given little bedrock drainage in the OEW (Oda et al. 2013) and the Q expressed as the function of soil water storage, ET

(mm) in the specific hydrological period t_1 to t_2 can be expressed by the short-term water budget method (STWB; Linsley et al. 1958; Suzuki 1985) as:

$$ET = \int_{t_1}^{t_2} p_r(t)dt - \int_{t_1}^{t_2} q(t)dt, \quad (1)$$

where t is the time (days), p_r is the daily P_r rate (mm day^{-1}), and q is the daily Q rate (mm day^{-1}). The start and end dates of the specific hydrological period, that is, t_1 and t_2 respectively, were determined by the following criteria: (1) no p_r on those dates and during the previous two days, (2) the difference in q between t_1 and t_2 is within 5% of q at t_1 , (3) the period duration is more than 8 days and less than 85 days, and (4) the total P_r amount in the period is more than 30 mm. ET in mm obtained in the specific hydrological period was divided by its duration (days), resulting in a daily evapotranspiration rate ET in mm day^{-1} .

Delineating interception loss and transpiration

Komatsu et al. (2007) found a moderate relationship between the interception ratio (R_{IC}), which denotes the interception loss (IC) divided by P_r as a yearly value, and the stem density (T_D ; trees ha^{-1}) from 12 previous studies throughout Japan ($R^2 = 0.42$) as:

$$R_{IC} = 4.98 \times 10^{-5} T_D + 0.120 \quad (2)$$

We confirmed that the estimated R_{IC} ($=0.184$, in which $T_D = 1280$ trees ha^{-1}) for the studied site is consistent with the preliminary observation at the several sites in the OEW (0.14–0.25). Kumagai et al. (2014) suggested that Equation (2) is applicable to monthly estimates, and thus we derived the monthly IC from the product of the R_{IC} and the monthly P_r .

In general, the boundary conductance of conifers is sufficiently large, and Kumagai et al. (2008) confirmed *Cr. japonica* canopies are aerodynamically well coupled to the atmosphere. Therefore, in this study, transpiration (TR) was calculated using the simplified form of the Penman-Monteith equation (McNaughton and Black 1973):

$$T_r = 12 \times 3600 \times \frac{\rho_a c_p D}{\rho_w \lambda \gamma} G_s \quad (3)$$

where T_r is the monthly mean daily transpiration rate (mm day^{-1}), ρ_a is the density of dry air (g m^{-3}), c_p is the heat capacity of air ($\text{J g}^{-1} \text{K}^{-1}$), D is the monthly mean atmospheric vapor pressure deficit (Pa), ρ_w is the density of water (g m^{-3}), λ is the latent heat of vaporization of water (J g^{-1}), γ is a psychrometric constant (Pa K^{-1}), and G_s is the monthly mean surface conductance (mm s^{-1}). Here, given the monthly mean estimation in the mid-latitude zone, TR rate in mm s^{-1} was summed over daylight hours ($=12$ h) with mean daytime D to be T_r .

Canopy conductance

The data-based T_r (TR_{STWB}) was derived from the monthly mean ET, estimated using the STWB method with the Q and P_r observations (ET_{STWB}), minus the monthly mean IC (cf. Equation (2)). Then, G_s was calculated from an inverted Equation (3) with the TR_{STWB} . Here, we assumed that the forest floor evaporation is insignificant compared to the ET for the canopy trees (given the high leaf area index (LAI) ($> \text{ca. } 3.0$), because the LAI of

coniferous forests in Japan is usually higher than 3.0 (Komatsu et al. 2007), and the leaf biomass is generally considered to be constant for each species once the forest attains a canopy closure stage regardless of T_D or intensity of thinning (Tadaki 1976)). Under this assumption, G_s can be regarded as the canopy conductance (G_c ; mm s^{-1}) (see Kelliher et al. 1995).

To facilitate the interpretation of the influence of environmental variables on G_c (resulting in the G_c and ET modelling), we used a multiplicative-type function (e.g. Jarvis 1976) as:

$$G_c = G_{\text{cref}}(1 - \mu \ln D) \quad (4)$$

where G_{cref} is the reference value of G_c , μ is an empirical parameter, and D is represented in kPa. G_{cref} can be related to R_s and the soil moisture (e.g. Granier and Bréda 1996; Pataki and Oren 2003). If G_{cref} reflects the nonlimiting light and soil moisture, μ would be the proportionality m/b (in which m and b are the sensitivity of G_c to D (i.e. $-\partial G_c / \partial \ln D$) and the value of G_c at $D = 1$ kPa, respectively) (see Oren et al. 1999; Kumagai et al. 2008).

Results and discussion

Seasonal variations in ET and T_r (i.e. ET_{STWB} and TR_{STWB} , respectively) were reasonably evaluated by the STWB method (cf. Kumagai et al. 2014); while the monthly ET_{STWB} peaked around September–October due to enhanced IC from heavy rainfall in the typhoon season in Japan, the maximum monthly TR_{STWB} appeared in August because of the higher incident radiative energy (Figure 1). Snow in the wintertime and snowmelt in the late winter and early spring might delay Q and cause an increase in the Q in April, resulting in underestimation of ET_{STWB} and TR_{STWB} in April. Furthermore, note that snow accumulation and snowfall result in low Q and underestimation of P_r respectively in the mid-winter, and thus ET_{STWB} and TR_{STWB} in mid-winter might be unreliable.

An analysis of the relationship between G_c and D (Equation (4)) revealed that the primary driver for G_c is the incident radiative energy, and the soil moisture status least affects the G_c (cf. Kumagai et al. 2008). Therefore, we assumed the G_{cref} formulation as:

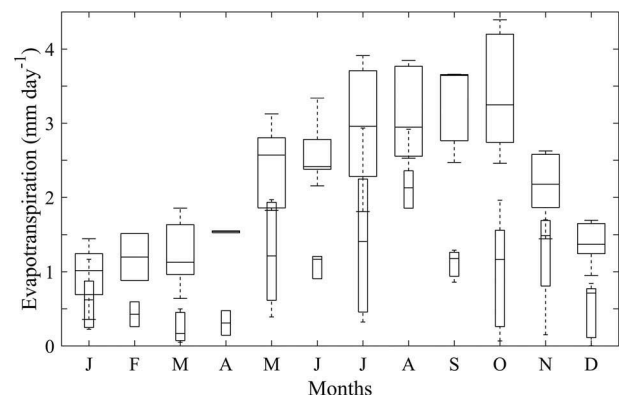


Figure 1. Box plots of monthly evapotranspiration (wide boxes) and transpiration (narrow boxes) based on the short-term water budget method estimation with the 2010–2017 hydrological data. Note that despite a few outliers, they are not shown here.

$$G_{\text{cref}} = \frac{bR_s}{R_s + a} \quad (5)$$

The parameters in Equation (4) with Equation (5) were estimated through non-linear regression analysis as: $a = 574.6$, $b = -2.05$, and $m = 39.2$ ($R^2 = 0.16$). In Figure 2, G_c data were plotted against D with the data partitioned into several R_s classes, and the determined G_c model is also shown. A very moist environment, that is, regularly $D < 0.7$ kPa, at the study site would cause a drastic decrease in G_c within a very narrow range of D , with parameter values beyond what one may expect such that b would be a positive value and m/b would be around 0.6 (see Oren et al. 1999; Kumagai et al. 2008).

Modelled ET (ET_{mod}), that is, dry canopy evaporation formulas (Equation (3) with the parameterized G_c model) (TR_{mod}) and wet canopy evaporation (Equation (2)), reproduced the canonical form of the ET_{STWB} well, despite unreliable ET_{STWB} in the mid-winter and ET_{mod} being higher than ET_{STWB} in March and April (Figure 3(a)). In practice, the differences between ET_{mod} and ET_{STWB} were not significant in most seasons (analysis of median test, $p > 0.23$) except for March-April-May ($p = 0.09$). In the mid-winter, both smaller estimations of P_r and smaller Q might have caused some cancellation and therefore somewhat realistic ET_{STWB} . Again, the ET_{STWB} in April might underestimate the ET, and may be unreliable because of a lack of data. This implies that ET_{mod} could be a better estimation than the ET_{STWB} in early spring. Figure 3(b) shows the monthly values of ET_{mod} , IC and TR_{mod} . Both seasonal variations in IC and TR_{mod} generate significant seasonality of ET_{mod} , and abundant rainfall conditions contribute significantly to temporally enhanced IC and ET_{mod} in September and October (see Kumagai et al. 2014).

Estimated annual IC using Equation (2) was 542.1 mm. Annual ET_{STWB} and TR_{STWB} were 799.0 and 256.9 mm, respectively, while annual ET_{mod} and TR_{mod} were 898.1 and 356.0 mm, respectively. Komatsu et al. (2008b) formulated a simple annual ET model as a function of the annual mean T (i.e. $ET \text{ (mm year}^{-1}\text{)} = 31.4 T \text{ (}^\circ\text{C)} + 376$) using water balance data from 43 watersheds throughout Japan ($R^2 = 0.38$) (Figure 4). Plotting the values in this study (12.3°C, 799.0 and 898.1 mm) in Figure 4 represents the plausibility of both ET_{STWB} and ET_{mod} , and also the practicality of Komatsu et al.'s (2008b) model. Note that although ET_{mod} and TR_{mod} were ca. 100 mm higher than their STWB estimates, those values were thought to be more

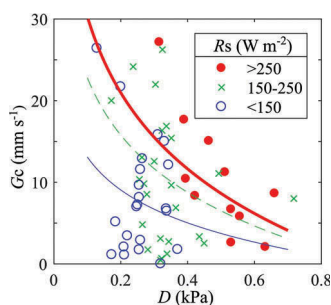


Figure 2. Relationship between daytime vapor pressure deficit (D) and canopy conductance (G_c) for different solar radiation (R_s) classes. Here, the monthly mean values are presented. The lines denote the determined G_c model (Equation (4) with Equation (5)) for $R_s = 300$ (thick solid line), 200 (dashed line) and 100 (thin solid line) W m^{-2} .

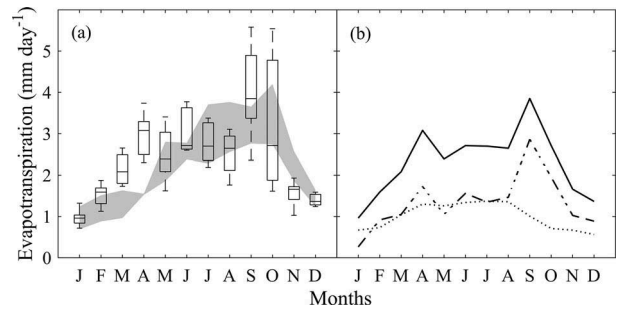


Figure 3. (a) Comparison between monthly evapotranspiration estimated by the short-term water budget method (ET_{STWB} : gray zone) and calculated with Equations (2)–(5) (ET_{mod} : boxes with whiskers). ET_{STWB} and ET_{mod} are represented as the range of middle two quartiles of the data and the box plots, respectively. (b) Components of ET_{mod} : ET_{mod} (solid line), interception loss (dashed line) calculated with Equation (2), and transpiration (dotted line) calculated with Equations (3)–(5). Note that medians of monthly mean values in 2010–2017 are used.

realistic because of the errors in estimating ET by the STWB method in early spring.

We confirmed that IC, which is more amenable to forest thinning than TR, is the major component of the ET at the study site, implying that forest management can play an important role in the conservation of this forest's water resources. Taking into consideration this ET characteristic derived from observation, we formulated and parameterized a submodel for the hydrological process models, describing the relationship between ET and the stand density for the study site. Incorporating the ET submodel into a full hydrological process model will enable us to evaluate the effect of FWM.

However, this relationship was assumed to be a relatively short-time response of less than 10-years after forest thinning. In reality, at longer time scales, thinning alters the forest ecophysiological characteristics and even its morphology via changes in tree-to-tree competition for light, water, and nutrients. Further investigation, for example, more mechanistic/physiological observations based on a longer campaign period, is required

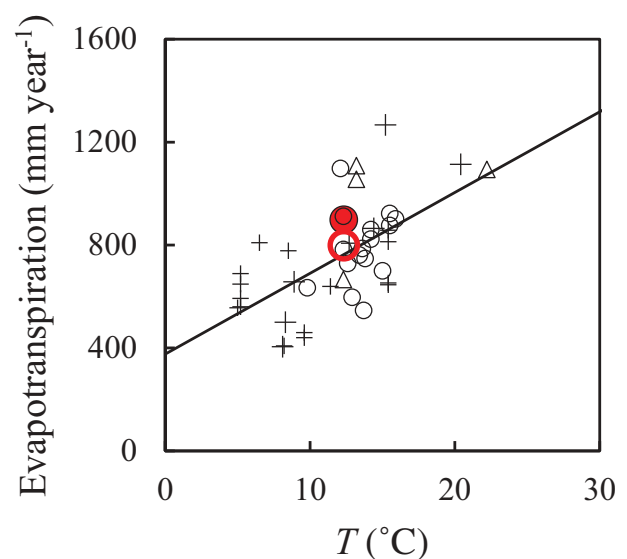


Figure 4. Relationship between annual mean air temperature (T) and annual evapotranspiration (ET) across Japan. Solid line denotes Komatsu et al. (2008b) model, that is, $ET = 31.47T + 376$. Forest types: this study (conifer, ET estimated by the short-term water budget method (open red circle) and calculated with Equations (2)–(5) (closed red circle)), conifers (open circles), hardwood (triangles) and mix (crosses).

for an extensive and longer time scale evaluation of water resources from forest watersheds.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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