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A model relating transpiration for Japanese cedar and cypress plantations with stand structure

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ABSTRACT

Previous studies have revealed that changes in forest structure due to management (e.g., thinning, aging, and clearcutting) could affect the forest water balance. However, there are unexplained variability in changes in the annual water balance with changing structure among different sites. This is the case even when analyzing data for specific species/regions. For a more advanced and process-based understanding of changes in the water balance with changing forest structure, we examined transpiration (E) observed using the sap-flux method for 14 Japanese cedar and cypress plantations with various structure (e.g., stem density and diameter) in Japan and surrounding areas and developed a model relating E with structural parameters. We expressed E using the simplified Penman–Monteith equation and modeled canopy conductance (G_c) as a product of reference G_c (G_{cref}) when vapor pressure deficit is 1.0 kPa and functions expressing the responses of G_c to meteorological factors. We determined G_{cref} and parameters of the functions for the sites separately. E observed for the 14 sites was not reproduced well by the model when using mean values of G_{cref} and the parameters among the sites. However, E observed for the sites was reproduced well when using G_{cref} determined for each site and mean values of the parameters of the functions among the sites, similar to the case when using G_{cref} and the parameters of the functions determined for each site. These results suggest that considering variations in G_{cref} among the sites was important to reproduce variations in E, but considering variations in the parameters of the functions was not. Our analysis revealed that G_{cref} linearly related with the sapwood area on a stand scale (A) and that A linearly related with stem density (N) and powers of the mean stem diameter (d_m). Thus, we proposed a model relating E with A (or N and d_m), where G_{cref} was calculated from A (or N and d_m) and the parameters of the functions were assumed to be the mean values among the sites. This model estimates changes in E with changing structure from commonly available data (N and d_m), and therefore helps improve our understanding of the underlying processes of the changes in the water balance for Japanese cedar and cypress plantations.

1. Introduction

Changes in forest structure due to management (e.g., planting, growth, thinning, aging, and clearcutting) can affect the forest water balance. Numerous studies (Scott and Lesch, 1997; Cornish and Vertessy, 2001) have examined changes in the annual water balance with changing forest structure on the basis of catchment

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water balance data. Summarizing data derived from such studies and analyzing them using linear regression, researchers have identified several important parameters (e.g., the ratio of the cutting area to the total catchment area, annual rainfall, and leaf phenology) determining changes in annual runoff with changing structure (Bosch and Hewlett, 1982; Brown et al., 2005; Komatsu et al., 2011). However, there remains unexplained variability in changes in the annual water balance (Bosch and Hewlett, 1982; Brown et al., 2005). This is the case even for data for a single species within a specific region, although the variability is less pronounced (Adams and Fowler, 2006; Komatsu et al., 2011). This suggests the limitation of analyzing catchment water balance data simply using linear regression without considering underlying processes (e.g., canopy transpiration and interception evaporation). For a more advanced understanding of changes in the annual water balance with changing structure, examining relationships of canopy transpiration and interception for given species with various structure (e.g., stem density and diameter) would be useful (Komatsu et al., 2007d). Variations in stem density and diameter relate with the sapwood area on a stand scale and leaf area index, which could in turn relate with canopy transpiration (Granier et al., 2000a; Ewers et al., 2011). Focusing on specific species would be useful in reducing factors to be considered, because there are factors (e.g., the clumpling factor and stem conductivity) that could differ among different species and affect canopy transpiration (Baldocchi and Meyers, 1998; Zwieniecki and Holbrook, 1998; Bréda, 2003).

Japanese cedar (*Cryptomeria japonica*) and cypress (*Chamaeryparis obtusa*) are major plantation species in Japan and surrounding areas such as China and Taiwan (Japan Forestry Agency, 2014). Examining the water balance of these plantations is highly important from a practical viewpoint. Forest management (e.g., thinning) has been performed to increase water resources in Japan, although its effectiveness has not been assessed sufficiently (Komatsu et al., 2010). Summarizing data for interception evaporation of Japanese cedar and cypress plantations (Hattori et al., 1982; Tanaka et al., 2005), Komatsu et al. (2007a) found a relationship between stem density and interception evaporation and then developed a model relating interception evaporation with stem density. However, there have been few studies examining the relationship between forest structure and canopy transpiration (E) for Japanese cedar and cypress plantations.

To assess changes in the water balance of Japanese cedar and cypress plantations with changing forest structure, we developed a model relating E for Japanese cedar and cypress plantations with meteorological and structural variables. The model formulates E using the simplified Penman–Monteith equation (McNaughton and Black, 1973; Jarvis and McNaughton, 1986). Canopy conductance (G_c) in the equation was written as a series of functions expressing responses of G_c to meteorological factors (Jarvis, 1976; Lohammer et al., 1980). This study comprises three steps. First, we calculated G_c using E data derived employing the sap-flux method for 14 sites and the inverted form of the simplified Penman–Monteith equation to determine parameters of the model for the sites separately. Second, we assessed the importance of each parameter in determining E on the basis of sensitivity analysis. Third, we examined the relationship of the important parameters with structural parameters. Here, we tried to relate the structural parameters with commonly available data such as stem density and diameter for wide use of the model.

Models estimating E are roughly classified into two groups. One uses many empirical parameters for modeling stomatal/canopy conductance to avoid considering internal hydraulics and keep the model structure simple (Granier et al., 2000a; Komatsu, 2004), while the other considers internal hydraulics (Domec et al., 2012; McDowell et al., 2013). Our model belongs to the former group. Most models of the former group focus on reproducing E for a specific site (Cienciala et al., 1994a,b; Granier and Bréda, 1996). Several models (Granier et al., 2000a; Komatsu, 2004) are applicable to various sites, similar to our model. Our model differs from these models in that our model focuses on two species, which suggests higher predictability of the model when applied to the species. Furthermore, our model differs from the models in that our model would be tested against E data recorded not only during growing seasons but during winter, suggesting higher reliability of the model to predict E on a long time scale (e.g., one year).

2. Theory

The model, using the simplified Penman–Monteith equation (McNaughton and Black, 1973; Jarvis and McNaughton, 1986), expresses E as

$$E = \frac{\rho C_p G_c D}{\gamma \lambda} \tag{1}$$

where ρ is the air density, C_p is the specific heat of air, G_c is canopy conductance, D is the vapor pressure deficit, γ is the psychrometric constant, and λ is the latent heat of water vaporization. This equation is derived from the Penman–Monteith equation under the assumption of complete coupling between the canopy and atmosphere.

G_c is formulated as a product of the reference value of G_c when D is 1.0 kPa (G_{cref}, Oren et al., 1999) and functions expressing responses of G_c to meteorological factors (Jarvis, 1976; Lohammer et al., 1980):

$$G_c = G_{cref} \cdot f(D) \cdot g(R) \cdot h(T) \tag{2}$$

where $f(D)$, $g(R)$, and $h(T)$ are functions expressing the responses of G_c to mean daytime D, solar radiation (R), and air temperature (T), respectively. $f(D)$, $g(R)$, and $h(T)$ are respectively modeled as (Oren et al., 1999; Granier et al., 2000b)

$$f(D) = 1.00 - \beta \cdot ln(D), \tag{3}$$

$$g(R) = \min\left\{\left(\frac{R}{600}\right)^{\delta}, 1.00\right\}, \tag{4}$$

$$h(T) = \begin{cases} 1.00 & (T \geqslant \epsilon) \\ \frac{T-\zeta}{\epsilon-\zeta} & (\zeta < T < \epsilon) \\ 0.00 & (T \leqslant \zeta) \end{cases}, \tag{5}$$

where β, δ, ε, and ζ are parameters. The model does not consider the effect of the soil water deficit on G_c. Most previous studies, making continuous measurements of E (or its substitutes) for forests in Japan including Japanese cedar and cypress plantations (Komatsu et al., 2006; Kosugi et al., 2007; Kumagai et al., 2007), did not report a clear reduction in G_c or E with a soil water deficit, although there were a few exceptions (Tanaka et al., 2002; Komatsu et al., 2007c).

We hypothesized that considering the variation in G_{cref} among sites would be important but considering variations in β, δ, ε, and ζ among sites would not be in reproducing E for the sites. Our hypothesis was based on results of previous studies. G_{cref} linearly relates with E in the simplified Penman–Monteith equation. G_{cref} values reported previously (Granier et al., 2000a; Komatsu et al., 2012, 2013) often differ greatly among different forest sites comprising the same species, implying that considering the variation in G_{cref} among the sites is important in estimating E. Oren et al. (1999) and succeeding studies (Addington et al., 2004; Ewers et al., 2008) noted a fairly conservative β among different sites. Thus, assuming β as constant among sites might not introduce large errors in E estimates. Komatsu et al. (2006) analyzed sap flux data on an hourly time scale for a Japanese cedar plantation and