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Transpiration and canopy conductance at two slope positions in a Japanese cedar forest watershed

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ABSTRACT

Plant–soil system patterns and processes along a slope are among the greatest causes of uncertainty in estimating watershed-scale transpiration (*E*). Tree-to-tree and radial variations in xylem sap flux density (F_d), in addition to tree biometrics, were measured over a 2-year period (2005–2006) in two slope stand positions. The areas of interest consisted of an upper slope plot (UP) and a lower slope plot (LP) in a Japanese cedar (*Cryptomeria japonica* D. Don) forest watershed and the environmental controls of stand *E* for each plot were compared. Canopy stand *E* (E_C) and canopy stomatal conductance (G_C) in the UP were less than those in the LP during the growing season, while those in the UP were greater than those in the LP over winter. In addition, mean stand F_d (J_S) in the UP was greater than that in the LP over winter, but J_S values were similar in the UP and LP except in the winter, which allows us to extrapolate watershed-scale *E* based on J_S estimated from F_d measurements of a partial stand in the watershed. However, this relationship contains a bias and differed between 2005 and 2006. Although there were significant differences in soil moisture conditions between the UP and LP in both years, a systematic relationship between the similarity in J_S and soil moisture conditions was not found. The bias was due to a tendency for J_S in the LP to be greater than that in the UP in 2006. This tendency was amplified because J_S in the LP was greater than that in the UP around an atmospheric humidity deficit (*D*) of 1–1.5 kPa and frequencies of this *D* range were higher in 2006 than in 2005. The greater J_S in the LP at $D \sim$ 1–1.5 kPa could be explained by the difference in the response of G_C to *D* between the UP and LP. Our results suggest this to be the cause of the similarity in J_S values for the UP and LP and for the occasional abortion of its similarity. However, even when the bias or the occasional deviation is disregarded, the error in estimating stand *E* from a partial stand is so small that it is comparable to an F_d measurement error. For example, the error when using only the LP was 6.6% for stand *E*.

1. Introduction

In Japan, forests cover 64% of the total land area (World Resources Institute, 2004) with the majority situated in mountain regions (Sawano et al., 2005). Since mountains receive higher precipitation and play a role in supplying water to lowlands, quantifying hydrologic components in montane-forested catchments is critical for water resource management in Japan. Surprisingly, 22% of the total forest area is composed of a single tree species, *Cryptomeria japonica* D. Don (Japanese cedar) (Japan Forestry Agency, 2002). Therefore, understanding water use in *C. japonica* trees is the first and

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crucial step for water resource research in Japan. Recently, a few studies (Kumagai et al., 2005a, 2007; Komatsu et al., 2006a,b) discussed their potential as a water-consumer whereas the emphasis previously in the literature has been on their functions as woody material and as a silvicultural species.

The sap flow technique is a useful methodology for investigating forest water use at temporal and spatial scales because complex terrain and spatial heterogeneity do not limit its applicability (e.g., Wilson et al., 2001; Kumagai et al., 2007; Ford et al., 2007), which is important in a mountainous country like Japan. Furthermore, this technique can examine the effects of species composition on stand, watershed or landscape scale transpiration (E) (e.g., Ewers et al., 2002, 2005; Mackay et al., 2002; Pataki and Oren, 2003; Bladon et al., 2006). Despite the robustness of the sap flow technique, three level scaling procedures are required to extrapolate the watershed scale E, i.e., from within-tree to the tree, from the tree to the stand, and from the stand to the watershed (see Ford et al., 2007). These procedures can be difficult owing to tree-to-tree variations in xylem sap flux density (F_d) (Granier et al., 1996a; Wullschleger et al., 2001; Pataki and Oren, 2003), tree sapwood area (A_{S_tree}) (Kumagai et al., 2005b), and spatial variations in F_d in the trunk of individual trees (Zang et al., 1996; Lu et al., 2000; Wullschleger and King, 2000; Delzon et al., 2004b; Kumagai et al., 2005a).

Topographic gradients influence the soil texture and availability of water and nutrients, resulting in plant–soil systems and plant growth patterns along a slope (Sabate et al., 1995; Tokuchi et al., 1999; Hanba et al., 2000; Luizao et al., 2004; Tateno et al., 2004). In particular, Tromp-van Meerveld and McDonnell (2006) reported the relationships between soil moisture, soil depth, and individual tree water use (E_T) and their influence on the hillslope water balance, and implied their resultant spatial differences in growth and species distribution along a slope. Two considerations must be kept in mind when we apply sap flow measurements to estimate the watershed scale E. The first is the difference in tree-to-tree and within-tree variations in F_d and the second is the allometric relationship between the stem diameter at breast height (DBH) and A_{S_tree} between slope positions. In a previous study (Kumagai et al., 2007), we examined slope-position variations in total sapwood area of the stand (A_{S_stand}), the radial trend in F_d, and the mean stand sap flux density (J_S), taking into account the above factors. The results showed that J_S measured at different positions along the slope was similar during the period studied despite significant variations in environmental factors, e.g., soil moisture conditions, and tree growth, e.g., DBH and tree height. These similarities implied the potential of a relationship for determining the watershed scale E based on J_S estimated from F_d measurements of a partial stand in a watershed.

Although the J_S values at different slope positions were similar, there were systematic inconsistencies between them, i.e., ''biases'', and the studied period was limited to a single growing season. Thus, three questions arise: (1) are the J_S values at different slope positions similar over a longer period and (2) what factors generated the bias? Additionally, since the tree densities and individual tree sizes along the slope were considerably different despite the forest being of even age (Kumagai et al., 2007), it would also be interesting to examine (3) the degree of difference in how E_T respond to soil conditions among the slope positions. To address these questions, we conducted tree-level measurements of F_d at several depths of sapwood in upper and lower slope plots of a watershed over a 2-year period and compared environmental controls of stand E for the different plots. The outcome of this study was also used to provide strategies for watershed-scale sap flow estimates of E and minimize potential errors in the estimate.

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 Kyushu Island, 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 1999–2004 was around 2150 mm with the rainy season occurring from mid-June to early July. The mean annual temperature was around 15 °C with a minimum mean monthly temperature of about 4 °C in January–February and a maximum mean monthly temperature of about 26 °C in August.

The forest in the watershed consists mainly of even-aged 50-year-old *C. japonica* stands, and to a lesser degree, *Chamaecyparis obtusa* Endl. (Japanese cypress) stands ranging from 30 to 50 years old. Understory vegetation is dense and consists of various species of evergreen *Quercus* and *Castanopsis* trees. For this study, two *C. japonica* stand plots, an upper slope plot (UP) and a lower slope plot (LP), located less than 100 m from each other on a 20° slope in the watershed were sampled (see Table 1). The UP and LP have similar ground areas and are of identical age; however, while there are more trees in the UP than in the LP, the stand basal area and individual tree sizes in the UP are smaller than in the LP (Table 1). These differences result in a frequency distributions

Table 1 – Stand characteristics of the two study plots, the upper slope plot (UP) and lower slope plot (LP)

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

[a] PAI was measured from 2004 to 2005, and ranges of values denote seasonal variations.
[b] Measured at other slope positions with similar slope height to the UP.
[c] Sapwood area was estimated based on the allometric relationship of each study plot (Kumagai et al., 2007).