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Changes in spatial variations of sap flow in Korean pine trees due to environmental factors and their effects on estimates of stand transpiration

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Abstract: It is difficult to scale up measurements of the sap flux density (J_S) for the characterization of tree or stand transpiration (E) due to spatial variations in J_S and their temporal changes. To assess spatial variations in the sap flux density of Korean pine (*Pinus koraiensis*) and their effects on E estimates, we measured the J_S using Granier-type sensors. Within trees, the J_S decreased exponentially with the radial depth, and the J_S of the east aspects were higher than those of the west aspects. Among trees, there was a positive relationship between J_S and the tree diameter at breast height, and this positive relationship became stronger as the transpiration demand increased. The spatial variations that caused large errors in E estimates (i.e., up to 110.8 % when radial variation was ignored) had varied systematically with environmental factors systematic characteristics in relation to environmental factors. However, changes in these variations did not generate substantial errors in the E estimates. For our study periods, the differences in the daily E (E_D) calculated by ignoring radial, azimuthal and tree-to-tree variations and the measured E_D were fairly constant, especially when the daily vapor pressure deficit ($D_{\_D}$) was higher than 0.6 kPa. These results imply that the effect of spatial variations changes on sap flow can be a minor source of error compared with spatial variations (radial, azimuthal and tree-to-tree variations) when considering E estimates.

Keywords: Sap flow; Environmental factors; *Pinus koraiensis*; Scale-up; Stand transpiration

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Introduction

The use of the sap flux density (J_S) sensor is one of the most commonly used techniques for estimating transpiration from the tree level to the stand or catchment levels (Granier et al. 1996; Köstner et al. 1998; Wilson et al. 2001; Cermak et al. 2004; Kubota et al. 2005; Ewers et al. 2008; Kume et al. 2010; Vandegehuchte and Steppe 2013). However, there are some practical difficulties in calculating tree or stand transpiration using this technique due to spatial variations in J_S, i.e., radial (e.g., Delzon et al. 2004; Fiora and Cescatti 2006; Lüttschwager and Remus 2007; Chang et al. 2014), azimuthal (e.g., Tsuruta et al. 2010; Barij et al. 2011; Shinohara et al. 2013) and tree-to-tree variations (e.g., Kumagai et al. 2005; Kume et al. 2010; Shinohara et al. 2013) and temporal changes for each of the spatial variations (e.g., Oliveras and Llorens 2001; Oren and Pataki 2001; Ford et al. 2004; Saveyn et al. 2008; Alvarado-Barrientos et al. 2013; Catoni and Gratani 2014). Furthermore, almost all types of J_S measurement sensors, including the Granier-type heat dissipation sensor (Granier 1985; Granier 1987), can only cover a small part of the xylem's area; therefore, spatial variations in J_S are not captured (Clearwater et al. 1999; Caylor and Dragoni 2009; Sun et al. 2012; Paudel et al. 2013). Consequently, large errors may occur when J_S is scaled from a single point measurement to an entire tree or multiple trees if spatial variations are not taken into account (Hatton et al. 1995; Pausch et al. 2000; Nadezhdina et al. 2002; Cermak et al. 2004; Delzon et al. 2004; Ford et al. 2004; Fiora and Cescatti 2006).

In addition, changes in spatial variations of J_S add another layer of complexity to J_S estimation and scaling. Spatial variations change temporally with stand conditions such as site microclimate (Alvarado-Barrientos et al. 2013; Chang et al. 2014; Guo and Zhang 2015), soil moisture (Lu et al. 2000; Kubota et al. 2005; Fiora and Cescatti 2006) and crown sun exposure (Oren et al. 1999; Shinohara et al. 2013). Accordingly, a number of studies have quantified not only the spatial variations but also how they changed and highlighted the importance of long-term measurements to account for the effects of environmental conditions on spatial variations (Oliveras and Llorens 2001; Fiora and Cescatti 2006; Poyatos et al. 2007; Saveyn et al. 2008; Alvarado-Barrientos et al. 2013; Chang et al. 2014).

Korean pine (*Pinus koraiensis*) is an evergreen, coniferous tree distributed widely in Southeast Asia including China, Russia, Japan and Korea. In South Korea, Korean pines are found at elevations of 100 m to 1900 m, and it has been one of the major plantation species since the 1960s, resulting in 20% of the total conifer plantation area. Accordingly, the estimation of transpiration in Korean pine stands is one of the most important factors for understanding the hydrological cycle on the Korean peninsula. Our previous study on 50-year-old Korean pine trees quantified spatial variations in J_S and their effects on stand transpiration (E) estimates of Korean pines (Moon et al. 2015). The results of that study verified that Korean pine trees exhibited significant spatial variations in J_S and that consideration of these spatial variations, particularly radial variations, was essential for the accurate estimation of E because they were the largest source of error for E estimates (up to 109.2%). However, our previous study did not include temporal changes in the spatial variations and their effects on E estimates, even though the spatial variations in J_S could be substantially dependent on the environmental conditions in the stand. Therefore, in this study, we have assessed how the changes in spatial variations are related to environmental factors in the stand and their effects on E estimation.

1 Materials and Methods

1.1 Site description

This study was conducted at a 50-year-old Korean pine plantation located on the northeast side of Mt. Taehwa, GyeongGi (37°18'15"N, 127°19'00"E). The site was established at approximately 180 m above sea level in 1963. The average air temperature and precipitation in this area are 11.5°C and 1471 mm, respectively, and more than 60% of the annual precipitation occurs from July to September due to summer monsoons in East Asia. The bedrock of Mt. Taehwa is primarily composed of granite, and the soil type is sandy loam with a field capacity of 65% and a soil

density of 1.37 g cm^{-3} (Suh et al. 2014). This plantation has several sub-canopy species including *Toxicodendron trichocarpum, Rhododendron yedoense, Magnolia kobus* and *Zanthoxylum schinifolium*, which comprise less than 10% of the total basal area (Moon et al. 2015). In addition, the average daily sunshine at the study site occurs from 06:43 to 18:36 in March and from 05:10 to 19:54 in June.

For the study, we chose three control plots (i.e., no treatment) within the experimental plantation, which were composed of nine 20 m × 20 m plots each, and these were located within 80 m of each other. The first plot was established in April 2011, and the remaining plots were added in March 2012. The average tree density of the three plots was 455 trees ha^{-1}. Each plot had at least a 10 m buffer on each side. The average tree diameter at breast height (DBH) was 29.0 cm, and the stand canopy height was approximately 18 m.

The meteorological variables were measured at a tower, which was located at the center of the first established plot. The photosynthetically active radiation (Q) (measured with a LI-190, LI-COR, Lincoln, USA), air temperature (T) and relative humidity (RH) (measured with an HMP35C, Campbell Scientific, Utah, USA) were measured at the top of the tower, which was slightly higher than the canopy height of the stand. The volumetric soil water content of the upper 30 cm of the soil layer (θ) (measured with a CS616, Campbell Scientific, Utah, USA) was measured in the first plot using three randomly distributed sensors. All of the measurements were taken every 30 s, and the 30 min average was stored on a data logger (CR1000, Campbell Scientific, Utah, USA). The vapor pressure deficit (D) was calculated using T and RH. The leaf area index (LAI) was determined using a site- and species-specific allometric equation by Ryu et al. (2014). The maximum and minimum leaf area indices (LAIs) during the growing season were approximately 5.40 m^2 m^{-2} around early September and 3.81 m^2 m^{-2} around late March, respectively.

1.2 Sap flux density measurement

The J_S was measured with custom-built heat dissipation sensors according to the method of Granier (1985; 1987). Each sensor was composed of two different probes, an upper probe heated by constant power (0.2 W) and a lower reference probe without a heat source. Refer to our previous study (Moon et al. 2015) for more detailed information about the sensor set-up. Table 1 shows the number of trees, the depths and aspects of the J_S sensors, the DBHs of the study trees, and the measurement periods for each variation. For the analysis of radial variation, we used fourteen trees from the first plot. Four of these trees had three J_S sensors installed at different depths covering 0-60 mm of the xylem ($J_{S\_D\_0\text{-}20}$, $J_{S\_D\_20\text{-}40}$ and $J_{S\_D\_40\text{-}60}$). Outer sensors were installed on the rest of the trees. For the analysis of azimuthal variation, the J_S from six aspects were measured on three trees located at one of the later established plots. The DBH of the three trees were 26.0, 28.4 and 36.8 cm, respectively. For the analysis of tree-to-tree variation, thirty-four trees from each of the study plots covering a range of tree sizes and their north-facing outer sensors were used. Measurements were taken every 30 sec, and the 30 min averages were stored in the data logger (CR1000, Campbell Scientific, Utah, USA).

The daily average J_S (J_{S_D}) from each sensor was calculated to quantify the relative contribution of each xylem depth and aspect and to assess the relationship between J_S and tree size (i.e., DBH). The daily average environmental variables were also calculated. For the daily average environmental variables, we calculated a 24-hour

Table 1 Characteristics of the Korean pine trees studied, the depths and aspects of the sap flux density sensors, the diameter at breast height (DBH) of the study trees, and the measurement periods for each variation. Sensors were installed 0-20 mm, 20-40 mm and 40-60 mm from the cambium. N, NE, SE, S, SW, and NW represent the aspects of the circumferentially installed sensors, and the sensors were sequentially installed 60° apart starting from the north aspect (N, north; NE, northeast; SE, southeast; S, south; SW, southwest; NW, northwest).

Variation	No. of trees	Depth (mm) and aspect(s)	DBH (cm)	Data collection period
Radial	4	0-20, 20-40 and 40-60 at N	28.0 (21.7-31.7)	May 26 to June 20, 2011
	10	0-20 at N	29.5 (21.5-36.4)	
Azimuthal	3	0-20 at N, NE, SE, S, SW and NW	30.4 (26.0-36.8)	May 5 to June 28, 2012
Tree-to-tree	34	0-20 at N	29.0 (21.5-36.4)	March 14 to June 11, 2013

average rather than a daytime average to take nighttime transpiration into account (Caird et al. 2007; Dawson et al. 2007). The study periods for the radial, azimuthal and tree-to-tree variations were 26, 55 and 90 days, respectively (Table 1).

1.3 Quantifying the effect of changes in the spatial variations

To quantify the effect of changes in the spatial variations of sap flow on E estimates, we calculated the differences in daily E (E_D) between the E calculated by ignoring radial, azimuthal and tree-to-tree variations and the measured E (E_M). First, the individual tree transpiration (E_T) was calculated using the following equation:

$$E_T = \sum_{i=1}^{n} J_{S\_A\_i} A_i$$

where n is the number of sensor depths examined within the xylem, A_i is the xylem area at depth i, and $J_{S\_A\_i}$ is the daily average J_S of the individual tree at depth i. The sapwood depth was determined to be the point where J_S reaches zero because our study trees showed no clear distinction between sapwood and heartwood by color. Our previous study (Moon et al. 2015) can be referenced for more details about the issue of determining sapwood depth. Consequently, the E_M was calculated using the following equation: $E_M = \sum E_T / A_G$, where A_G is the study plot area.

Similar to the methods of Moon et al. (2015), E that did not account for radial variation was calculated assuming that the inner J_S values ($J_{S\_20\text{-}40}$ and $J_{S\_40\text{-}60}$) were the same as the $J_{S\_0\text{-}20}$ value. E that did not account for azimuthal variation was calculated using the J_S from each aspect. Similarly, the error caused by ignoring tree-to-tree variation was calculated using the J_S from each tree.

1.4 Statistical analysis

All of the curves were fit with SigmaPlot 12.0 software (Systat Software). The coefficients of variation (CVs) for all of the variations (i.e., three depths for radial variation, six aspects for azimuthal variation, and 34 trees for tree-to-tree variation) were calculated to quantify these variations and assess the changes in the J_S contribution. Analysis of variance (ANOVA) was conducted for the comparison of the relative J_S of each aspect. Statistical analysis was performed with SAS Version 9.3 software (SAS Institute).

2 Results

2.1 Environmental variables

Experiments were conducted from early or mid-spring to early summer in each year (Table 2). A large portion of the summer data was excluded from the analysis due to frequent thunderstorms and flood-related data loss. The averages and ranges of the environmental variables for the radial and azimuthal variation experiments were similar. However, the tree-to-tree variation, which was measured starting approximately two months earlier than the other experiments, had wider ranges and lower averages for T, Q and D. The maximum and minimum LAIs were similar over all of the study years because the Korean pine stand was mature with a closed canopy, and all of the experimental periods ended at approximately the same time of the year. These results are summarized in Table 2.

2.2 Changes in spatial variations of sap flow

To examine the changes in spatial variations of J_S in relation to environmental factors, the CV of J_S due to radial variation was analyzed using meteorological variables. With an exponential decrease in J_S, J_{S_D} of the inner sensors showed a

Table 2 The averages and ranges of the daily environmental variables (T, air temperature; Q, photosynthetically active radiation; D, vapor pressure deficit; θ, volumetric soil water content) and the leaf area indices (LAIs) of the plots for each of the study periods

Variation	Data collection period	T (°C)	Q (μmol m^{-2} s^{-1})	D (kPa)	θ (%)	LAI (m^2 m^{-2})
Radial	May 26 to June 20, 2011	20.4 (15.8-24.6)	448(142-623)	0.96 (0.17-1.63)	-	3.89 (3.81-4.00)
Azimuthal	May 5 to June 28, 2012	19.5 (12.7-24.5)	460(79-632)	1.03 (0.20-1.65)	17.7 (13.4-23.5)	4.11 (3.98-4.38)
Tree-to-tree	March 14 to June 11, 2013	12.4 (0.0-23.7)	389(63-626)	0.73 (0.13-1.67)	21.2 (16.8-26.3)	4.01 (3.96-4.16)

linear relationship with $J_{S\_D\_00\text{-}20}$ ($J_{S\_D\_20\text{-}40}$ and $J_{S\_D\_40\text{-}60}$ were 9.3% and 2.1% of $J_{S\_D\_00\text{-}20}$ on average, respectively, Figure 1a). Our data also showed that there were weak, but positive significant relationships between the CV and the daily average Q ($Q_{\_D}$) and D ($D_{\_D}$) (maximum P = 0.038, Figures 1b and c, respectively). These results could imply that the relative contributions of the inner sensors decreased with increasing D and Q because increasing CV represents an increase in the relative contribution of the outer sensors (Shinohara et al. 2013; Moon et al. 2015). The J_S was significantly different among the aspects (P<0.05, Figure 2a). The averages of J_S for east aspects (i.e., southeast and northeast) were higher than those for west aspects (i.e., southwest and northwest). In addition, the daily CV of azimuthal variation showed no significant relationships with $Q_{\_D}$ and $D_{\_D}$ according to regression analysis; therefore, regression lines were excluded (minimum P = 0.066, Figures 2b and c).

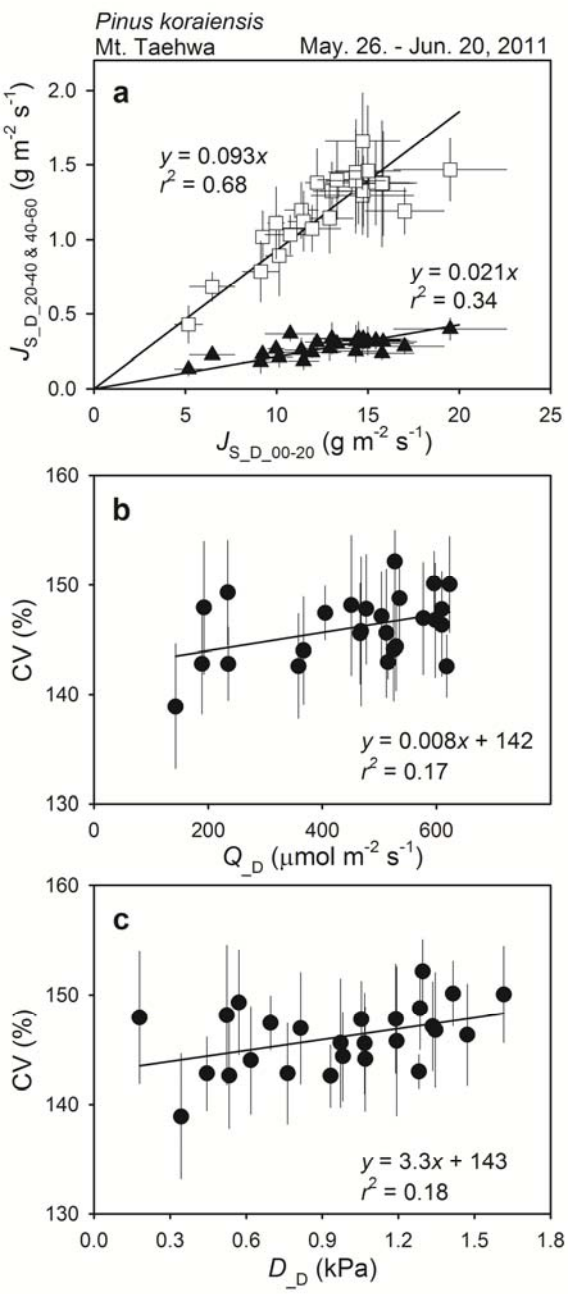

Figure 1 (a) Relationship between daily average sap flux densities at 0-20 mm ($J_{S\_D\_0\text{-}20}$)and 20-40 mm ($J_{S\_D\_20\text{-}40}$) (□) and at 0-20 mm ($J_{S\_D\_0\text{-}20}$) and 40-60 mm ($J_{S\_D\_40\text{-}60}$) (▲); **(b)** the daily average coefficient of variation (CV) for radial variation and daily average photosynthetically active radiation ($Q_{\_D}$); and **(c)** the relationship to the daily average vapor pressure deficit ($D_{\_D}$). Each point in the panels represents one of 26 days, and the error bars represent the standard error of tree sampling (n=4).

In Figure 3a, each point represents the daily average J_S (J_{S_D}) of each tree over 90 days. The average J_S of the thirty-four trees was 7.7 g m^{-2} s^{-1}, and the range was 3.9 to 11.8 g m^{-2} s^{-1}. The average CV of tree-to-tree variation over 90 days was 30.0%. The J_{S_D} of the individual trees showed a positive relationship with the DBH (y = 0.21x +1.5, r^2 = 0.15, P = 0.018), and this positive relationship was stronger on sunny days than on cloudy days. This result implies that bigger trees contribute more to the entire E on sunny days (Figure 3). Further analysis of the changing relationship between J_{S_D} and DBH revealed that the slope increased hyperbolically with increasing $Q_{\_D}$ and $D_{\_D}$ (Figures 3b and c, respectively).

2.3 Effect of changes in spatial variations of sap flow on estimates of stand transpiration

Figure 4 shows the differences in daily E (E_D) for each variation. For the entire study period, the average E_Ds for radial, azimuthal, and tree-to-tree variations were 106%±1.8%, 15.3%±1.1%, and 29.8%±9.4%, respectively, and their CVs were 1.7%, 7.2%, and 31.7%, respectively. Although the E_D for radial and azimuthal variations did not vary over the entire range, for tree-to-tree variations, the E_D decreased with increasing $D_{\_D}$ until $D_{\_D}$ reached 0.6 kPa and then remained constant with further increases in $D_{\_D}$. These results imply that the changes in radial and azimuthal variations did not

result in additional errors in E estimates; however, the error in E estimates in tree-to-tree variation increased with decreasing $D_{\_D}$ when $D_{\_D}$ was lower than 0.6 kPa, and above 0.6 kPa, tree-to-tree variations also gave fairly constant values for E_D, similar to radial and azimuthal variations. Consequently, the average E_Ds for radial, azimuthal, and tree-to-tree variations were 107%±1.3%,

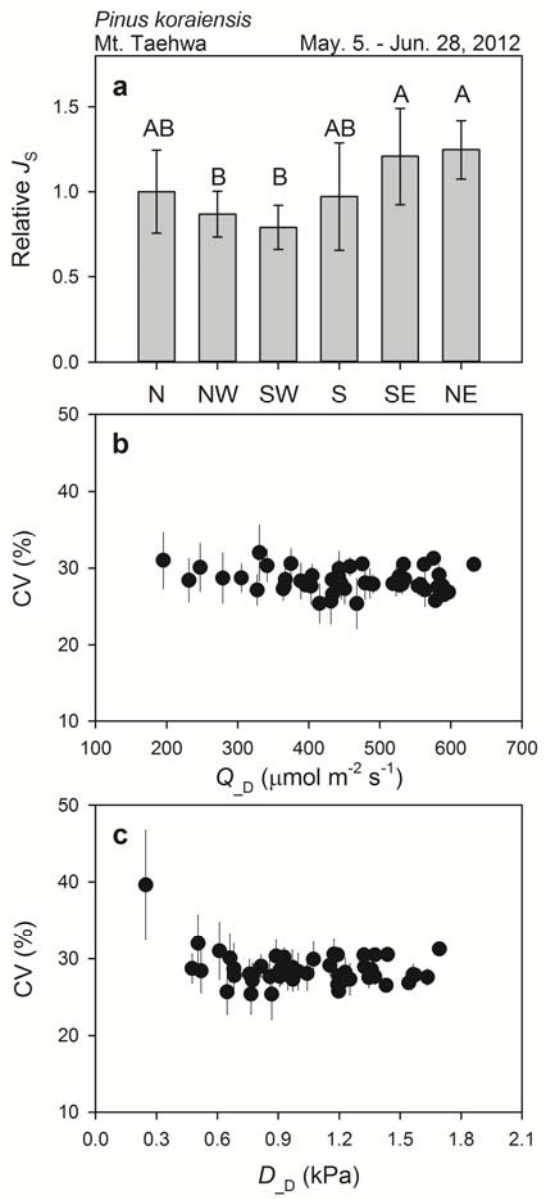

Figure 2 (a) Averages of sap flux densities (average J_S) at the northwest (NW), southwest (SW), south (S), southeast (SE), and northeast (NE) aspects relative to the average J_S at the north (N) aspects; **(b)** the relationship between the daily average coefficient of variation (CV) for azimuthal variation and daily average photosynthetically active radiation ($Q_{\_D}$); and **(c)** the relationship with the daily average vapor pressure deficit ($D_{\_D}$). In panel (a), error bars represent the standard error of tree sampling (n=3), and different letters indicate significant differences at the level of P< 0.05. Each point in panels (b) and (c) represents one of 55 days. In all of the panels, the error bars represent the standard error of tree sampling (n=3).

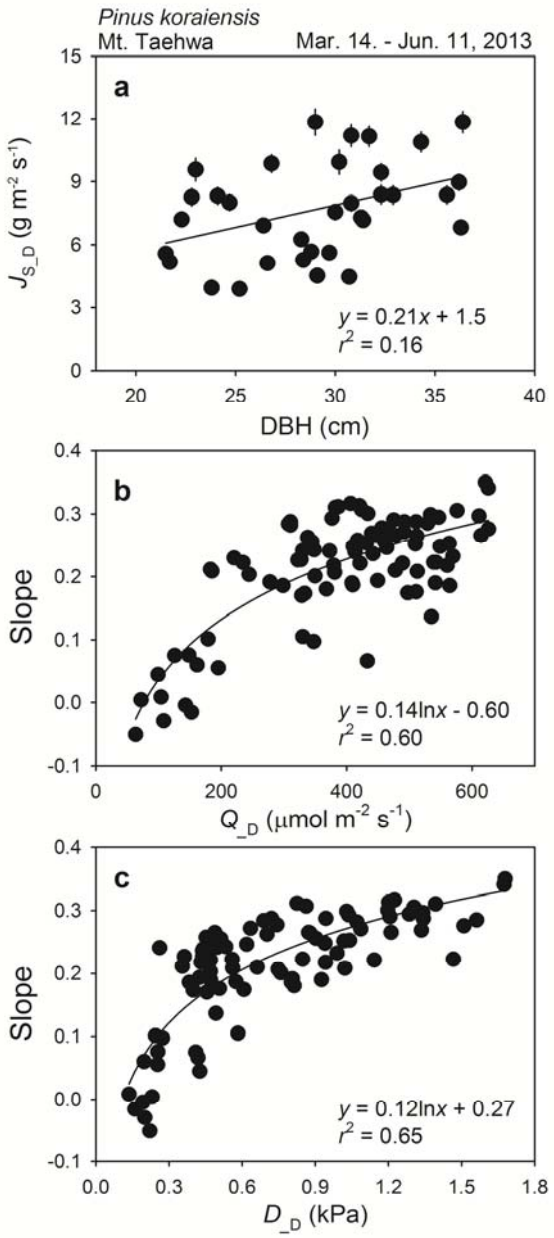

Figure 3 (a) The relationship between the average daily sap flux densities (J_{S_D}) and tree diameter at breast height (DBH) and the changes in the slope representing this relationship from day to day with daily average; **(b)** photosynthetically active radiation ($Q_{\_D}$); and **(c)** vapor pressure deficit ($D_{\_D}$). Each point in panel (a) represents one of 34 trees, and error bars represent the standard error over 90 days (n=90). Each point in panels (b) and (c) represents the slope of (a) for 90 days.

15.2%±0.9%, and 26.1%±1.3%, respectively, and their CVs were 1.6%, 6.1%, and 4.8%, respectively, when $D_{\_D}$ was higher than 0.6 kPa.

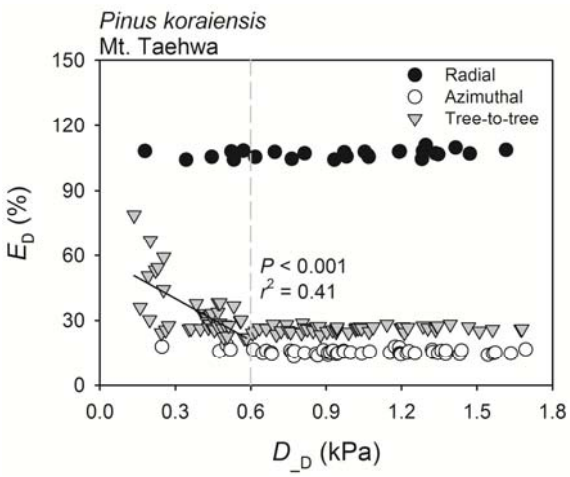

Figure 4 The differences in daily stand transpiration (E_D) between the measured stand transpiration and the E calculated by not considering radial (●), azimuthal (○), and tree-to-tree (▼) variations for each of the study periods (i.e., 26, 50, and 90 day for radial, azimuthal, and tree-to-tree variations, respectively) as they relate to the daily average vapor pressure deficit ($D_{\_D}$). The regression line represents the relationship between E_D and $D_{\_D}$ for tree-to-tree variation when $D_{\_D}$ was lower than 0.6 kPa.

3 Discussion

3.1 Variation of sap flow within trees

Although our study was extended to include more trees and a longer experimental period (i.e., total of 14 trees and 26 days, respectively) than our previous study (Moon et al. 2015), the relationship between the $J_{S\_D\_00\text{-}20}$ and J_{S_D} of the inner sensors was not different between the current and previous studies (9.3% and 9.7% for $J_{S\_D\_20\text{-}40}$ and $J_{S\_D\_00\text{-}20}$ on average, respectively and 2.1% and 2.2% for $J_{S\_D\_40\text{-}60}$ and $J_{S\_D\_00\text{-}20}$ on average, respectively; refer to Figure 3b in Moon et al. 2015). The consistency of radial spatial variation might be attributed to the small sapwood area (i.e., a small area of hydraulic conducting tissue within the trunk) of the studied trees (Moon et al. 2015). Saveyn et al. (2008) suggested that trees having a large area of sapwood could cause high spatial variability in sap flow within the sapwood because different sections could have different responses to various environmental conditions within the tree. For instance, they reported that sap flow in the deeper sapwood corresponds to water absorption from the deeper roots.

Figures 1b and c show that there are significant day-to-day variations in the radial variation related to meteorological variables, although their magnitude was found to be smaller than that of previous studies (e.g., Wullschleger and King 2000; Delzon et al. 2004; Fiora and Cescatti 2006). The CV of the radial variation increased linearly with $Q_{\_D}$ and $D_{\_D}$, indicating that the relative contribution of the inner J_S to the total J_S was higher when Q and D were lower. This result is in contrast with the results of Fiora and Cescatti (2006), who showed that an increase in the relative contribution from inner xylem occurred when Q and D were higher, especially in large trees at different positions in a stand. However, Jiménez et al. (2000) reported that the radial variations of suppressed trees were lower than those of large dominant trees because they were mainly exposed to diffuse and direct radiation, respectively. Diffuse radiation penetrates more evenly and deeply into the crown than direct radiation; therefore, the incident light on the crown was more homogeneously distributed on cloudy days than on sunny days (Gu et al. 1999; Farquhar and Roderick 2003; Kim et al. 2011). These homogenous light environments within the crown could have reduced the variation in the relative contributions from different xylem depths on cloudy days.

Although the azimuthal variation in the J_S was much smaller than the radial variations in our study (i.e., higher CVs for radial variation than for azimuthal variation (Figures 1 and 2)), there were significant differences among the aspects (Figure 2a). Our previous study performed at this site (Moon et al. 2015) suggested that the azimuthal variation at this site could be attributed to variations in sun exposure of the crowns. Because our study site faced northeast, it is likely that the amount of canopy sun exposure was substantially higher in the eastern part of the crown than the western part. To provide evidence to support our hypothesis, we compared the sum of Q from the southwest and southeast. Between 14:00 and 16:00, when most of the radiation came from the southwest aspect, the sum of Q, was 12.3% lower

than the sum of Q between 09:00 to 11:00, when most of the radiation came from the southeast aspect (i.e., 7.2 mol m^{-2} versus 8.2 mol m^{-2}, Figure 5). Note that our solar noon was 12:30 instead of 12:00.

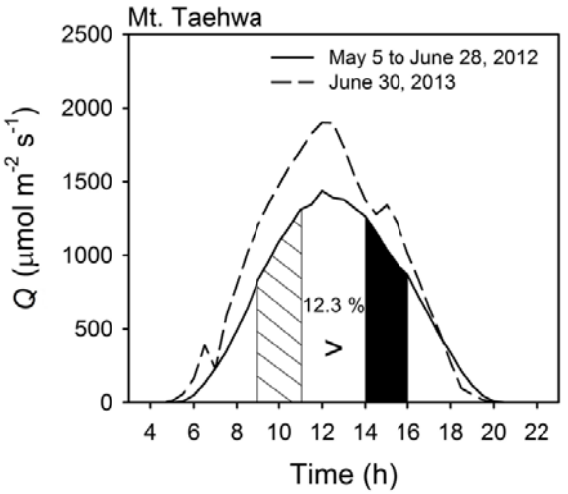

Figure 5 The solid line represents the average diurnal patterns of photosynthetically active radiation (Q) from May 10 to June 28, 2012, and the dashed line represents the diurnal pattern of Q on June 30, 2013. Refer to the main text for additional details.

3.2 Variation in sap flow among trees

Although some studies did not show a relationship between the J_S and tree size (Oren et al. 1999; Kumagai et al. 2005), many previous studies revealed that tree-to-tree variations were related to tree size as a result of differences in the sizes of the leaf areas (Martin et al. 1997; Oren et al. 1998; Delzon et al. 2004), competition among trees in the stand (Lagergren and Lindroth 2004; Jimenez et al. 2010; Shinohara et al. 2013) or heterogeneity of the soil moisture content within the stand (Nadezhdina et al. 2002; Zhang et al. 2015). As mentioned by Shinohara et al. (2013), the studies that did not show a relationship between the J_S and tree size were conducted in locations where there was little competition for water. For example, trees with sufficient self-thinning due to heavy snowfall (Kumagai et al. 2005) and trees growing under nearly continuous flood conditions (Oren et al. 1999) had J_S that were independent of tree size. As we discussed in our previous study (Moon et al. 2015), the competition for water among trees at this site was considered to be the driving force behind the significant relationship between the J_S and tree size (Figure 3a). When the demand for water was low (i.e., low Q and D) and there was little competition for it, the transpiration was similar between the trees; however, the transpiration between the trees showed bigger differences when the demand and competition for water were high (Figures 3b and c). These results indicate that the bigger trees were able to take advantage of their size to outcompete the smaller trees when water demand was high. These results suggest that the large trees dominate the competition for water when transpiration demand is high. As a result, the trees that used more water experienced more growth because tree productivity is directly connected to tree water use (Ares and Fownes 1999; Schäfer et al. 2003; Kim et al. 2008).

3.3 Effect of changes in spatial variations on sap flow on estimates of stand transpiration

This study confirmed that spatial variations cause substantial error in E estimates, especially radial spatial variation (Figure 4) and revealed that there were systematic correlations between their temporal changes and meteorological variables (refer to Figures 1 and 3 for radial spatial and tree-to-tree variations, respectively). These results imply that the relative contributions to E from xylem at different depths, different aspects within the sapwood or from a specific tree within a stand were not constant over time, and their variations were related to environmental conditions within the stand.

Many previous studies have emphasized that changes in spatial variation should be considered when attempting to scale up to whole-stand E estimates from point measurements (i.e., sap flux sensor) due to their significance and dependence on environmental factors (Dragoni et al. 2009; Alvarado-Barrientos et al. 2013; Zhang et al. 2015). Nevertheless, these studies suggested that even though changes in spatial variation should be considered, especially over longer time periods, a constant ratio for spatial variation could be applicable in many cases. This study also showed that the effects of changes in these spatial variations may not have a large effect on the accuracy of E estimates (Figure 4). The estimated

error in E_D caused by radial and azimuthal variations was constant over the entire $D_{\_D}$ range for different reasons. For radial variation, the contribution of the outer xylem to E_T was much larger than the contributions of the middle and inner xylem because the average J_S of the middle and inner xylem (9.3%) was much smaller than the average J_S of the outer xylem (2.1%). As a result, the effect of changes in radial variation on the estimate of E was trivial due to the small contribution of the middle and inner xylem. Meanwhile, the error in E estimates caused by not considering azimuthal variation in the Korean pine trees (12.6%) was minimal compared with the errors introduced when radial (109.2%) and tree-to-tree variations (24.3%) were ignored (Table 3 in Moon et al. 2015); therefore, its changes yielded no appreciable error in E estimates.

For tree-to-tree variation, the E_D exhibited large variation compared with the E_D for radial and azimuthal variations, and it had two distinct relationships with $D_{\_D}$ (Figure 4). The large variation was mainly related to low $D_{\_D}$ and was negatively correlated with $D_{\_D}$ (the regression line in Figure 4). The probable reason for the large variation is the small mean J_{S_D} on low $D_{\_D}$ days due to a lower water demand. In other words, the relative error caused by the same amount of variation would be larger on low $D_{\_D}$ days. Therefore, the effect of these changes on E estimates might be minor for long-term E estimation.

4 Conclusions

We assessed the changes in the spatial variations in relation to environmental factors in the stand and their effects on the E estimation because J_S spatial variations were potentially dependent on the stand's environmental conditions. Our results clarified the importance of spatial variation to J_S. Nevertheless, this study suggests that considering the changes in spatial variations in Korean pine trees was not necessary to accurately estimate E, especially at high $D_{\_D}$ (i.e., $D_{\_D} \geq 0.6$ kPa). In other words, although the errors in E estimates caused by not considering radial, azimuthal, and tree-to-tree variations were substantial (i.e., 107%, 15.2%, and 26.1%, respectively), the amount of error in E estimates did not vary during the study periods even when there was a high demand for transpiration. For radial variation, the constancy of the errors in the E estimates could be attributed to a large contribution from the outer xylem compared with the contributions of the middle and inner xylem. For azimuthal variation, there was only a minor contribution to the error in the E estimates. Although the error in the E estimates that was introduced by not considering tree-to-tree variation varied with $D_{\_D}$, the results indicated that its value was constant, except when the transpiration demand was low. These results imply that the effect of spatial variations changes on sap flow can be a minor source of error compared with spatial variations (radial, azimuthal and tree-to-tree variations) when considering E estimates.

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