Changes in canopy transpiration due to thinning of a *Cryptomeria japonica* plantation

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Abstract:

There is a strong pressing to clarify the effect of thinning coniferous plantations on components of the forest water cycle in Japan. This study evaluates changes in canopy transpiration (E) due to thinning of a *Cryptomeria japonica* plantation, the most common type of plantation in Japan. Using E derived with the sap-flux method, we modeled canopy conductance (G_c) for periods before thinning and after thinning with the input of the vapor pressure deficit separately. We hypothetically calculated E values using these G_c models, respectively, under the same meteorological conditions. The ratio of E estimated using the G_c model after thinning to that before thinning was 56%. This value was comparable to the ratio of the total sapwood area for the stand (A_s) before thinning to that after thinning (63%). This suggests the possibility of predicting the relative change in E due to thinning using data for the mean diameter at breast height and stem density for the target stand before and after thinning, which are readily available for most *C. japonica* plantations in Japan and are used to predict A_s .

KEYWORDS canopy conductance; *Cryptomeria japonica*; sap-flux method; sapwood area; thinning; transpiration

INTRODUCTION

Forests are often situated upstream of urban and agricultural areas, and the water cycle in forested areas affects water resources downstream (Vertessy *et al.*, 2001). The effect of forestry practices (e.g., clearcutting, afforestation, and thinning) on the water cycle of a forest is an important topic in forest hydrology. Numerous studies (e.g., Komatsu *et al.*, 2008a) have examined changes in catchment runoff due to forestry practices. Besides these studies, recent studies (e.g., Forrester *et al.*, 2012) have examined changes in various components of the forest water cycle (e.g., transpiration and interception evaporation) due to forestry practices. Such examinations enhance our understanding of processes underlying changes in catchment runoff.

In Japan, there is a strong need to clarify the effect of thinning on components of the water cycle for coniferous plantations (Komatsu *et al.*, 2007). Coniferous plantations

cover approximately 40% of the forested area in Japan. These plantations need to be thinned twice or three times before they are harvested at an age of ~50 years. Such thinning has been phased out since 1980 mainly because of an increase in the importation of cheap timbers and woody products from other countries and an increase in employment costs. Several leading researchers in Japan (Tsukamoto, 1998; Kuraji, 2003) pointed out that plantations that have not been thinned could consume more water by evapotranspiration from the dense canopies and reduce catchment runoff and water resources.

Among components of evapotranspiration, several studies (Hattori and Chikaraashi, 1988; Murai and Kumagai, 1989) have examined changes in interception evaporation due to thinning of coniferous plantations in Japan. On the other hand, information on changes in canopy transpiration (E) induced by thinning of coniferous plantations in Japan is quite limited. There has been only one study (Morikawa *et al.*, 1986) that examined changes in E due to thinning. Further, there have been no studies examining changes in E due to thinning of *Cryptomeria japonica* plantations, although *C. japonica* is the most dominant plantation species.

This study aimed to evaluate changes in E due to thinning of a *C. japonica* plantation. We used data for meteorological factors and E derived using the sap-flux method for two months in growing seasons before thinning and after thinning. As E is the multiplicative product of the sapwood area (A_s) and the mean sap flux per unit sapwood area (J_s) for the stand (Kumagai *et al.*, 2007), the change in E relates to changes in A_s and J_s . Our hypothesis was that the change in E would be primarily due to the change in A_s , and therefore, the relative change in E due to thinning would be comparable to that in A_s . We developed this hypothesis on the basis of the results of Kumagai *et al.*'s (2007) study. Kumagai *et al.* (2007) examined differences in E between two *C. japonica* stands with different stand structure (i.e., stem density, the diameter at breast height (DBH), and tree height). They reported that the difference in E between stands was primarily due to the difference in A_s . There are several studies (e.g., Lagergren *et al.*, 2008) reporting relatively small differences in E between thinned and control plots (or before and after thinning) especially for drought periods, because the practice of thinning could relax soil-water competition among trees by reducing interception evaporation and canopy transpiration. This process was not considered in our hypothesis. Soil-water competition is not expected to be severe in Japan, because precipitation is

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generally higher than potential evaporation (Komatsu *et al.*, 2008b).

MATERIALS AND METHODS

Site description

We used data for meteorological factors and E obtained at the Yamanokami site. The site is situated 12 km east of Fukuoka city, Japan (33°38'N, 130°31'E, 100 m a.s.l.). The mean air temperature, recorded between 1995 and 2005 at a meteorological observatory situated 15 km from the site, was approximately 17.2°C. The mean annual precipitation was 1790 mm.

The site was approximately 0.12 hectare in area and located on an east-facing slope of a small hill. The site was covered with *C. japonica* plantations with an age of 39 years in 2010. Surrounding vegetation was broadleaf forest. Thinning was performed uniformly at the site in October 2010. Note that thinning of coniferous plantations in Japan is generally performed during fall–winter. Trees to be cut were selected randomly and pruning of the remaining trees was not performed.

Data on meteorological factors were recorded at a station in an open space situated adjacent to the site (Supplement Text S1). Data for E were recorded at a 10 m × 10 m plot located in the middle of the slope. Stand structure for the plot before and after thinning is summarized in Table I. The ratio of A_s after thinning to that before thinning was 63%. (Measurements of the sapwood area are detailed later in the text.)

Data

Data for E were determined from sap flux measurements using the thermal dissipation method with Granier-type sensors (Granier, 1987, Supplement Text S2). Sap flux measurements were made for all trees in the plot during August 2010–September 2011. A sensor was inserted, before thinning, on the northern inside of each tree at a depth of 0–20 mm to measure sap flux density (F_d), i.e., radial and circumference variations in F_d were not considered in this

study. We aimed to assess changes in E due to thinning relative to E recorded before thinning. This assessment would be possible even when neglecting radial and circumference variations in F_d because of the correlation between F_d values for different directions/depths for *C. japonica* trees (Shinohara *et al.*, 2013). Furthermore, the following information could legitimize our experimental design. Consideration of radial and circumference variations in F_d is less important than that of tree-to-tree variations for estimating E of a *C. japonica* plantation (Shinohara *et al.*, 2013). F_d decreases with depth for *C. japonica* trees (Kumagai *et al.*, 2007) and the sapwood area at a depth of 0–20 mm for the plot was approximately 80% of the total sapwood area for the plot.

Using F_d data, we estimated E during August–September 2010 and August–September 2011 (i.e., the same months of the year before and after thinning) because we aimed to model canopy conductance (G_c) before and after thinning under similar meteorological conditions. When F_d data for a tree were unavailable in a specific period, we filled the data gap using the relationship for F_d between the tree and another tree. Using these data, E was estimated as (Kume *et al.*, 2010)

$$E = \frac{\sum_{i=1}^n F_{di} \cdot a_{Si}}{A_G} \quad (1)$$

where a_s is the tree sapwood area, n is the number of the trees included in the plot, and A_G is the ground area. a_s was determined on the basis of measurements of sapwood thickness. Sapwood thickness was determined for all individuals in the plot using a ruler on a core extracted with a 5-mm increment borer at 1.3 m above the ground and assessed as the mean of two orthogonal measurements. Distinct color differences were used to identify the boundary between sapwood and heartwood. a_s was obtained from the difference between the heartwood area and the stem cross-sectional area beneath the bark, where we assumed that the stem cross-sections were circular. In sapwood of *C. japonica*, a “white zone”, the water content of which is much lower than that of the heartwood, exists adjacent to the heartwood. There is no water movement in the white zone (Kumagai *et al.*, 2005). The width of the white zone was assumed to be 10 mm, as in Kumagai *et al.* (2007). The area of the white zone was subtracted from the sapwood area to determine the sapwood area effective for water movement (i.e., a_s)

Methods of analysis

We first calculated and modeled canopy conductance (G_c) with the input of meteorological factors separately for the periods before and after thinning. We then hypothetically calculated E using the G_c models before and after thinning under the same meteorological conditions and assessed the change in E due to thinning.

We calculated G_c using the simplified Penman–Monteith equation (McNaughton and Black, 1973):

$$G_c = \frac{\gamma \lambda E}{c_p \rho D}, \quad (2)$$

Table I. Stand structure of the plot for transpiration measurements

Parameter	Before thinning	After thinning* ¹
The number of trees	11	6
Stem density (stems ha ⁻¹)	1100	600
Leaf area index* ² (m ² m ⁻²)	4.7	2.3
Mean DBH* ³ (cm)	28.9 (6.1)* ⁴	31.6 (5.4)
Total basal area (m ² ha ⁻¹)	75.1	48.1
Mean tree height (m)	21.2 (1.7)	22.1 (1.4)
Total sapwood area (A_s , m ² ha ⁻¹)	22.4	14.1

*¹ We calculated the mean DBH, total basal area, mean tree height, and total sapwood area after thinning from measurements made on March 3, 2010; i.e., before thinning. We thus assumed that temporal changes in these parameters due to tree growth were negligible.

*² Measured using the plant-canopy analyzer (LI-2000, Li-Cor Inc., Lincoln, Nebraska, USA) on September 28, 2010 and August 31, 2011 (i.e., before and after thinning, respectively).

*³ Diameter at breast height

*⁴ A numeral in the parentheses indicates the standard deviation.

where γ is the psychrometric constant, λ is the latent heat of water vaporization, c_p is the specific heat of air, and ρ is the air density. This equation is derived from the Penman–Monteith equation under the assumption of complete coupling between the canopy and atmosphere (see Supplement Text S3). G_c was calculated as a daily average conductance using mean daytime T and D , and E summed over 24 hr but divided by daylight hours (Phillips and Oren, 1998). G_c calculations were made only for days without rain, because F_d data could be subject to noise on rainy days (Kumagai *et al.*, 2008).

Using G_c data, we developed separate G_c models before and after thinning. We assumed that D and solar radiation (S) were the possible factors to be considered in our G_c models. As D is generally the most important factor determining G_c , we regressed the relationship between D and G_c on the basis of the least-squares method, to determine the function expressing the effect of D on G_c ($f(D)$) (Oren *et al.*, 1999):

$$f(D) = G_{c\text{ref}}(1.00 - s \ln(D)), \quad (3)$$

where $G_{c\text{ref}}$ and s express the reference value for G_c and the relative sensitivity of G_c to D , respectively. We used G_c data recorded when S was no less than 400 W m^{-2} for this regression, because G_c was light-saturated under this condition for *C. japonica* stands examined by Kumagai *et al.* (2008). We then examined correlation between S and observed G_c divided by $f(D)$ to determine whether S needed to be considered.

For the assessment of the change in E due to thinning, we calculated E using G_c models separately determined using data before and after thinning. For these hypothetical calculations, we used meteorological data for August and September 2011 as input (Supplement Text S4). We confirmed that our results did not change qualitatively when using meteorological data obtained in August and September 2010.

RESULTS

Figure 1 shows time series of meteorological factors and E in August and September 2010 and in August and September 2011. There was frequent precipitation in both years (Figure 1a and 1b). The total P values were 304.0 and 581.5 mm, respectively. S did not show clear temporal trends in either year (Figure 1c and 1d). Day-to-day variations in S generally corresponded to P . T tended to be higher in August than in September for both years (Figure 1e and 1f), although a reduction in T was observed in mid-August 2011. Day-to-day variations in D generally corresponded to those in T (Figure 1g and 1h). E was higher for 2010 than for 2011 (Figure 1i and 1j). Day-to-day variations in E generally corresponded to those in D in both years. The total E values were 71.0 and 37.3 mm, respectively.

We observed significant ($p < 0.01$) negative ($R = -0.716$ and $R = -0.590$, respectively) correlations between D and G_c with S no less than 400 W m^{-2} for 2010 and 2011 according to a two-tailed Pearson's correlation coefficient test (Figure 2). Regressing the relationship between D and G_c for 2010, $G_{c\text{ref}}$ and s for 2010 were determined as 0.00341 m s^{-1} and $0.432 \ln(\text{kPa})^{-1}$, respectively. Similarly,

$G_{c\text{ref}}$ and s for 2011 were determined as 0.00190 m s^{-1} and $0.430 \ln(\text{kPa})^{-1}$, respectively. s was nearly the same for the two years, indicating that the difference in G_c between 2010 and 2011 for a given meteorological condition was primarily due to the difference in $G_{c\text{ref}}$. The correlation between observed G_c divided by $f(D)$ and S was not significant ($p >$

Figure 1. Time series of meteorological factors and canopy transpiration (E); (a, b) daily precipitation (P), (c, d) daytime-mean (6 a.m.–6 p.m.) solar radiation (S), (e, f) daytime-mean temperature (T), (g, h) daytime-mean vapor pressure deficit (D), and (i, j) daily E for August and September 2010 and for August and September 2011, respectively. Data for E on September 30, 2010 were missing, because data on sap flux density were unavailable on that day for all trees

Figure 2. Relationships between vapor pressure deficit (D) and canopy conductance (G_c) with solar radiation no less than 400 W m^{-2} for (a) August and September 2010 and (b) August and September 2011. The solid line is the regression line determined by the least-squares method

0.10) for either 2010 or 2011 (Figure 3), suggesting that taking S into account did not improve the predictability of G_c models developed in this study. Additionally, correlation between observed G_c divided by $f(D)$ and the number of successive days with P less than 5 mm day^{-1} before the G_c data recorded was not significantly negative ($p > 0.10$), suggesting unimportance of soil water content in determination of G_c . Thus, G_c (in m s^{-1}) for 2010 and 2011 were respectively modeled as (see Supplement Text S5)

$$G_c = 0.00341 (1.00 - 0.432 \ln(D)) \quad (4)$$

and

$$G_c = 0.00190 (1.00 - 0.430 \ln(D)). \quad (5)$$

Figure 4 shows E values calculated using the G_c models for 2010 and 2011, respectively, with input of the same meteorological data (i.e., those recorded in August and September 2011). E calculated using the G_c model for 2010 was higher than that calculated using the G_c model for 2011 throughout the period. The total E was 67.0 mm for the G_c model for 2010 and 37.3 mm for 2011. The ratio of the latter

Figure 3. Relationships between solar radiation (S) and observed canopy conductance (G_c) divided by the function expressing the dependency of G_c on the vapor pressure deficit (i.e., $f(D)$) for (a) August and September 2010 and (b) August and September 2011. Solid lines indicate the regression lines determined by the least-squares method

Figure 4. Time series of canopy transpiration (E) calculated with the G_c model determined using data for August and September 2010 and August and September 2011. These calculations were made using meteorological data recorded in August and September 2011

relative to the former was 56%. This ratio was comparable to the ratio of A_s before thinning to that after thinning (63%). E for each day determined using the G_c model for 2011 strongly correlated with that determined using the G_c model for 2010 ($R > 0.99$, $p < 0.01$), which agrees with the fact that s was nearly the same for 2010 and 2011.

DISCUSSION

The relative change in E due to thinning was comparable to that in A_s for our case. This is expected on the basis of the assumption that P is generally higher than potential evaporation (E_p) in Japan. The data used in this study indeed satisfy this assumption. The total E_p values for August and September 2010 and for August and September 2011 were estimated as 283 and 254 mm , respectively (Supplement Text S6), on the basis of observed meteorological data (Figure 1). The total P values for these periods were 304.0 and 581.5 mm , respectively. Thus, P is higher than E_p in both periods.

The assumption of higher P than E_p is generally valid in an average year in Japan, implying that our results would be reflective of most cases in Japan. This is supported by the data presented by Morikawa *et al.* (1986), who carried out another study on changes in E due to thinning for a coniferous plantation in Japan. Morikawa *et al.* (1986) did not explicitly present A_s data for their plot and therefore did not compare the relative change in E with that in A_s . However, it is possible to estimate A_s for their plot using data for the DBH and stem density (Table 1 of Morikawa *et al.*, 1986) and the relationship between DBH and a_s (Figure 1 of Morikawa *et al.*, 1986). A_s values before and after thinning are estimated as 23.3 and $17.4 \text{ m}^2 \text{ ha}^{-1}$, respectively. Thus, the relative change in A_s is 74%, which is comparable to that in E (79%). There are very few studies reporting both changes in E and A_s due to thinning of forests not only in Japan but also in other countries. However, the results of Gebauer *et al.* (2011) examining transpiration at a single-tree scale seem to support our discussion (Supplement Text S7).

It is possible that the assumption of P being higher than E_p is not satisfied for specific periods in a low-precipitation year in Japan. The relative change in E due to thinning might be less than that in A_s in such cases. Thinning would relax soil-water competition among trees by reducing interception evaporation and canopy transpiration. This results in less significant reduction in transpiration during drought periods for a thinned plot than for a control plot. Several studies (Simonin *et al.*, 2007; Lagergren *et al.*, 2008) have observed such a phenomenon. Simonin *et al.* (2007) measured E for a pine forest. They reported considerable differences in E between thinned and control plots when soil water content was high. However, the difference was much less when the soil water content was low. Lagergren *et al.* (2008) conducted measurements in a pine–spruce forest and compared E between thinned and control plots. E for the thinned plot was generally lower than that for the control plot in the first year after thinning. However, E for the thinned plot was rather higher than that for the control plot in the drought period (July–September) of the year when soil water content was low owing to low precipitation. We thus recommend

further studies examining E for coniferous plantations in Japan before and after thinning using E data recorded in low-precipitation years.

Thinning could improve a light environment in the stand and increase E relative to A_s or tree-scale transpiration (Tang *et al.*, 2003). In reality, we did not obtain any evidence of such an increase for our site. This result would not change even when the intensity and/or method of thinning were different from those for this study. We obtained no evidence of an effect of S on G_c even for the case before thinning (Figure 3a). This suggests insignificant light competition among trees for our site, because the relationship between S and G_c reflects the change in stomatal conductance with S , and therefore our results suggest light saturation of stomatal conductance even for the case before thinning. Thus, the improved light environment induced by thinning would not contribute to increasing stomatal conductance for our site. When we analyzed the data at hourly (or half-hourly) time resolution, we might observe evidence of an effect of S on G_c (Komatsu *et al.*, 2006). However, this effect is unimportant in determination of G_c and E at daily or longer time scales (Figure 3).

Evidence of an effect of S on G_c for forests has been reported in previous studies including that made by Kumagai *et al.* (2008) on *C. japonica* stands. Thinning might increase E relative to A_s or tree-scale transpiration for such cases. However, we presume that this increase would not be considerable. Variations in the relationship between S and G_c cause slight differences in E for forests at daily or longer time-scales (Komatsu, 2004). Indeed, most studies examining changes in E due to thinning at these scales did not observe evidence of an increase in E due to the improved light-environment by thinning (Whitehead and Kelliher, 1991; Lagergren *et al.*, 2008).

This study did not attempt to examine gradual changes in E after thinning that might persist for several years. Previous studies for other species (Bréda *et al.*, 1995; Lagergren *et al.*, 2008) reported such gradual changes in E for several years after thinning. Measurement studies at a multi-year scale are required to examine whether such gradual changes in E could occur for *C. japonica* plantations in Japan. Our results have implications for such changes. Water and light competition just after thinning would be less significant than that for the succeeding years. However, the change in E was comparable to that in A_s , i.e., J did not increase due to thinning, according to data recorded just after thinning. This suggests that J for the succeeding years would be nearly the same as that just after thinning and that the change in E for the years would be caused primarily by the change in A_s , if meteorological factors for the years did not differ greatly from those for the experimental period of this study.

An increase in leaf area for the succeeding years could cause an increase in E . However, the increase in leaf area would accompany an increase in a_s and therefore that in A_s according to the pipe-model theory (Shinozaki *et al.*, 1964a,b) and observation results for other species (Medhurst and Beadle, 2002). Therefore, an increase in E caused by the increase in leaf area would be regarded as corresponding to the increase in A_s . Here, we assumed that the relationship between leaf area and a_s for an unthinned tree does not change by thinning. Although this assumption is valid for

several species (Medhurst and Beadle, 2002), it is unclear whether it is the case for *C. japonica* trees. Further studies examining this uncertainty are required.

It is, at this stage, unclear whether the relative change in E is generally comparable to that in A_s for *C. japonica* plantations in Japan. If this is the case, it suggests the possibility of predicting the relative change in E due to thinning on the basis of data for stem density and the mean DBH for a stand before and after thinning. Tsuruta *et al.* (2011) found a linear relationship between the DBH and a_s for *C. japonica* trees (and a similar relationship for *C. obtusa* trees). If we input data for the mean DBH and stem density for a stand before and after thinning, we can obtain data for A_s before and after thinning of the stand. On the basis of these A_s data and the assumption that the relative change in E is equal to that in A_s , we can predict the relative change in E due to thinning. This method for predicting the relative change in E is practically useful. Data required for the prediction are the mean DBH and stem density. These data are generally available for most *C. japonica* (and also *C. obtusa*) plantations in Japan. Besides A_s , the leaf area index (LAI), stem density, and basal area could be used to predict the relative change in E due to thinning (Table I). The use of A_s or LAI is more process-based than the use of the stem density or basal area, because A_s and LAI directly relate to E . The use of A_s is more practical than the use of LAI, because the error in A_s estimates would be generally less than that in LAI estimates (Tsuruta *et al.*, 2012).

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SUPPLEMENTS

Text S1. Measurements of meteorological factors
Text S2. Granier-type sensors
Text S3. Use of the simplified Penman–Monteith equation
Text S4. Interaction between transpiration and meteorological factors
Text S5. Comparison of the model parameters determined
Text S6. Potential evapotranspiration estimates
Text S7. Change in tree-transpiration with thinning
Figure S1. Relationships between the vapor pressure deficit (D) and canopy transpiration (E)
Figure S2. Relationships between the vapor pressure deficit (D) and tree transpiration

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