1 The effect of strip thinning on tree transpiration in a Japanese cypress
2 (*Chamaecyparis obtusa* Endl.) plantation

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ABSTRACT

This study analyzes the effect of strip thinning on tree transpiration (E_t) in a dense and mature Japanese cypress (*Chamaecyparis obtusa* Endl.) plantation in central Japan. Strip thinning, which removed 50% of stems, was conducted in a headwater basin in October 2011. Xylem sap flow densities (F_d) were measured using thermal dissipation (Granier-type) sensors in a 156-m² plot before and after thinning. The canopy conductance (G_c) was calculated on the basis of E_t values. The results revealed that the F_d at the outer xylem (0-20 mm) increased remarkably, whereas the F_d at the inner xylem (20-40 mm) had no significant change after thinning. Mean stand sap flow density (J_s) values were higher in the post-thinning period than in the pre-thinning period, and the differences significantly increased with increasing vapor pressure deficit (VPD) values. Furthermore, the daily single tree E_t increased, particularly in the small tree class. Unlike the daily tree E_t , the daily stand E_t decreased from 1.29 ± 0.60 to 1.00 ± 0.40 mm d⁻¹ during the growing season or decreased from 1.23 ± 0.48 to 0.74 ± 0.42 mm d⁻¹ on the annual scale. The total stand E_t decreased by 23.0%, from 214.9 to 165.5 mm, during the growing season or decreased by 38.3%, from 441.0 to 272.1 mm, on the annual scale. G_c decreased after thinning, which implies lower stand E_t and photosynthesis. G_c was primarily related to the VPD and would be an effective model to predict E_t from these Japanese cypress plantations. This study provides useful information for understanding the E_t responses at individual tree and stand levels to strip thinning and contributes to obtaining a thorough understanding of the change in tree water use under different management strategies.

35 **Keywords**

36 Canopy conductance; *Chamaecyparis obtusa*; Granier-type sensor; Sap flow; Strip thinning;

37 Transpiration

1. Introduction

Tree transpiration (E_t) is a main part in the forest water balance and for modeling water, energy and carbon exchange in the forest ecosystem. In coniferous forests, E_t may account for approximately 19.0-72.4% of evapotranspiration for different species and climates (Sun et al., 2013b). E_t is influenced by environmental variables, including vapor pressure deficit, solar radiation, wind speed and temperature (Morikawa et al., 1986; Granier et al., 1996b; Oren et al., 1999; Clausnitzer et al., 2011), and by the availability of soil water within the rooting zone (Black et al., 1980; Breda et al., 1995; Simonin et al., 2007; Sun et al., 2013b). The thinning of forests results in more open stand canopies. Accordingly, the remained individual trees have apportioned a higher availability of site resources (e.g., soil water) due to thinning treatment (Black et al., 1980; Breda et al., 1995; Morikawa et al., 1986). However, thinning can affect various factors that influence the growth rate of trees, and it is difficult to determine the single most important factor affecting tree water use (Medhurst et al., 2002). Therefore, studies regarding changes in E_t that are induced by thinning are necessary for predicting tree water use and for guiding integrated forest and water management.

Among several methods for quantifying E_t at both temporal and spatial scales, the thermal dissipation sap flow technique (Granier, 1987) is the most useful, particularly in mountainous countries such as Japan because complex terrain and spatial heterogeneity does not restrain its applicability (e.g., Wilson et al., 2001). This technique can be effectively applied to estimate the tree water use on a continuous basis, which has made it feasible to examine the thinning effects on water uptake and E_t at both tree and stand levels, at a high

60 temporal resolution. When climatic data are properly collected simultaneously with sap flow
61 data, this method can supply forceful insights into atmospheric-biological controls of tree
62 water use ([Whitehead, 1998](#)).

63 Several studies have focused on the changes in E_t by thinning in different species
64 (e.g., [Breda et al., 1995](#); [Lagergren et al., 2008](#); [Morikawa et al., 1986](#); [Reid et al., 2006](#);
65 [Simonin et al., 2006, 2007](#); [Stogsdill et al., 1992](#)). For example, [Morikawa et al. \(1986\)](#)
66 reported that the stand E_t decreased by 21.2% after 24% thinning in a Japanese cypress
67 (*Chamaecyparis obtusa* Endl.) forest. In addition, the daily single tree E_t was higher at a
68 given range of solar radiation, except in the small tree class. [Breda et al. \(1995\)](#) reported that
69 thinning caused the stand E_t value to decrease in the thinned plot of an oak forest for the first
70 year, whereas the stand E_t approached the same level as that on the control plot after two
71 years of thinning. Furthermore, the difference in the stand E_t between the thinned and the
72 control plot may not significantly decrease due to the drought periods. [Simonin et al. \(2007\)](#)
73 found that the difference in the stand E_t between the thinned and the control plot was much
74 less when the soil water content was low in semi-arid *Pinus ponderosa* forests. [Lagergren et](#)
75 [al. \(2008\)](#) reported that the stand E_t in the thinned plot was rather higher than that in the
76 control plot during the drought period in a mixed pine-spruce forest in Sweden.

77 In Japan, forests cover 67% of the total land area, and approximately 40% of the
78 forested land area is composed of coniferous plantation forests ([National Astronomical](#)
79 [Observatory, 2009](#)). Japanese cypress and Japanese cedar (*Cryptomeria japonica* D. Don) are
80 the main two coniferous plantation species. However, these plantations received no
81 management practices and have been abandoned since their planting, primarily after the

82 Second World War, because of low wood value and high labor costs (Iwamoto, 2002). As a
83 result, the lack of management leads to high stem density, dense canopy density, and sparse
84 or no understory vegetation, particularly in Japanese cypress forests (Onda et al., 2010).
85 Therefore, these cypress plantations need to be thinned about 40-60% to induce recovery of
86 understory vegetation (Sun et al., 2013b). However, previous studies only examined changes
87 in E_t by light thinning (removing 24% of stems) (Morikawa et al., 1986) or during a short
88 measuring period (two months before and after thinning, respectively) (Komatsu et al., 2013).
89 Until now, little data have been available to document the changes in E_t induced by heavy
90 thinning during a long measurement period for Japanese coniferous plantations.

91 Strip thinning, which is a heavy and cost-effective thinning method, has been
92 extensively carried out in these poorly managed plantation stands in Japan primarily because
93 this method does not need to select trees that are involved in conventional selective thinning
94 operations and thus requires less time and skill (Taniguchi, 1999), whereas it cannot
95 effectively improve the stand structure. Furthermore, strip thinning results in different
96 changes in the canopy density and in the structure of the forest compared with other forestry
97 practices (e.g., selective thinning and partial cutting). The different forest structures can lead
98 to resultant changes in environmental variables (Oguntunde and Oguntuase, 2007; Wilson et
99 al., 2000), in the availability of soil water (Aboal et al., 2000; Molina and del Campo, 2012;
100 Stogsdill et al., 1989), and in boundary layer conductance (Teklehaimanot et al., 1991). For
101 example, Teklehaimanot et al. (1991) reported that the greater ventilation (i.e., wind speed)
102 with an increase in tree spacing resulted in greater boundary layer conductance per tree in
103 *Picea sitchensis* (Bong.) Carr forest stands. Thus, E_t responses to different management

104 strategies would be different. However, studies on the strip thinning effect on E_t are limited
105 and are necessary for achieving an optimized water and forest management.

106 This study aimed to examine the effect of strip thinning on E_t at individual tree and
107 stand levels for a Japanese cypress plantation. The study period was divided into the pre-
108 thinning period (November 2010 – October 2011) and the post-thinning period (November
109 2011 – October 2012). Sap flow densities were measured using thermal dissipation (Granier-
110 type) sensors.

2. Methods

2.1. Site description

Our study was carried out in a 156-m² plot (12×13 m) at a mean elevation of 198 m on a mountain slope (31°) with southwest exposure. The study plot is in the headwater catchment K2 in Mt. Karasawa, Tochigi Prefecture (36°22' N, 139°36' E), central Japan (Fig. 1a). The forest in catchment K2 consists of even-aged 32-year-old Japanese cypress stands. However, these plantations have been abandoned since their planting (Sun et al., 2013a). The drainage area is 13.3 ha. The understory vegetation is nonexistent or sparse and primarily consists of fern and evergreen shrubs. The soil is orthic brown soil of cambisols, with a silt-loam texture. The climate in this study area is humid and temperate. The average annual temperature and precipitation between 1991 and 2011 was 14.1 ± 0.6 °C and 1265 ± 220 mm, respectively. The detailed characteristics of the study site can be referred from Sun et al. (2013b).

2.2. Thinning treatment

Strip thinning, which includes each interval of two lines of trees that were felled, was performed in catchment K2 in October 2011 (Fig. 1b). All thinning operations were conducted by forest workers using no-heavy machinery, except for chainsaws, to minimize the soil disturbance on the hillslope. All twigs, branches, and timber from thinned trees were removed from the stand. In total, 50% of the stems were felled, corresponding to 48% of the basal area. The number of trees in the plot decreased from 27 to 13. The stand density decreased from 2198 to 1099 trees ha⁻¹. The basal area was reduced from 50.4 to 26.2 m² ha⁻¹. The canopy density diminished from 0.974 to 0.758. The change in diameter at breast height (DBH) was relatively small, decreasing from 19.1 to 18.9 cm (Table 1).

2.3. Measurements

2.3.1. Meteorological conditions

Meteorological conditions, including gross precipitation (P_g), wind speed and direction, solar radiation (R_s), temperature (T) and relative humidity (RH), were measured using an automatic weather station (HOBO U30-NRC Weather Station; Onset Computer Corporation, MA, USA). It was located ~250 m northeast of the study plot in an open space along a forestry road. The weather station was placed on the edge of the forestry road where its height was higher than trees because of steep slope gradient, and its distance from the other edge of forest road was far enough that it cannot be influenced by tree canopies on the meteorological measurements. P_g was measured at 2 m height above ground using a recording rain gauge with 0.2 mm per tip. T , RH and R_s were measured at 2 m height above ground. Wind speed and direction were measured at 2.5 m height above ground. Data was stored using a data logger at 5 min intervals.

2.3.2. Sap flux measurements

The sap flux density (F_d) measurements were carried out by the thermal dissipation method, using Granier-type sensors ([Granier, 1987](#)). Each sensor was 20 mm in length and 2 mm in diameter. Three sensors were installed approximately 0.15 m circumferentially apart at ~1.3 m in height at north azimuthal aspect. The upper two sensors included a heater that was supplied with a 0.2 W constant power, and were inserted in each selected tree at depths of 0-20 and 20-40 mm to cover the entire sapwood (mean sapwood depth: 31 ± 7 mm). The lower sensor was inserted at a depth of 0-20 mm, representing the sapwood temperature. The

recorded temperature difference between the upper two heated sensors and the lower unheated reference sensor was converted into F_d as described by Granier (1987). All signals were recorded every 30 s, and averaged at 30 min interval on a data logger (CR1000, Campbell Scientific, Logan, UT, USA) with a multiplexer (AM 16/32, Campbell Scientific). A complete description of the measurements is available in the study of Sun et al. (2013b).

We measured F_d in 10 trees before thinning. After thinning, six trees were left (Table 1). The frequency distributions of DBH showed in Fig. 2 represents the corresponding number of sample trees. The sampled trees were divided into three tree classes: large, medium and small, and the number and mean DBH with standard deviation for each tree class are summarized in Table 2. Sap flow measurements began on April 28, 2011, and the measuring period is shown in Fig. 3.

2.3.3. Individual and stand-scale transpiration

The value calculated from F_d measurements represents tree water uptake rather than whole-tree transpiration (E_{t-tree}) because of a time lag between the sap flow measured at the stem and transpired at the canopy (e.g., Kumagai, 2001). However, for Japanese cypress plantations, Kumagai et al. (2009) found that there were no significant differences between the daily stem sap flow and the daily E_{t-tree} . Therefore, we regarded the daily stem sap flow as the daily E_{t-tree} . In this study, the daily E_{t-tree} (kg d^{-1}) was calculated as

$$E_{t-tree} = F_{d_A} \cdot A_{s_tree_A} + F_{d_B} \cdot A_{s_tree_B} \quad (1)$$

where F_{d_A} and F_{d_B} are the sap flow density ($\text{m}^3 \text{ m}^{-2} \text{ d}^{-1}$) at depths of 0-20 and 20-40 mm for the measured tree, respectively, and $A_{s_tree_A}$ and $A_{s_tree_B}$ are the sapwood area

(m²) at depths of 0-20 and 20-40 mm for the measured tree, respectively.

Daily stand-level transpiration ($E_{t-stand}$) (mm d⁻¹) was calculated using the following equation (e.g., [Kumagai et al., 2007](#); [Wilson et al., 2001](#)):

$$E_{t-stand} = J_s \frac{A_{s-stand}}{A_G} \quad (2)$$

where J_s is the mean stand sap flux density (m³ m⁻² d⁻¹); $A_{s-stand}$ is the stand sapwood area (m²); and A_G is the study plot area (m²).

2.3.3. Calculations of potential evapotranspiration and canopy conductance

In this study, potential evapotranspiration (PET) (mm d⁻¹) was calculated as ([Priestley and Taylor, 1972](#))

$$PET = \alpha_{PT} \cdot \left[\frac{\Delta}{\Delta + \gamma} \cdot \frac{R_n - G}{\lambda} \right] \quad (3)$$

where α_{PT} is the Priestley-Taylor constant, $\alpha_{PT} = 1.26$; γ is the psychrometric constant (kPa °C⁻¹); Δ is the slope of the vapor saturation curve (kPa °C⁻¹); λ is the latent heat of water vaporization (MJ kg⁻¹); R_n is the net radiation (MJ m⁻² d⁻¹); and G is the soil heat storage (MJ m⁻² d⁻¹). In the absence of G and R_n measurements, we did not take these terms into account here. We assumed $R_n = 0.8R_s$ and $G=0$ for the context of closed Japanese forests (i.e., leaf area index LAI ≥ 3) ([Komatsu et al., 2007](#)). The other parameters in the above equation were obtained from the automatic weather station.

The environmental control of $E_{t-stand}$ has been characterized in terms of the response of canopy conductance (G_c) to environmental factors (e.g., [Cienciala et al., 2000](#); [Granier et al., 1996a](#); [Kumagai et al., 2004](#); [Meinzer and Grantz, 1990](#)). Thus, the data gap was filled using the G_c model for the pre-thinning period from November 1, 2010 to April 27, 2011.

196 Then we could analyze the annual changes in $E_{t-stand}$ after filling the data gap. The G_c was
197 calculated on the basis of the following simplified Penman-Monteith equation (McNaughton
198 and Black, 1973):

$$199 \quad G_c = \frac{\gamma \cdot \lambda \cdot E_{t-stand}}{c_p \cdot \rho \cdot VPD} \quad (4)$$

200 where c_p is the specific heat of air at constant pressure ($\text{MJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$); ρ is the air density
201 (kg m^{-3}); and VPD is the above canopy atmospheric vapor pressure deficit (kPa).

202 This equation is obtained by assuming a complete coupling of the canopy with the
203 atmosphere (Kumagai et al., 2009; Komatsu et al., 2012). Furthermore, we calculated the G_c
204 as a daily average conductance using the mean daytime T and VPD . However, the $E_{t-stand}$
205 was summed over 24 h but divided by daylight hours (Phillips and Oren, 1998). The G_c
206 values were calculated only for no-rainy days, because the F_d data could be subject to noise
207 on rainy days (Kumagai et al., 2008). Daylight hours refer to photosynthetically active
208 radiation (PAR) $> 0 \mu \text{mol m}^{-2} \text{s}^{-1}$. In the present study, the daytime records were taken from
209 06:00 h to 18:00 h.

3. Results

3.1. Environmental conditions and sapwood area estimates in pre- and post-thinning

The time series of meteorological factors in the pre- and post-thinning periods are shown in Fig. 3. The meteorological variables (e.g., RH , T , VPD , R_s and PET) show clear seasonal trends and reached higher values during the growing season (May - October) in both periods. The day-to-day variations in R_s generally corresponded to P_g and were low during the regular rainy season from mid-June to mid-July in Japan. The day-to-day variations in the VPD generally corresponded to those changes in T and RH . The frequency of P_g was almost similar in both periods. The total P_g values were 1444.6 and 1266.8 mm, respectively. The P_g values during the growing season were 1139.8 mm and 869.0 mm, respectively. The total PET values were 1036.1 and 1095.0 mm, respectively. The PET values during the growing season were 618.6 mm and 701.4 mm, respectively (Table 3). The P_g values were higher than PET in the annual and growing season scales, respectively.

A_{s_stand} in the pre-thinning period was $26.1 \text{ m}^2 \text{ ha}^{-1}$ and decreased by 46.4% after 50% thinning (Table 1). The sapwood area at xylem bands of 0-20 and 20-40 mm before and after thinning are also shown in Table 1. Fig. 4 shows the relations between the DBH and A_{s_tree} in the both periods (DBH and A_{s_tree} were measured in/around the observation plot, with 44 trees selected before thinning, and 18 trees left after thinning). The A_{s_tree} in the pre-thinning period ranged from 57.7 to 229.6 cm^2 , with a mean of 150.8 cm^2 , and ranged from 71.9 to 223.1 cm^2 , with a mean of 155.5 cm^2 in the post-thinning period. Power functions of DBH were fitted to A_{s_tree} using linear regression analysis. The R^2 values were 0.83 for both the pre- and post-thinning periods.

3.2. Changes in the F_d caused by thinning

Fig. 5 shows the diurnal courses in the F_d at depths of 0-20 (outer xylem) and 20-40 mm (inner xylem) in the three tree classes (large, medium and small), with the R_s and VPD values on given days without rain (Aug 9, 2011 and Aug 9, 2012) representing the pre- and post-thinning days, respectively. The R_s values were 18.3 and 17.5 MJ m⁻², and VPD values were 1.2 and 1.3 kPa on August 9 in 2011 and 2012, respectively. The climatic conditions are considered similar on these two days, with a moderate atmospheric evaporative demand. The dynamics of the F_d reflected R_s and VPD values; however, the F_d at the outer xylem was more sensitive to climatic conditions in the post-thinning day compared with the pre-thinning day. For example, the F_d decreased sharply when the VPD declined suddenly on August 9, 2012. However, the F_d slightly changed when the VPD decreased abruptly on August 9, 2011.

Furthermore, the F_d decreased with an increase in the measurement depth. In addition, the F_d at the outer xylem obviously increased in the three tree classes, particularly in the small tree class, whereas the F_d at the inner xylem did not significantly change after thinning (**Fig. 5**). The maximum F_d (outer xylem + inner xylem) of the three classes (large, medium and small) increased from 47.15 to 60.41 cm³ m⁻² s⁻¹, from 48.25 to 57.70 cm³ m⁻² s⁻¹ and from 20.91 to 36.88 cm³ m⁻² s⁻¹, respectively. In addition, the daily F_d of the three classes increased by $20.2 \pm 0.5\%$, reaching 1040.24 cm³ m⁻² d⁻¹, by $19.9 \pm 0.4\%$, reaching 990.86 cm³ m⁻² d⁻¹, and by $92.2 \pm 2.1\%$, reaching 610.37 cm³ m⁻² d⁻¹, respectively.

The daily mean stand sap flow densities for xylem bands of 0-20 (J_{S_A}) and 20-40 mm (J_{S_B}) for all measured trees before and after thinning during the growing season are shown in

Fig. 6a. The mean stand F_d measured at radial depths of 0-20 and 20-40 mm consistently

decreased with depth over both periods and varied with meteorological conditions (e.g., VPD and R_s). During the rainy period (e.g., May 22-29, 2011), the sap flow was appreciably reduced due to the low VPD and R_s .

The J_{S_A} values were higher in the post-thinning period than in the pre-thinning period ($P < 0.01$: Mann-Whitney U test), and the differences significantly increased with increasing VPD (Fig. 6b). The daily J_{S_A} values ranged from 0.03 to 1.26 $\text{m}^3 \text{m}^{-2} \text{d}^{-1}$, with a mean of $0.62 \pm 0.31 \text{ m}^3 \text{m}^{-2} \text{d}^{-1}$ in the pre-thinning period, and ranged from 0.06 to 1.72 $\text{m}^3 \text{m}^{-2} \text{d}^{-1}$, with a mean of $0.97 \pm 0.40 \text{ m}^3 \text{m}^{-2} \text{d}^{-1}$, in the post-thinning period. However, unlike the J_{S_A} values, the J_{S_B} values had no significant differences between the two periods ($P > 0.05$: Mann-Whitney U test) (Fig. 6c). The daily J_{S_B} values ranged from 0.02 to 0.58 $\text{m}^3 \text{m}^{-2} \text{d}^{-1}$, with a mean of $0.23 \pm 0.10 \text{ m}^3 \text{m}^{-2} \text{d}^{-1}$ in the pre-thinning period, and ranged from 0.06 to 0.44 $\text{m}^3 \text{m}^{-2} \text{d}^{-1}$, with a mean of $0.22 \pm 0.08 \text{ m}^3 \text{m}^{-2} \text{d}^{-1}$, in the post-thinning period. The changes in J_s values reflected a similar trend compared with the J_{S_A} values and were higher in the post-thinning period than in the pre-thinning period ($P < 0.05$: Mann-Whitney U test). The differences significantly increased with increasing VPD (Fig. 6d). The daily J_s values averaged over the growing season were $0.50 \pm 0.23 \text{ m}^3 \text{m}^{-2} \text{d}^{-1}$, ranging from 0.03 to 1.00 $\text{m}^3 \text{m}^{-2} \text{d}^{-1}$, in the pre-thinning period, whereas the daily J_s values were $0.71 \pm 0.29 \text{ m}^3 \text{m}^{-2} \text{d}^{-1}$, ranging from 0.07 to 1.27 $\text{m}^3 \text{m}^{-2} \text{d}^{-1}$, in the post-thinning period.

3.3. Changes in E_t and G_c caused by thinning

3.3.1. E_{t-tree} response to thinning

The diurnal courses in E_{t-tree} in the three tree classes (large, medium and small) under given similar climatic conditions without rain on Aug 9, 2011 and Aug 9, 2012 are

shown in Fig. 7a. E_{t-tree} correlated with tree sizes and was smallest in the small tree class on both days. Furthermore, E_{t-tree} increased after thinning. The maximum half-hourly E_{t-tree} in the three classes (large, medium and small) increased from 1.069 to 1.361 kg tree⁻¹ 30 min⁻¹, from 0.912 to 1.121 kg tree⁻¹ 30 min⁻¹, and from 0.308 to 0.629 kg tree⁻¹ 30 min⁻¹, respectively. The daily E_{t-tree} in the three classes (large, medium and small) increased by 20.1%, reaching 23.535 kg d⁻¹, by 24.2%, reaching 19.379 kg d⁻¹, and by 121.3%, reaching 10.405 kg d⁻¹, respectively. In particular, the daily E_{t-tree} in the small class significantly increased.

Fig. 7b shows the mean daily sampled E_{t-tree} response to the mean daily daytime VPD in the pre- and post-thinning periods during the growing season. The mean daily E_{t-tree} was 8.382 ± 3.866 kg d⁻¹, ranging from 0.487 to 16.233 kg d⁻¹, in the pre-thinning period, whereas the mean daily E_{t-tree} was 12.314 ± 4.965 kg d⁻¹, ranging from 1.265 to 21.386 kg d⁻¹, in the post-thinning period. The daily E_{t-tree} was significantly higher in the post-thinning period than in the pre-thinning period during the growing season ($P < 0.01$: Mann-Whitney U test). Moreover, the difference between both periods became remarkable with increasing mean daily daytime VPD .

3.3.2. $E_{t-stand}$ response to thinning during the growing season

The daily variations in $E_{t-stand}$, which are related to the mean daily daytime VPD in the pre- and post-thinning periods during the growing season, are shown in Fig. 8. Although J_s values in the post-thinning period increased (Fig. 6d), the daily $E_{t-stand}$ was significantly lower in the post-thinning period than in the pre-thinning period ($P < 0.01$: Mann-Whitney U test) because $A_{s-stand}$ was reduced by 46.4% after 50% thinning (Table 1). The mean daily

298 $E_{t-stand}$ was $1.29 \pm 0.60 \text{ mm d}^{-1}$, ranging from 0.07 to 2.36 mm d^{-1} , in the pre-thinning
 299 period, whereas the mean daily $E_{t-stand}$ was $1.00 \pm 0.40 \text{ mm d}^{-1}$, ranging from 0.10 to 1.77
 300 mm d^{-1} , in the post-thinning period (Table 3; Fig. 8). The total $E_{t-stand}$ during the growing
 301 season was 214.9 mm , accounting for 18.9% of P_g or 34.7% of PET in the pre-thinning
 302 period. After thinning, the total $E_{t-stand}$ decreased by 23.0% and was 165.5 mm , accounting
 303 for 19.0% of P_g or 23.6% of PET (Table 3).

304 3.3.3. G_c response to thinning and model $E_{t-stand}$

305 Fig. 9 shows the relations between the mean daily daytime VPD and G_c for the Japanese
 306 cypress forest during the growing season in pre- and post-thinning periods, respectively. The
 307 G_c was $0.0031 \pm 0.0035 \text{ m s}^{-1}$ in the pre-thinning period, whereas the G_c was 0.0021 ± 0.0017
 308 m s^{-1} in the post-thinning period. We observed significantly ($P < 0.01$) negative correlations in
 309 both periods; thus, the G_c values were modeled before and after thinning, respectively, as:

$$310 \quad G_c = 0.0021 - 0.001 \ln(VPD) \quad R^2 = 0.51 \quad (5)$$

$$311 \quad G_c = 0.0016 - 0.001 \ln(VPD) \quad R^2 = 0.54 \quad (6)$$

312 G_c was estimated based on eq. 5 that used mean daily daytime VPD as input for the
 313 whole pre-thinning period. Then $E_{t-stand}$ during the growing season from April 28 to
 314 October 10, 2011 was predicted using the eq. 4 with the input of estimated G_c as shown in
 315 Fig. 10a. The estimated $E_{t-stand}$ corresponded to the measured values. The correlation
 316 between estimated and measured $E_{t-stand}$ was significant ($P < 0.01$: a two-tailed Pearson
 317 correlation test, $R = 0.807$). Thus, the G_c model was robust in estimating daily $E_{t-stand}$ and
 318 could be used to extend the $E_{t-stand}$ time scale in the Japanese cypress plantation, although
 319 the estimated values were slightly higher than the actual values observed at the beginning of

320 May 2011.

321 **Fig. 10b** shows the time series of the predicted daily $E_{t-stand}$ using the estimated G_c for
322 the pre-thinning period from the November 1, 2010 to October 31, 2011. The daily $E_{t-stand}$
323 at the annual scale was also significantly lower in the post-thinning period than in the pre-
324 thinning period ($P<0.01$: Mann-Whitney U test). The mean daily $E_{t-stand}$ decreased by
325 39.8%, from 1.23 ± 0.48 mm d⁻¹ in the pre-thinning period to 0.74 ± 0.42 mm d⁻¹ in the post-
326 thinning period (**Table 3**). The annual $E_{t-stand}$ in the pre-thinning period was 441.0 mm,
327 accounting for 30.5% of P_g or 42.6% of PET. After thinning, the annual $E_{t-stand}$ decreased
328 by 38.3% and was 272.1 mm, accounting for 21.5% of P_g or 24.8% of PET (**Table 3**; **Fig. 11**).

4. Discussion

4.1. Effect of thinning on A_{s_stand} and J_s

A_{s_stand} in the present study decreased by 46.4% after 50% thinning (Table 1). The sapwood area at xylem bands of 0-20 and 20-40 mm also showed similar trends and declined by 47.5% and by 44.0%, respectively (Table 1). The decline of A_{s_stand} corresponded to the ratio to thinning. A linear relation between DBH and A_{s_tree} was found for Japanese cypress plantations (Fig. 4). Several studies estimated the A_{s_tree} from a power function-based regression (Kumagai et al., 2007; Vertessy et al., 1995; Wullschlegel and King, 2000). However, this regression did not drastically heighten the relation between DBH and A_{s_tree} because the DBH of individual trees were larger than approximately 10 cm in this study plot (Fig. 4). Kume et al. (2009) reported that there was no significant change between the measured and estimated A_{s_tree} using the linear relation between DBH and A_{s_tree} from 58 Japanese cypress trees. A linear relation was also produced from an allometric data set on 1226 Japanese cypress plantations (Kumagai et al., 2005b). These findings can be used to estimate A_{s_tree} according to the allometric data (e.g., DBH) and then to obtain A_{s_stand} for Japanese cypress plantations.

Radial patterns in the F_d declined with depth (Fig. 5, 6a), which have often been investigated in different species (e.g., Kumagai et al., 2005a; Oren et al., 1999), indicating that xylem conductivity decreases quickly with radial depth. The F_d at the outer xylem significantly increased, whereas the F_d at the inner xylem did not significantly change after thinning (Fig. 5, 6b and c). This result indicates that thinning only enhanced the capacity of conducting water at the outer xylem. Furthermore, the effect of tree classes (large, medium

and small) on the F_d showed that the F_d for the three tree classes increased significantly after thinning, particularly for the small class. The differences in the F_d between small trees and dominant trees were reduced due to the thinning treatment (Fig. 5). The transpiration rate (i.e., the physical process of water vaporization) is mostly determined by the amount of available solar radiation above the canopy (Gebauer et al., 2011). For example, in a fully closed Norway canopy, the uppermost 10% of needle biomass intercepted as much as 50% of the incoming solar radiation (Kucera et al., 2002). The higher radiation interception in the upper canopy in turn results in higher transpiration (Moren et al., 2000). Indeed, the F_d was related to the tree class, and co-dominant trees exhibited a lower F_d in *Eperua falcata* forest (Granier et al., 1996b). In this study, the high stand density (2198 tree ha⁻¹) caused an almost fully closed canopy density (canopy density fraction: 0.974); thus, the small trees were partly shaded by dominant trees and experienced lower light before thinning. However, after 50% thinning, solar radiation can penetrate deeper into the lower crowns. Therefore, small trees were able to receive more irradiance, and F_d largely increased.

The dynamic of F_d was more sensitive to climatic variables (e.g., VPD and R_s) after thinning, and the differences in J_s were significantly higher with increasing VPD in the post-thinning (Fig. 5, 6d). This result suggests a higher influence of climatic factors on J_s after thinning. In this study, we did not consider the effect of soil water content on J_s . This was consistent with previous studies (e.g., Komatsu et al., 2006, 2012; Kumagai et al., 2008; Morikawa et al., 1986) without considering the effect of soil water deficit on the examination of E_t and evapotranspiration in Japan. Kumagai et al. (2008) reported that there were no clear relationships between J_s and soil water content at specific soil layers and whole profile, and

thus they excluded the parameter of soil water content affecting J_s when they analyzed the environmental controls on E_t in a Japanese coniferous plantation. In the context of Japan, precipitation is relatively higher than equilibrium evaporation, which could be the possible reason for poor effect of soil water content on J_s (Komatsu et al., 2008).

4.2. Effect of thinning on G_c

The relations between VPD and G_c for Japanese cypress forests during the growing season in pre- and post-thinning periods are shown in Fig. 9. There are significant ($P<0.01$) negative correlations, and the coefficient of determination (R^2) values were 0.51 and 0.54 in the pre- and post-thinning periods, respectively. This result suggests that VPD was the primary factor controlling G_c in the Japanese cypress forests, which is consistent with previous studies examining controlling factors affecting G_c in forests during growing seasons without a severe soil water deficit (Granier et al., 1996b; Komatsu et al., 2006, 2012). The data for different R_s classes are located along the regression line, which was determined using all data (Fig. 9). When R_s was $> 250 \text{ W m}^{-2}$ (i.e., light-saturated conditions) (Komatsu et al., 2012), the correlation was not particularly strong, and R^2 values were 0.46 and 0.58 in the pre- and post-thinning periods, respectively.

The predicted $E_{t-stand}$ from the G_c model had a significant correlation ($P<0.01$: a two-tailed Pearson correlation test, $R=0.807$) and a good performance with the measured values during the growing season in the pre-thinning period (Fig. 10a). Komatsu et al. (2012) also reported that the estimated $E_{t-stand}$ using the G_c model corresponded to the observed $E_{t-stand}$ and that the correlation coefficient ($R=0.878$) between these values was significant ($P<0.01$) for the Japanese cypress forests during the growing season. The G_c was related to

various environmental variables, including VPD , R_s , and the soil water deficit (Granier et al., 2000a, 2000b). In this study, the estimated $E_{t-stand}$ values were slightly higher than those values observed at the beginning of the growing season of 2011 (Fig. 10a). This observation may be caused by the initial transition of the trees from physiologically phase of rest to active period, which might cause soil water deficit from late April to May 2011 (Fig. 11). The shortage of soil-water storage may partly restrain the water uptake and overestimate $E_{t-stand}$. However, the soil water deficit was not severe from November 2010 to mid-April 2011 (Fig. 11). Thus, the time series of estimated $E_{t-stand}$ can be well explained by the response of G_c to VPD in the pre-thinning period, without considering the response of G_c to the soil water deficit.

In this study, the G_c significantly decreased after thinning (Fig. 9). G_c expresses the physiological control of E_t (Kelliher et al., 1995; Raupach, 1995) and affects the transpiration rates of forest canopies (Jarvis and Mcnaughton, 1986; Kelliher et al., 1993; Komatsu, 2004). G_c also strongly correlates with canopy photosynthesis rates (Lai et al., 2000; Law et al., 2001). Therefore, the low G_c after thinning implies lower $E_{t-stand}$ and photosynthesis and, thus, possible changes in terrestrial water and carbon cycles due to the thinning treatment.

4.3. Effect of thinning on E_t

The daily E_{t-tree} in the present study increased after thinning (Fig. 7a and b). The increase in the daily E_{t-tree} may primarily be due to the increase in the F_d (Fig. 5) because the F_d increased significantly at the outer xylem (0-20 mm) after thinning (Fig. 5, 6b) and because the growth of the sapwood area of residual trees was not significantly changed after one-year thinning. Breda et al. (1995) also observed that there were no significant differences

in the sapwood area in an oak forest. Our results regarding the daily E_{t-tree} increase were consistent with previous studies (Lagergren and Lindroth, 2004; Medhurst et al., 2002; Morikawa et al., 1986; Reid et al., 2006; Simonin et al., 2006). For example, Morikawa et al. (1986) reported that the daily E_{t-tree} was higher at a given level of R_s after 24% thinning in a 31-year-old Japanese cypress stand. Reid et al. (2006) found that individual trees in the thinned plot transpired more water in a lodgepole pine (*Pinus contorta*) forest in Alberta, Canada. However, several studies reported that E_{t-tree} had no clear differences when thinned. Gebauer et al. (2011) found that E_{t-tree} remained similar between thinned and control plots for a spruce forest in southeast Norway. These authors implied that sun-exposed needles were subjected to higher water shortage in the thinned plot.

Our results also show that the daily E_{t-tree} for the small tree class increased by 121.3%, reaching 10.405 kg d⁻¹ on given days after thinning (Fig. 7a). This result was contrary to the results of Morikawa et al. (1986), who reported that there was no significant difference in the daily E_{t-tree} on the small Japanese cypress tree class before and after thinning. This conflict may be related to the difference of the stand density and the ratio of thinning. In their study, the ratio of thinning was 24% and stand density decreased from 1750 to 1325 trees ha⁻¹. The spacing for small tree class was not significantly changed. In the present study, the ratio of thinning was 50%, and the stand density decreased from 2198 to 1099 trees ha⁻¹. The openness of the canopy increased with thinning (Table 1). Solar radiation can penetrate deeper into the dense canopy by heavy thinning. Additionally, the change in the aerodynamics (e.g., wind speed) after thinning resulted higher tree boundary layer conductance. The boundary layer conductance per tree linearly increased with an increase in

tree spacing (Teklehaimanot et al., 1991). These reasons may partially result in remarkably increases in the F_d of small tree class (Fig. 5). Therefore, the daily E_{t-tree} for the small class significantly increased after thinning in the present study.

In addition, contrary to the daily E_{t-tree} increased (Fig. 7b), the daily $E_{t-stand}$ decreased significantly after thinning (Fig. 8). This result was consistent with the lower G_c that was caused by thinning in this study (Fig. 9). The daily $E_{t-stand}$ was calculated from A_{S_stand} / A_G and J_s (Eq. 2). Therefore, the decreases in the daily $E_{t-stand}$ were caused by the reduction in the sapwood area (46.4%) (Table 1), although there was an increase in J_s after thinning (Fig. 6d). The total $E_{t-stand}$ decreased by 23.0% during the growing season and by 38.3% at the annual scale after thinning. Our results agree with previous studies (Breda et al., 1995; Lagergren et al., 2008; Morikawa et al., 1986; Simonin et al., 2007). For example, Morikawa et al. (1986) reported that $E_{t-stand}$ decreased by 21.2% after 24% thinning in a 31-year-old Japanese cypress forest. Lagergren et al. (2008) found that $E_{t-stand}$ for a thinned plot of a pine-spruce forest was lowered by 40% than that for the control plot for the first year after removing 24% of the basal area. However, the drought period or temporal changes in $E_{t-stand}$ after thinning can affect the difference in $E_{t-stand}$ caused by thinning treatment. Simonin et al. (2007) found considerable differences in $E_{t-stand}$ between the thinned and control plots when the soil water content was high in semi-arid *Pinus ponderosa* forests, whereas the difference was much less when the soil water content was low. Lagergren et al. (2008) reported that $E_{t-stand}$ in the thinned plot was rather higher than in the control plot during the drought period (July-September) when soil water content was low due to low precipitation. Additionally, $E_{t-stand}$ might gradually increase for several years after thinning

and approach the total $E_{t-stand}$ value before thinning. [Breda et al. \(1995\)](#) reported that $E_{t-stand}$ was lower in the thinned plot of an oak forest for the first year after thinning. However, $E_{t-stand}$ was nearly the same between the thinned and control plots for the second year after thinning. [Lagergren et al. \(2008\)](#) also found that the difference in $E_{t-stand}$ between the thinned and control plots diminished successively for the second year after thinning. Therefore, further studies were recommended to examine the variation in $E_{t-stand}$ for Japanese coniferous forests during drought (low-precipitation) years, although the annual P_g is usually higher than PET, and the soil water deficit is not severe in Japan ([Komatsu et al., 2006, 2012; Kumagai et al., 2008](#)). Furthermore, measurement studies at a multi-year scale are also required to elucidate the temporal changes in $E_{t-stand}$ after thinning in Japanese coniferous forests.

In the present study, the response of E_t at individual tree and stand levels to strip thinning was examined in a Japanese cypress plantation. Different forestry practices can result different changes in stand structures and environmental variables. The resultant changes in stand/tree E_t under different forestry practices would be different. Recently, [Komatsu et al. \(2013\)](#) conducted 45% selective thinning (from 1100 to 600 stem ha⁻¹) in a *Cryptomeria japonica* plantation in Japan and reported that the change in $E_{t-stand}$ was comparable to that in $A_{s-stand}$ and that J_s did not increase due to thinning unlike of our results. However, until now, data regarding the stand/tree E_t response to forest managements are so limited that it is difficult to obtain the single most important factor affecting tree water use. Therefore, further research should evaluate the responses of stand/tree E_t under different management plans to identify those practices that are most optimized for water and forest

483 management in forest watersheds.

5. Conclusions

This study elucidated the variations in E_t and G_c , in addition to tree-to-tree and radial F_d , by 50% strip thinning in a Japanese cypress forest. Our results showed that the F_d at the outer xylem (0-20 mm) increased remarkably, whereas the F_d at the inner xylem (20-40 mm) had no significant change in three tree classes (large, medium and small) after thinning. This result implies that thinning only enhanced the capacity of conducting water at the outer xylem. Correspondingly, the J_{S_A} values were higher in the post-thinning period, whereas the J_{S_B} values had no significant differences between the pre- and post-thinning periods. Similar to J_{S_A} , the J_S values were higher in the post-thinning period than in the pre-thinning period, and the differences significantly increased with increasing VPD . Furthermore, the daily E_{t-tree} increased in the three tree classes after thinning. Specially, the daily E_{t-tree} for the small class significantly increased, which may due to deeper solar radiation penetration into the canopy after heavy thinning, and then increased the transpiration of the lower crowns. Unlike the daily E_{t-tree} , the daily $E_{t-stand}$ decreased by 39.8%, from 1.23 ± 0.48 to 0.74 ± 0.42 mm d⁻¹, on the annual scale, which is due to the reduction in the sapwood area (46.4%) that is caused by thinning, although there was an increase in J_S . The annual $E_{t-stand}$ decreased by 38.3%, from 441.0 to 272.1 mm. The G_c values were significantly lower in the post-thinning period during the growing season. This result implies lower $E_{t-stand}$ and photosynthesis and would be useful for simulating possible changes in terrestrial water and carbon cycles due to the thinning treatment using ecosystem models. This study was conducted only one year after thinning, without soil water stress. Thus, further studies are recommended to examine the variation in E_t for drought (low-precipitation) years and the

506 temporal changes in E_t at a multi-year scale by thinning. Further research should also
507 evaluate the effects of different management practices on tree water use to identify those
508 practices that are most appropriate for water and forest management in forest watersheds.

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Table 1 Stand characteristics of the study plot in the pre- and post-thinning periods.

Characteristic	Pre-thinning	Post-thinning	Ratio of thinning (%)
Plot area (m ²)	156	156	
Age (year)	32	33	
Mean height (m)	16.0	16.0	
Mean DBH (cm)	19.1	18.9	
Canopy cover (%)	97.4	75.8	22.2
Density (trees ha ⁻¹)	2198	1099	50.0
Basal area (m ² ha ⁻¹)	50.4	26.2	48.0
Sapwood area (m ² ha ⁻¹)	26.1	14.0	46.4
Sapwood area at xylem band (m ² ha ⁻¹)			
0-20 mm	17.7	9.3	47.5
20-40 mm	8.4	4.7	44.0
Sap flux measurements (trees)	10	6	

Table 2 Number (n) and mean diameter at 1.3 m aboveground (DBH) of sampled Japanese cypress trees for each size class before and after thinning. Values in parentheses are ± 1 SD (SD: standard deviation).

Size class	Pre-thinning		Post-thinning	
	n	DBH (cm)	n	DBH (cm)
Small	3	16.4 (0.5)	2	16.7 (0.3)
Medium	3	19.3 (0.7)	2	19.7 (0.5)
Large	4	22.1 (1.0)	2	21.7 (0.9)

Table 3 Gross precipitation (P_g), potential evapotranspiration (PET), and stand transpiration (E_t) on the annual- and growing season-scale for the pre- and post-thinning periods, respectively.

Period	P_g		PET				E_t							
	Annual	Season	Annual		Season		Annual				Season			
			Total	Daily mean	Total	Daily mean	Total	Daily mean	E_t/P_g	E_t/PET	Total	Daily mean	E_t/P_g	E_t/PET
			mm	mm d ⁻¹	mm	mm d ⁻¹	mm	mm d ⁻¹	%	%	mm	mm d ⁻¹	%	%
Pre-thinning (Nov 2010 - Oct 2011)	1444.6	1139.8	1036.1	2.84±1.66	618.6	3.73±1.76	441.0	1.23±0.48	30.5	42.6	214.9	1.29±0.60	18.9	34.7
Post-thinning (Nov 2011 - Oct 2012)	1266.8	869.0	1095.0	3.00±1.85	701.4	4.23±1.78	272.1	0.74±0.42	21.5	24.8	165.5	1.00±0.40	19.0	23.6

Season refers to the growing period from April 28 to October 10.

Figure captions

Fig. 1 Location and topography of the Japanese cypress forest field site on Mt. Karasawa, Sano City, Tochigi Prefecture, Japan (a) and (b) photos of the study plot before and after thinning.

Fig. 2 Frequency distributions of stem diameters at breast height (DBH) in the pre- and post-thinning periods, respectively. Note that the number at the top of each bar denotes the number of trees used for the sap flow measurements in each DBH class.

Fig. 3 Time series of meteorological factors from November 2010 to October 2012. Reading from the top: daily precipitation (P_g); daytime (6 a.m.-6 p.m.) maximum, mean and minimum relative humidity (RH) ($RH_{\max}$, RH_{mean} and $RH_{\min}$, respectively); daytime maximum, mean and minimum temperature (T) ($T_{\max}$, T_{mean} and $T_{\min}$, respectively); daytime-mean vapor pressure deficit (VPD); daytime-mean solar radiation (R_s); and daily potential evapotranspiration (PET). Gray areas indicate the growing season (May-October). Vertical area with bias indicates the period of the thinning treatment (October 11-November 5, 2011). Horizontal areas with bias indicate the period of sap flow measurement (April 28-October 10, 2011 and November 6, 2011-October 31, 2012 for the pre- and post-thinning periods, respectively).

Fig. 4 Stem diameters at breast height (DBH) versus tree sapwood area (A_{S_tree}) for 44 Japanese cypress trees in the pre-thinning and 18 Japanese cypress trees in the post-thinning. The trees are selected in/around the study plot; the overlapped scatters indicate the trees that were not felled after thinning. Black line represents the regression equation derived in the pre-thinning ($y = 12.18 x - 82.9$ ($R^2 = 0.83$)). Dotted line represents the regression equation generated after thinning ($y = 12.16 x - 72.0$ ($R^2 = 0.83$)).

Fig. 5 Half-hourly patterns of sap flux density (F_d) in two depth categories (outer xylem: 0-20 mm, and inner xylem: 20-40 mm) and three tree size classes (large, medium and small) on August 9, 2011 (pre-thinning) and on August 9, 2012 (post-thinning). Climatic conditions (e.g., vapor pressure deficit (VPD) and solar radiation (R_s)) are also shown. Vertical bars represent the standard deviation (SD) (see Table 2 for the number of each tree class).

Fig. 6 (a) Time series of mean daily sap flux densities for xylem bands 0-20 (J_{S_A}) and 20-40 mm (J_{S_B}), (b) relation between mean daily daytime vapor pressure deficit (VPD) and J_{S_A} , J_{S_B} (c) for all measured Japanese cypress trees, and (d) stand sap flux density (J_s) during the growing season in the pre-thinning period (April 28 – October 10, 2011) and in the post-thinning period (April 28 – October 10, 2012).

Fig. 7 (a) Half-hourly patterns of tree transpiration (E_{t-tree}) in three tree size classes (large, medium and small) and vapor pressure deficit (VPD) on August 9, 2011 (pre-thinning) and on August 9, 2012 (post-thinning). Vertical bars represent the standard deviation (SD) (see Table

2 for the number of each tree class). (b) Mean daily E_{t-tree} averaged by all measured Japanese cypress trees using the Granier method response to the mean daily daytime vapor pressure deficit (VPD) in the pre- and post-thinning periods during the growing season (April 28 – October 10).

Fig. 8 Daily stand transpiration ($E_{t-stand}$) response to the mean daily daytime vapor pressure deficit (VPD) in the pre- and post-thinning periods during the growing season (April 28 – October 10).

Fig. 9 Relations between the mean daily daytime vapor pressure deficit (VPD) and the canopy conductance (G_c) for Japanese cypress forests during the growing season (April 28 – October 10) in the pre-thinning period (solid circle) and the post-thinning period (white circle). The data are classified according to solar radiation (R_s). The solid lines are the regression lines, which were determined using the least-squares method for all data, representing the pre- and post-thinning periods, respectively.

Fig. 10 Time series of the daily stand transpiration ($E_{t-stand}$), which was measured using the Granier method (solid circle) and estimated using the G_c model (solid line), for the pre-thinning period from November 1, 2010 to October 31, 2011 (b) and detailed for the period from April 28 to October 10, 2011 (a).

Fig. 11 Cumulative daily values of the gross precipitation (P_g), potential evapotranspiration (PET), and stand transpiration ($E_{t-stand}$) in the pre-thinning period (November 1, 2010 – October 31, 2011) and in the post-thinning period (November 1, 2011 – October 31, 2012), respectively.

Fig. 1

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