

Stand-scale transpiration estimates in a Moso bamboo forest: II. Comparison with coniferous forests

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ABSTRACT

In western Japan, Moso bamboo (*Phyllostachys pubescens*) forests have been expanding by replacing surrounding vegetation such as coniferous plantation forests and natural broadleaved forests. It has been speculated that the replacement of surrounding vegetation by bamboo forests could alter the vegetation water cycle and available water resources. We quantified stand-scale transpiration (E) in a bamboo forest on the basis of sap-flux measurements and compared the E value with values for coniferous forests. The annual E was estimated to be 567 mm. Seasonal trends in E primarily corresponded to seasonal trends in the vapor pressure deficit. Annual E for the bamboo forest was higher than that for the coniferous forests by 12% of annual precipitation (P). This difference in annual E is comparable with the difference in annual interception evaporation (I) relative to P between bamboo and coniferous forests; previous studies reported lower I for bamboo forests by ~10% of P . Thus, the sum of E and I was comparable for bamboo and coniferous forests. As this study is the first measuring E of bamboo forests, further studies are required to examine the generality of our results.

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1. Introduction

Some species of bamboos (e.g., Moso bamboo; *Phyllostachys pubescens*) are useful plants in terms of providing food and materials in East Asia. Moso bamboo forests had been developed and managed in western Japan. However, these forests are now being abandoned as bamboo is imported from other countries (Torii and Isagi, 1997; Torii, 1998, 2003). Bamboo forests have thus expanded by replacing surrounding vegetation such as coniferous plantation forests and natural broadleaved forests (e.g., Isagi et al., 1997; Nishikawa et al., 2005; Suzuki and Nakagoshi, 2008). Significant increases in bamboo forested area in various local provinces in western Japan have been reported (e.g., Yamamoto et al., 2004; Nishikawa et al., 2005; Toriyabe and Kai, 2005; Akashi et al., 2006; Himiyama and Nakamura, 2006; Kobayashi and Tada, 2010). For example, Kobayashi and Tada (2010) reported an increase of more than 200% in the bamboo forested area between the late 1970s and the late 1990s in Kagawa prefecture.

Researchers have speculated that the replacement of coniferous forests and broadleaved forests by bamboo forests could alter the vegetation water cycle and available water resources (Ueda, 1979; Uchimura, 1994). Among various components of the vegetation water cycle, evapotranspiration is one of the most critical factors affecting the water yield and available water resources (e.g., Vertessy et al., 2001; Farley et al., 2005; Komatsu et al., 2008a). Thus, it is important to examine evapotranspiration in bamboo forests.

The main components of forest evapotranspiration are canopy transpiration and rainfall interception (e.g., Suzuki, 1980; Vertessy et al., 2001; Wilson et al., 2001). Several studies in Japan (Abe et al., 1984; Hattori and Abe, 1989; Onozawa et al., 2009; Shinohara et al., 2010a) have examined the rainfall interception of bamboo forests on the basis of throughfall and stem flow measurements. They reported lower rainfall interception for bamboo forests than for coniferous and broadleaved forests in Japan (Hattori and Abe, 1989; Onozawa et al., 2009).

On the other hand, there have been few studies examining transpiration in bamboo forests. The sap-flux method (e.g., Kumagai et al., 2007, 2009; Herbst et al., 2008; Kume et al., 2010a) is one of the most common methods of measuring forest transpiration. Applicability of the method to transpiration estimates for bamboo forests was examined in the accompanying paper (Kume et

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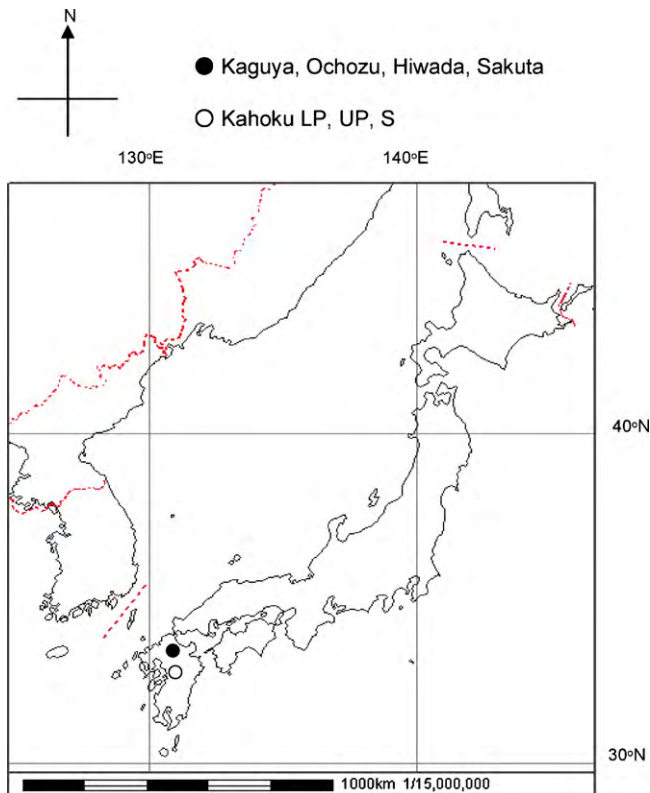


Fig. 1. Location of the bamboo forest (Kaguya) and coniferous forests (Kahoku LP, UP, and S, Ochozu, Hiwada, and Sakuta).

al., 2010b). In that paper, the method proved to be a valid means of detecting trends in transpiration despite the specific culm structure of bamboos, and an optimal scaling-up strategy was proposed for stand-scale transpiration estimates.

With this background, we measured stand-scale transpiration (E) in a Moso bamboo forest for 14 months. This paper presents annual E and the seasonal trend in E for the forest. To characterize E for the bamboo forest, we compared our results with those for coniferous forests. The results of this comparison are useful for evaluating changes in evapotranspiration and available water resources due to the replacement of coniferous forests by bamboo forests. As this study is the first measuring E for bamboo forests, future studies are required to examine the generality of our results. Thus, we identify research topics that should be examined in the future in this paper.

2. Materials and methods

2.1. Study area

A complete description of the site and measurements is available in the accompanying paper (Kume et al., 2010b). Here we give a brief description.

Our measurements were made at the Kaguya site located 12 km east of Fukuoka city, Japan (33°37'N, 130°31'E, 50 m a.s.l.) (Fig. 1). Moso bamboo (*P. pubescens*) forests are patchily distributed in the region of the site. The mean air temperature, recorded between 1995 and 2005 at a meteorological observatory situated 15 km from the site, was approximately 16°C. The mean annual precipitation was 1790 mm.

The site is covered with bamboo forest, which has invaded surrounding coniferous plantation forests and natural broadleaved forests. The canopy height of the site was approximately 15 m.

The mean diameter at breast height (DBH) was approximately 11 cm. The stem density of the bamboo forest was approximately 4000 stems ha⁻¹. Understory vegetation was scarcely distributed.

2.2. Measurements

Transpiration measurements were made in a 10 m × 10 m plot at the site. There were 40 individuals in the plot. The mean DBH for the individuals was 11.0 cm. The stand culm sectional area of the plot was 13.1 m² ha⁻¹.

Stand-scale transpiration (E) was estimated using the following equations (Wilson et al., 2001; Wullschlegel et al., 2001; Pataki and Oren, 2003).

$$E = J_S \cdot \frac{A_{S_stand}}{A_G} \quad (1)$$

where J_S is the mean stand sap flux, A_{S_stand} is the stand culm sectional area, and A_G is the ground area of the plot. This equation is based on the assumption of no time lag between water uptake and transpiration by trees. Our analysis was carried out for a daily time step as in previous studies (e.g., Phillips and Oren, 1998; Kumagai et al., 2007, 2008) because the assumption is satisfied on this time scale. J_S is further calculated as

$$J_S = \frac{\sum_{i=1}^n F_{d_ave\ i} \cdot A_{S_b_i}}{\sum_{i=1}^n A_{S_b_i}} \quad (2)$$

where n is the sample size of the sap-flux measurements, $F_{d_ave\ i}$ is the sap-flux averaged over the culm area of the i th sample, and $A_{S_b_i}$ is the culm sectional area of the i th sample.

F_d has been measured for 16 individuals employing the sap-flux method and Granier-type sensors since November of 2007. Note that the accompanying paper (Kume et al., 2010b) recommended F_d measurements of at least 11 individuals. The measurements were made using 10 mm sensors, which contrasts with most other studies (e.g., Ford et al., 2007; Kumagai et al., 2007, 2008; Kume et al., 2010a) using 20 mm sensors. F_d was determined using 10 mm sensors following the method proposed by Kume et al. (2010b). According to the method, F_d was assumed to be the value calculated using Granier's (1987) equation multiplied by 1.35. The mean DBH for the 16 samples was 11.4 cm and the range was between 9.6 and 13.2 cm.

Meteorological variables such as precipitation, temperature, and humidity were measured in an open space 200 m west of the Kaguya site. The volumetric soil water content was measured at the Kaguya site at depths of 10, 30, and 50 cm. These measurements were used to represent the average volumetric soil water content between 0 and 60 cm. The leaf area index (LAI) was measured from a digital non-spherical color photograph using Gap Light Analyzer software (Franzer et al., 1999).

2.3. Comparison data

We used stand-scale transpiration data of six coniferous forests located in western Japan (Fig. 1; Table 1). Kahoku LP, UP, and S sites were located approximately 50 km south of the bamboo forest. The mean annual precipitation and temperature for these sites were 2150 mm and 15°C, respectively. The Ochozu site was located 1 km to the east and the Hiwada and Sakuta sites 3 km to the northeast of the bamboo forest.

Canopy tree species were *Cryptomeria japonica* for the Kahoku LP, UP, and S sites and *Chamaecyparis obtusa* for the Ochozu, Hiwada, and Sakuta sites. These tree species are the most common plantation species in Japan (Fujimori, 2000) and largely distributed in western Japan (National Astronomical Observatory, 2009). Understory vegetation was evergreen *Quercus* and *Castanop-*

Table 1
Description of the coniferous forest sites from which data were used for comparison.

Name	Location	Age (years)	Mean DBH (cm)	Stem density (stems ha ⁻¹)	Mean height (m)	Projected LAI	Plot size (m ²)	Sap flow measurement (trees)	Data period
Kahoku LP ^a	33°08'N, 130°43'E	50	40.3	904	32	4.4–5.7	321	15	June 2005–November 2006
Kahoku UP ^a	33°08'N, 130°43'E	50	23.8	1575	22	3.2–5.4	318	23	June 2005–November 2006
Kahoku S ^b	33°08'N, 130°43'E	50	26.6	1330	24	n.a. ^e	203	19	March 2007–June 2008
Ochozu ^c	33°38'N, 130°32'E	50	21.0	1450	15.6	3.2	400	14	November 2007–December 2008
Hiwada ^d	33°38'N, 130°32'E	98	44.6	350	8	n.a.	100	7	April 2009–July 2009
Sakuta ^d	33°38'N, 130°32'E	18	13.5	2100	25	n.a.	200	10	April 2009–July 2009

^a Kumagai et al. (2007, 2008).

^b Kumagai (unpublished).

^c Kume et al. (2010b).

^d Tsuruta (unpublished).

^e Not available.

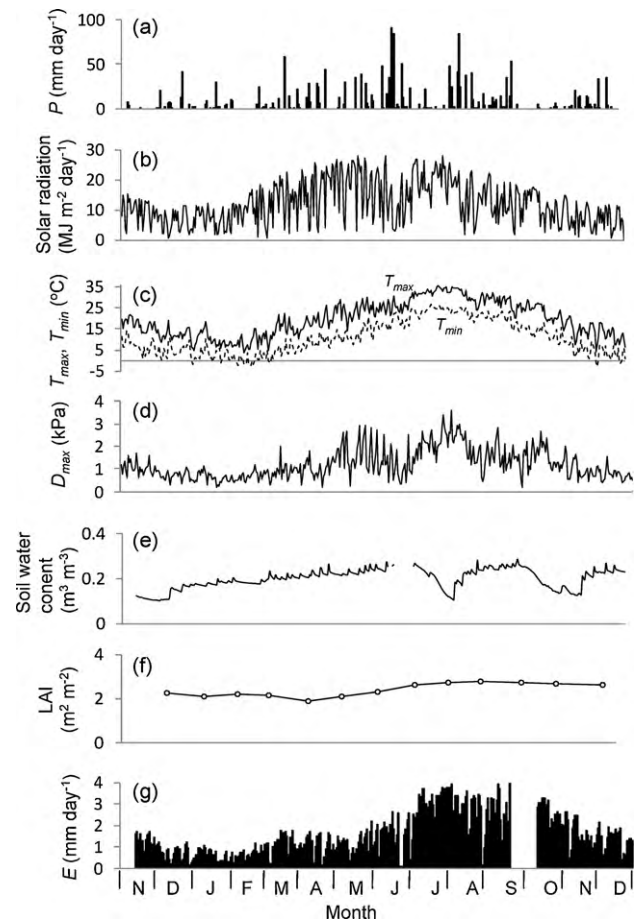


Fig. 2. Time series of (a) precipitation (P), (b) solar radiation, (c) daily maximum and minimum temperatures (T_{max} and T_{min} , respectively), (d) daily maximum vapor pressure deficit (D_{max}), (e) soil water content, (f) leaf area index (LAI), and (g) transpiration (E) during the period November 2007–December 2008.

sis trees at the Kahoku LP, UP, and S sites and *Eurya japonica*, *Ligustrum japonicum*, and *Zanthoxylum piperitum* at the Hiwada site. Understory vegetation was scarce at the Ochozu and Sakuta sites. More complete descriptions of the Kahoku LP and UP sites and the Ochozu site are available in Kumagai et al. (2007, 2008) and Kume et al. (2010a), respectively.

Transpiration of the canopy trees was measured employing the sap-flux method and Granier-type sensors of 20 mm length. F_d was calculated with Granier's (1987) equation, as detailed in Kumagai et al. (2007, 2008) and Kume et al. (2010a).

3. Results and discussion

3.1. Annual transpiration

Total precipitation (P) during the period November 2007–December 2008 was 1906 mm. Annual P for 2008 was 1780 mm, which is nearly the same as the long-term average value recorded at the nearest meteorological observatory. P occurred more frequently during summer than during winter (Fig. 2a), which is the typical seasonality of P in most regions in Japan (e.g., Shimizu et al., 2003; Komatsu et al., 2009, 2010a). Other meteorological variables, such as solar radiation (Fig. 2b), daily maximum and minimum temperatures (T_{max} and T_{min} , respectively) (Fig. 2c), the daily maximum vapor pressure deficit (D_{max}) (Fig. 2d), and the soil water content (Fig. 2e) were also higher in summer than in winter. LAI ranged between 1.9 and 2.8. The minimum LAI was recorded in

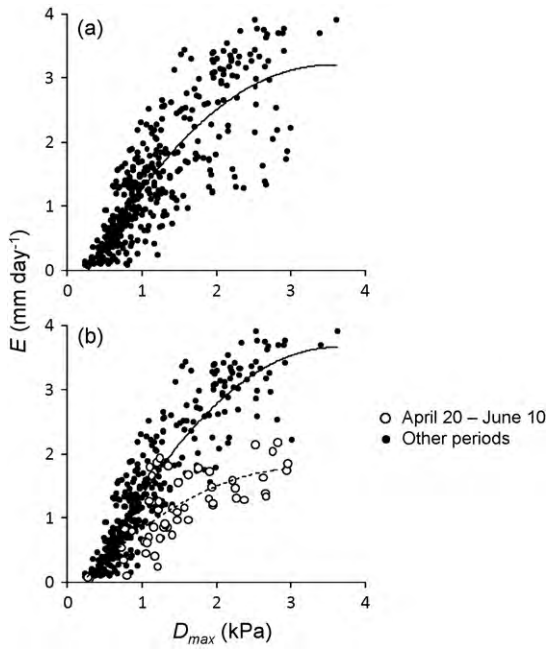


Fig. 3. (a) Relationship between the daily maximum vapor pressure deficit (D_{max}) and daily transpiration (E). The solid line, determined by the least-squares method, is written as $y = -0.307x^2 + 2.155x - 0.578$ ($R^2 = 0.706$). (b) Same as Fig. 3a but the data are divided according to the measurement period. The solid and dotted lines, determined by the least-squares method, are written as $y = -0.336x^2 + 2.433x - 0.731$ ($R^2 = 0.837$) and $y = -0.198x^2 + 1.267x - 0.244$ ($R^2 = 0.493$), respectively.

April (Fig. 2f), which was within the period of significant leaf senescence and replacement for bamboo forests (e.g., Onozawa et al., 2009).

E data for the period September 19–October 11, 2008 were missing (Fig. 2g). E was strongly related to D_{max} and the relationship was nearly the same for the 10 days before and the 10 days after the period when E data were missing (September 4–13 and October 12–21, 2008, respectively). Thus, we filled the data gap using the relationship between D_{max} and E for the period September 4–October 21, 2008.

Using the gap-filled data, annual E for 2008 (January 1–December 31, 2008) was estimated to be 567 mm. Annual E for the year after the beginning of E measurements (November 11, 2007–November 10, 2008) was estimated to be 549 mm. We arbitrarily determined the period in which data were used for developing the relationship between D_{max} and E . However, annual E was nearly unchanged when using data for other periods in determining the relationship. For example, annual E for 2008 was estimated to be 572 mm when the relationship was developed using data for 15 days before and after the data gap and 574 mm when the relationship was developed using data for 20 days before and after the data gap.

3.2. Seasonal trend in transpiration

E was greater in summer than in winter (Fig. 2g). Fig. 3a shows a clear correlation between D_{max} and E . The correlation indicates that the seasonal trend in E of the bamboo forest primarily corresponded to the seasonal trend in D_{max} .

Despite the clear correlation, the data had large scattering. To reduce the scattering, we classified the data according to the measurement period. As a result, we found that E recorded between late April and early June (April 20–June 10, 2008) was lower than E recorded outside the period for a given D_{max} , indicating E declined during this period. We calculated differences between measured E

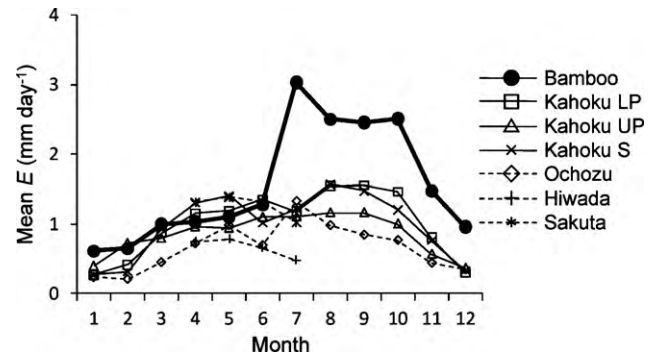


Fig. 4. Seasonal trends in E for the bamboo and coniferous forests.

and E calculated using the regression equation for Fig. 3a and examined relationships of the differences with solar radiation and soil water content. We found no clear correlations for the relationships (data not shown).

Though the total LAI changed little throughout the measurement period (Fig. 2f) compared with the change for deciduous forests in Japan (e.g., Park et al., 2000; Saigusa et al., 2002; Hirano et al., 2003), the period of E decline was almost identical to the period of significant leaf senescence and replacement of bamboo forests. We could not identify the cause of the E decline. However, Miyazawa et al. (1998) reported lower stomatal conductance just after leaf appearance for evergreen tree species in Japan. This might partly explain the E decline observed here.

3.3. Comparison with other forests

Annual E of the bamboo forest for 2008 was 567 mm. Annual E for Kahoku LP, UP, and S and Ochozu were 373, 296, 370, and 245 mm, respectively. Thus, annual E was higher for the bamboo forest than for the coniferous forests.

Fig. 4 shows seasonal trends in E for the bamboo and coniferous forests. The difference in E between the bamboo and coniferous forests was larger during July–October when the vapor pressure deficit was higher and there was no significant leaf senescence and replacement. The larger difference in E during July–October agrees with the difference in the D_{max} – E relationship among the forests. Fig. 5 shows D_{max} – E relationships for the bamboo forest and three coniferous forests. E for the bamboo forest was generally greater than that for the coniferous forests except for the period of significant leaf senescence and replacement (i.e., April 20–June 10). The difference in E was greater for greater D_{max} (Fig. 5).

Here, we note that the D_{max} – E relationships for the Kahoku LP and UP sites were obtained from the results of Kumagai et

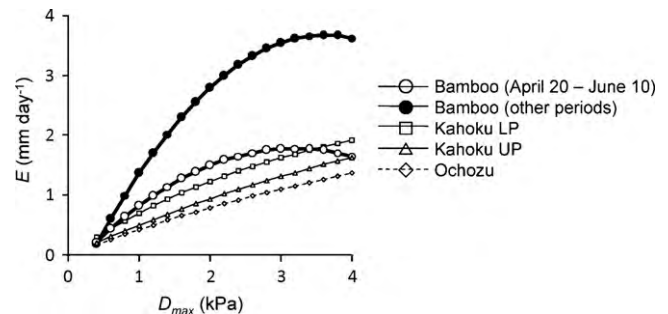


Fig. 5. Relationships between the maximum vapor pressure deficit (D_{max}) and daily transpiration (E) for the bamboo forest and three coniferous forests. The equations for the Kahoku LP and UP sites are written as $y = 2.83 \exp(-0.49x)$ and $y = 2.81 \exp(-0.86x)$, respectively. The equation for the Ochozu site is written as $y = -0.031x^2 + 0.531x - 0.002$.

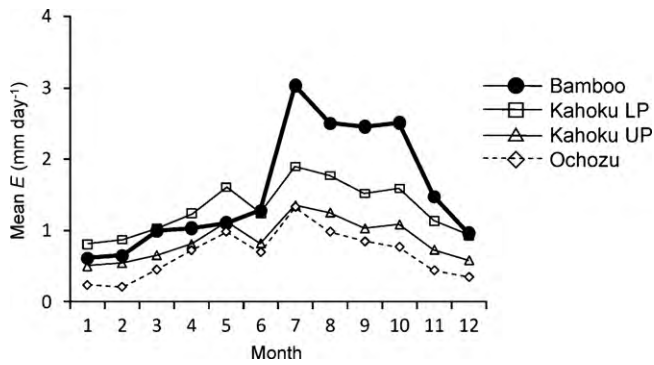


Fig. 6. Same as Fig. 4 but only for data of the same meteorological conditions.

al. (2008). They present the relationship between daytime vapor pressure deficit (D_{mean}) and J_s for the sites ($R^2 = 0.77$ and 0.78 for Kahoku LP and UP, respectively). We converted these relationships to relationships between D_{max} and E . In this conversion, we used total sapwood areas for the sites and assumed $D_{max} = 1.58 D_{mean}$ ($R^2 = 0.927$), which was developed using meteorological data of the bamboo forest. The D_{max} - E relationship for the Ochozu site was determined by the authors of this paper on the basis of the original data using the least-squares method ($R^2 = 0.801$).

3.4. Comparison assuming the same meteorological conditions

E depends on meteorological conditions as well as transpiration properties of the vegetation such as stomatal conductance (Campbell and Norman, 1998; Monteith and Unsworth, 2008). As the bamboo forest and Ochozu site are very near each other and the measurement periods are identical, the difference in E between the bamboo forest and Ochozu site is caused by the difference in transpiration properties between the two sites. Differences in E between the bamboo and other sites are affected by not only transpiration properties but also meteorological differences because the Kahoku LP, UP, and S sites are situated 50 km from the bamboo forest and the measurement periods for Hiwada and Sakuta differed from that for the bamboo forest.

The relationships between the vapor pressure deficit and E for Kahoku LP and UP were available (Fig. 5), though the relationships for Hiwada and Sakuta were unavailable. If we calculate E using the relationships with the input of vapor pressure deficit data recorded at the bamboo forest site in 2008, we can evaluate the differences in annual E and seasonal trends in E between the bamboo forest and Kahoku LP and UP sites under the same meteorological conditions. Note that we did not consider the effect of soil water content on E in these calculations for two reasons. First, E decline due to soil water deficit was not reported at the bamboo and Kahoku LP and UP sites. Second, E decline due to soil water content has not been reported for most E data derived using the micrometeorological and catchment water balance methods in Japan (Komatsu et al., 2010b).

Annual E for Kahoku LP and UP were estimated to be 478 and 322 mm, respectively, when meteorological conditions observed at the bamboo forest were assumed. The annual E for the bamboo forest was higher than these values. Seasonal trends in E were estimated as shown in Fig. 6. We again obtained higher annual E for the bamboo forest than for Kahoku LP and UP. The difference in E was larger during July–October. Thus, the results obtained in the previous section are qualitatively unchanged when assuming the same meteorological conditions for the bamboo forest and Kahoku LP and UP sites. This suggests that the differences in E between the bamboo and coniferous forests, obtained in the previous section, were primarily due to the differences in transpiration properties (e.g.,

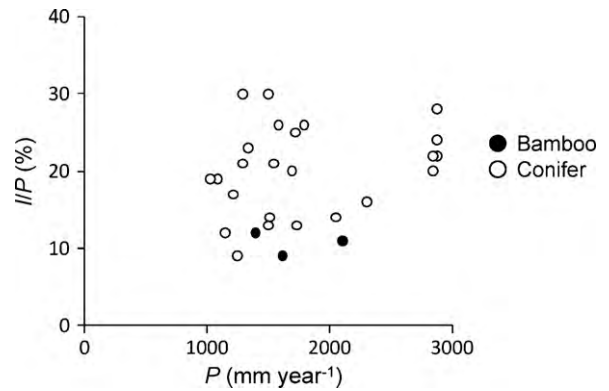


Fig. 7. Relationship between annual precipitation (P) and interception (I) divided by P for bamboo and coniferous forests.

stomatal conductance) rather than the difference in meteorological conditions.

3.5. Sum of transpiration and rainfall interception

The above results show higher annual E for the bamboo forest than for coniferous forests, which are extensively distributed in western Japan. Rainfall interception is the other major component of forest evapotranspiration in Japan (e.g., Suzuki, 1980; Komatsu et al., 2007a, 2008b; Shinohara et al., 2010b). Annual rainfall interception (I) for bamboo forests is less than that for coniferous forests (Onozawa et al., 2009). To evaluate changes in available water resources due to the replacement of coniferous plantations by bamboo forests, assessment of the sum of E and I rather than each component is required. This section discusses the difference in the sum of E and I between bamboo and coniferous forests.

The annual E in 2008 for the Ochozu site, situated near the bamboo forest, was 245 mm. The annual E values in 2008 calculated on the basis of the D_{max} - E relationships for Kahoku LP and UP were 478 and 322 mm, respectively. The mean of these three E values was 348 mm. The annual E for the bamboo forest was higher than this mean value by 219 mm.

This difference in E is comparable to the difference in I between bamboo and coniferous forests, as detailed below. We surveyed I data in regions without heavy snowfall in Japan. Note that these regions cover the whole of western Japan. We obtained three data for bamboo forests and 25 data for coniferous forests. Fig. 7 shows the relationship between annual P and I/P . We did not observe significant correlation between annual P and I/P ($R = 0.242$, $p > 0.05$ according to Pearson's correlation coefficient test), although some studies reported clear dependency of I/P on P (e.g., Ward and Robinson, 2000). We thus compared I/P values for bamboo and coniferous forests without considering the effect of the variation in annual P among measurement sites. The mean of I/P (\pm SD) for bamboo forests was 10.7% ($\pm 1.5\%$) ($n = 3$) and that for coniferous forests was 20.2% ($\pm 5.7\%$) ($n = 25$). This difference was found to be significant ($p < 0.01$) according to a t -test. As above, the difference in I between bamboo and coniferous forests is typically 10% of P . On the other hand, the difference in E between the bamboo and coniferous forests was 219 mm, as mentioned above. This value corresponds to 12% of annual P .

3.6. Recommendations for future studies

Our results suggest that the sums of E and I for bamboo and coniferous forests were comparable. As this is the first study measuring E for bamboo forests, further studies are required to examine

Table 2
Rainfall interception data for bamboo and coniferous forests summarized from earlier studies. Criteria for data collection are the same as those in Komatsu et al. (2007a) and Onozawa et al. (2009).

Site name	Location	Mean DBH (cm)	Stem density (stems ha ⁻¹)	Mean height (m)	Annual precipitation (P)	Interception (I) divided by P (%)	Reference
<i>Bamboo</i>							
Munakata	33°50'N, 130°31'E	11.3	6800	13	2105	11	Onozawa et al. (2009)
Shimazu	35°N, 136°E	9.6	7200	14	1398	12	Hattori and Abe (1989)
Kaguya	33°38'N, 133°31'E	10.6	4100	15	1618	9	Shinohara et al. (unpublished data)
<i>Conifer</i>							
Kamikamo	35°04'N, 135°46'E	7.6	3200	8	1793	26	Iwatsubo and Tsutsumi (1967)
Tengakura	36°N, 140°E	16.1	2051	11	1543	21	Hattori et al. (1982)
Tengakura	36°N, 140°E	18.2	1325	13.5	1087	19	Hattori and Chikaarashi (1988)
Tengakura	36°N, 140°E	18.2	1375	13.5	1336	23	Hattori and Chikaarashi (1988)
Fukuroyama	35°12'N, 140°07'E	34.2	923	19.3	2053	14	Tanaka et al. (2005)
Kasuya Research Forest	33°38'N, 130°32'E	23.2	1467	15.2	1584	26	Sato et al. (2003a,b)
Azuma	37°N, 139°E	29	750	25	1150	12	Haibara and Aiba (1982)
Fukuroyama	36°N, 140°E	38.5	513	26.5	2304	16	Tanaka et al. (2005)
Hitachi-ohta	36°34'N, 140°35'E	32	783	18	1734	13	Murakami et al. (2000)
Etajima	34°16'N, 132°29'E	12	1575	7	1513	14	Mitsudera et al. (1984)
Tsukuba	36°07'N, 140°06'E	20	2300	12	1291	21	Taniguchi et al. (1996)
Tsukuba	36°07'N, 140°06'E	20	1700	12	1291	30	Taniguchi et al. (1996)
Ochozu	33°38'N, 130°32'E	21	1700	14	1718	25	Shinohara et al. (2010b)
Shinshu University	36°N, 138°E	23	675	20	1499	30	Gomyo et al. (2004)
Shinshu University	36°N, 138°E	26	900	20	1499	13	Gomyo et al. (2004)
Tsukuba	36°07'N, 140°06'E	12.4	2700	10	1213	17	Iida et al. (2006)
Tsukuba	36°07'N, 140°06'E	18.4	680	15	1246	9	Iida et al. (2006)
Kiryu	34°58'N, 136°00'E				1693	20	Suzuki et al. (1979a,b)
Hikisa Forest	35°N, 138°E	5.5	3326	4	2876	22	Murai and Kumagai (1989)
Hikisa Forest	35°N, 138°E	9	3896	9	2876	28	Murai and Kumagai (1989)
Hikisa Forest	35°N, 138°E	7	3810	8	2876	24	Murai and Kumagai (1989)
Hikisa Forest	35°N, 138°E	5.5	3222	4	2847	22	Murai and Kumagai (1989)
Hikisa Forest	35°N, 138°E	11	2376	9	2847	22	Murai and Kumagai (1989)
Hikisa Forest	35°N, 138°E	10	1614	8	2847	20	Murai and Kumagai (1989)
Kouma	40°N, 141°E	20	830	15	1024	19	Murai (1970)

the generality of the results. For this purpose, we recommend the following for future studies.

We first recommend studies measuring E of bamboo forests with various structures and under various climatological conditions because E would vary with stand structures and climatological conditions. E for bamboo forests might vary with properties of the stand structure such as the stem density and LAI. The stem density reported at several bamboo sites was ~ 7000 stems ha⁻¹ (Hattori and Abe, 1989; Onozawa et al., 2009), which is much higher than that for our site (4000 stems ha⁻¹). The difference in E between bamboo and coniferous forests might be larger for those bamboo forests than for our bamboo forest. Therefore, the sum of E and I might be higher for those bamboo forests than that for coniferous forests. Thus, we recommend examinations of E for bamboo forests with high stem density and LAI.

Annual P is ~ 1000 mm in some regions in Japan (e.g., Komatsu et al., 2008c, 2009), which is lower than that for our site (~ 1800 mm). In such regions, reduction in E due to soil water deficit might be significant, which contrasts with our results. This factor might be critical in determining E for bamboo forests in these regions. Thus, we recommend examinations of E for bamboo forests in such regions.

The above discussion assumed that I for bamboo forests was $\sim 10\%$ of P . However, this assumption was made on the basis of three observational studies (Table 2). Note that although there have been several studies (Abe et al., 1984; Shinohara et al., 2010a) examining I for bamboo forests, they did not present I/P values for the forests. Thus, there is uncertainty in the assumption that I for bamboo forests is $\sim 10\%$ of P . As I might vary with stand structure, measurements of I for bamboo forests with various structural properties are required. However, note that the dependency of I/P on stem density might not be strong because the I/P value for a bamboo forest with stem density of 4000 stems ha⁻¹ was not greatly different from values for bamboo forests with stem density of ~ 7000 stems ha⁻¹

(Table 2). Further, I/P might vary with P (e.g., Komatsu et al., 2008b), suggesting that examinations of I/P dependency on P are required. For these examinations, long-term I measurements for more than several years would be useful.

We also recommend studies measuring evapotranspiration from understory vegetation and the ground surface in bamboo and coniferous forests. Evaluation of these components is also required to determine total evapotranspiration for bamboo and coniferous forests.

Further, we recommend measurements of E and I for broadleaved forests. Replacement of broadleaved forests by bamboo forests has been common in western Japan. However, there have been few studies in Japan measuring E for broadleaved forests using the sap-flux method, as pointed out by Komatsu et al. (2007b), despite the tree-scale transpiration measurements of broadleaved trees (e.g., Kubota et al., 2005; Tateishi et al., 2008). This is because natural broadleaved forests in Japan contain various tree species (e.g., Park et al., 2000; Goto et al., 2006) and E estimates for broadleaved forests using the sap-flux method would be more laborious than those for coniferous forests. Similarly, there have been only a few studies (Masukata et al., 1990; Park et al., 2000; Deguchi et al., 2006) reporting I for broadleaved forests in Japan, for the same reason as for E . Because of the lack of E and I data, it is impossible at present to evaluate differences in evapotranspiration and the water cycle between bamboo and natural broadleaved forests. Thus, intensive measurements of E and I in natural broadleaved forests are highly recommended.

The above discussion focuses on the water cycle of bamboo forests. Our results also have implications on the carbon cycle of bamboo forests, as canopy transpiration is tightly related to canopy photosynthesis (e.g., Leuning, 1995; Landsberg and Gower, 1997; Campbell and Norman, 1998). Higher E for bamboo forests than for coniferous forests suggests higher canopy photosynthetic

rates for bamboo forests than for coniferous forests when assuming an insignificant difference in intercellular CO₂ concentration in stomata and therefore water-use efficiency between the two forest types. To examine this possibility, measurements of carbon assimilation rates at leaf (e.g., Kutsch et al., 2001; Kosugi et al., 2003; Kosugi and Matsuo, 2006) and canopy scales (e.g., Herbst et al., 2002; Tanaka et al., 2002; Kumagai et al., 2006) are recommended.

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