J For Res (2009) 14:111–116
DOI 10.1007/s10310-008-0108-2

SHORT COMMUNICATION

Rainfall interception in a moso bamboo (*Phyllostachys pubescens*) forest

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Received: 14 April 2008 / Accepted: 3 December 2008 / Published online: 17 January 2009

Abstract In recent years, moso bamboo (*Phyllostachys pubescens*) forest areas in Japan have rapidly expanded, and bamboo is now invading nearby natural or plantation forests. To date, only one study has examined the rainfall interception of a moso bamboo forest. In that study, it was reported that the interception ratio (interception/rainfall) of the bamboo forest did not exceed the interception ratios of other natural and plantation forests ($n = 4$) in Japan. To expand the current state of knowledge about rainfall interception of bamboo forests, we measured throughfall and stemflow at another bamboo forest site. Annual rainfall (*Rf*), throughfall (*Tf*), and stemflow (*Sf*) during the measurement period were 2,105, 1,556, and 322 mm, respectively. Annual rainfall interception at the plot (*I*) was 228 mm. *Tf/Rf*, *Sf/Rf*, and *I/Rf* were 73.9, 15.3, 10.8%, respectively. *I/Rf* was less than 20% throughout the year except in October, the month with lowest rainfall. We also summarized rainfall interception data from 19 other natural and plantation forests. The *I/Rf* value of our site did not exceed the *I/Rf* values of these natural and plantation forests ($n = 19$). Our data will be useful for assessing changes in water resources that result from replacement of natural or plantation forests by bamboo forests.

Keywords Bamboo · Evapotranspiration · Rainfall interception · Water balance

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Introduction

In recent years, moso bamboo (*Phyllostachys pubescens*) forest areas have rapidly expanded in Japan (e.g., Torii and Isagi 1997; Torii 1998; Nishikawa et al. 2005). Moso bamboo was brought to Japan from China in the 1700s (e.g., Torii and Isagi 1997; Torii 2006), and moso bamboo forests were planted and managed in order to produce food, building materials, and traditional wood works. In recent times, bamboo forests have begun to be abandoned, and many are now left unmanaged (Nakashima 2001). Consequently, bamboo forests have spread, and have begun to invade natural and plantation forests.

This type of change in vegetation—from natural or plantation forests to bamboo forest—can change terrestrial water and nutrient cycles. Such changes ultimately affect the environment and human life (e.g., Hiura et al. 2004). From the viewpoint of water resources, some researchers have speculated that bamboo forests consume more water by evapotranspiration than other forest types (Ueda 1979; Uchimura 1994). Thus, the replacement of natural or plantation forests by bamboo forests would result in decreased water availability (Ueda 1979; Uchimura 1994), though scientific data supporting this speculation are unclear. However, only a few studies have examined the evapotranspiration of bamboo forests in Japan.

Tree transpiration and rainfall interception are two major components of evapotranspiration from forests. Although many studies have examined the transpiration and rainfall interception of natural and plantation forests to investigate their water consumption (e.g., Iida et al. 2006; Kumagai et al. 2004; Komatsu et al. 2007, 2008a), none have examined transpiration from bamboo forests, and only one study (Hattori and Abe 1989) has examined rainfall interception in a bamboo forest in Japan.

According to Hattori and Abe (1989), the rainfall interception ratio (interception/rainfall) of the bamboo forest was not higher than those of natural and plantation forests because of a higher stemflow ratio in the bamboo forest. This result does not support the speculation that there is greater evapotranspiration from bamboo forests, as proposed by Ueda (1979) and Uchimura (1994).

To date, only one study has examined the rainfall interception of bamboo forests (Hattori and Abe 1989), and therefore further studies on bamboo forests with different meteorological and stand conditions (e.g., precipitation, stem density, and DBH) are required. To accumulate rainfall interception data for bamboo forests and to clarify differences in rainfall interception amounts between bamboo and other forests, we carried out throughfall and stemflow measurements at another bamboo forest site and quantified rainfall interception. This data will be useful for assessing changes in water resources that result from the replacement of natural or plantation forests by bamboo forests.

Materials and methods

Site description

The study was carried out in an abandoned moso bamboo forest (*Phyllostachys pubescens*) in Munakata City, situated 30 km northeast of Fukuoka City (N33°50′, E130°31′, 10 m a.s.l.), Japan. This site was an agricultural cropland until the 1990s, but since then moso bamboo has invaded the area, spreading from an adjacent bamboo forest. A moso bamboo forest now covers the site.

The mean annual rainfall measured at the Munakata Meteorological Station, located 5 km south of the site, is 1,697 mm. The mean annual temperature is 15.3°C. Monthly temperatures range between 5.4°C (January) and 26.4°C (August). Precipitation is usually in the form of rainfall, not snowfall, but there are occasional snowfall events in January and/or February every year.

An experimental plot (10 m × 10 m) was established in the forest. Twenty-five subplots (2 m × 2 m) were sampled within the 10 m × 10 m plot. The slope angle of the plot was less than 5°. The plot contained 68 bamboo plants (i.e., 6,800 stems ha^{-1}) at the beginning of the measurement period. The diameter at breast height (DBH) ranged between 6.3 and 14.5 cm, and the mean DBH was 11.3 cm. Figure 1 shows the histogram of DBH distribution within this plot. The canopy height was ca. 13 m. During the measurement period, two bamboo plants emerged and six fell down. The six bamboo plants were removed from the plot as soon as they were found. There was scarce understory vegetation in this plot.

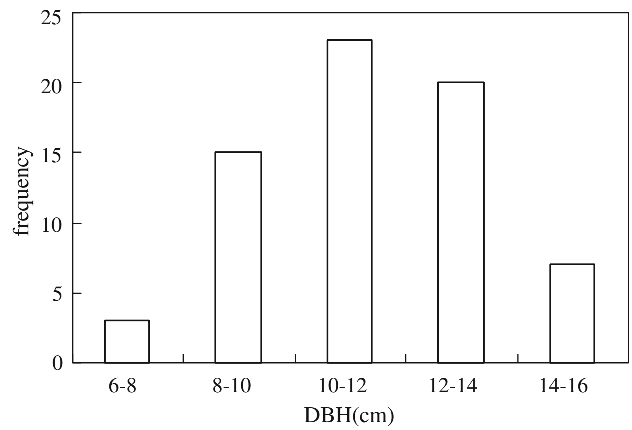

Fig. 1 Diameter at breast height (*DBH*) of bamboo plants within the study plot

Measurements

Gross rainfall was measured using two types of rain gauges; a storage-type rain gauge (funnel size: 210 mm in diameter), and a tipping rain gauge with resolution of 0.5 mm (Ohtakeiki, RA-1, Tokyo, Japan). Both types of rain gauges were located in an open space approximately 300 m west of the plot. The storage-type gauge measured rainfall on a weekly basis. The tipping rain gauge was connected to a data logger (HOBO Event, Onset Computer, Bourne, MA, USA) and tipping time was recorded. Rainfall amounts measured by the storage-type gauge (*Rf*) were tightly correlated to those of the tipping rain gauge (*Rf*′) as follows:

$$Rf = 1.01 \times Rf' + 2.89, \quad R^2 = 0.99, n = 35$$

Thus, we used the rainfall data from the storage-type gauge for our analysis.

We measured throughfall in each subplot. Storage-type throughfall collectors (funnel size: 210 mm diameter) were placed at the center of each subplot. When a bamboo plant was located at the center, the collector was placed next to the bamboo plant.

We measured stemflow in three bamboo plants, the DBHs of which were 12.4, 13.4, and 13.7 cm. Stemflow from the bamboo plants was collected and measured with a collar-type gauge. The stemflow collectors consisted of three parts: (i) a rubber hose sealed with silicone to form a watertight junction between the collector and the bamboo culm, (ii) a concentric collar placed around the bamboo trunk 1.5 m above the ground to trap stemflow, and (iii) a conducting hose to divert stemflow into a bottle. The method is described in detail in Manfroi et al. (2004).

Rainfall, throughfall, and stemflow measurements were carried out from 28 December 2005 to 26 December 2006. Because measurements were made weekly, rainfall, throughfall, and stemflow data often included several rainfall events. Two snowfall events were recorded during the measurement period. These data were excluded from the analysis because snowfall interception processes are different from rainfall interception processes (e.g., Lundberg and Halldin 2001).

Once a month, leaf area index (*LAI*) was measured at each subplot using digital nonspherical color photographs (Nikon Coolpix 990). The photographs were taken 0.8 m above the throughfall collectors on cloudy days to avoid the effects of direct sunlight, and *LAI* was determined from the photographs using Gap Light Analyzer software (Frazer et al. 1999).

Analysis

Interception (*I*) of the plot was calculated by the water balance method as follows:

$$I = Rf - Tf - Sf \quad (1)$$

where *Rf* is rainfall, *Tf* is throughfall, and *Sf* is stemflow at the plot. *Tf* was estimated by averaging throughfall amounts for the 25 subplots.

Our stemflow measurement data showed a positive correlation between DBH and stemflow amounts, which agrees with the results of Hattori and Abe (1989). The DBH–stemflow relationship was fitted by an exponential function:

$$Sf = a \cdot \exp(b \cdot \mathrm{DBH}), \quad (2)$$

where *a* and *b* are parameters. These parameters were determined for each week. The correlation coefficient *R* ranged between 0.83 and 1.00, and exceeded 0.90 in most cases. The DBH data for the plots were substituted into Eq. (2) to calculate the total stemflow volume of each plot. *Sf* was obtained by dividing the total stemflow volume by the plot area.

The *I/P* value of the bamboo plot was compared with those of other forest sites in Japan, which were obtained from published literature. We limited our study to include only Japanese data, because interception ratios are strongly associated with rainfall characteristics (e.g., intensity and duration), and such characteristics are relatively consistent within Japan (Komatsu et al. 2008b). For this summary, we applied two criteria: first, the observation periods should be longer than one year, because the monthly interception ratio value should vary from month to month (Hattori et al. 1982; Cape et al. 1991). Though the annual interception ratio value should vary from year to year, this year-to-year variability is much smaller than the month-to-month variability (e.g., Tanaka et al. 2005). We also excluded data collected from sites located in regions with heavy snowfall, because our focus was on rainfall interception rather than snowfall interception, and because bamboo forests are rarely distributed in heavy snowfall regions (Uchimura 1994).

Results and discussion

Annual sum

Rainfall (*Rf*), throughfall (*Tf*) and stemflow (*Sf*) during the measurement period were 2,105, 1,556, and 322 mm, respectively. Interception (*I*) of the plot calculated using Eq. (1) was 228 mm. *Tf/Rf*, *Sf/Rf*, and *I/Rf* were 73.9, 15.3, and 10.8%, respectively.

We carried out stemflow measurements on three bamboo plants, with DBH ranging from 12.4 to 13.7 cm. Our measurements, therefore, did not cover the whole range of DBH at the site (Fig. 1). This means that stand-scale stemflow in this study is an estimate, rather than an accurate measurement. For increased accuracy of stand-scale stemflow, a greater sample size that includes all size classes would be required. We discuss the accuracy of our stemflow measurement and its effects on our conclusions below (See "Comparison with other forest sites").

Seasonal variation

Figure 2a shows monthly variations in *Rf*, *Tf*, *Sf*, and *I*. Monthly variations in the distribution rates of *Tf/Rf*, *Sf/Rf*, and *I/Rf* are shown in Fig. 2b. *I/Rf* was less than 20% throughout the year, except in October. The higher *I/Rf* value in October was primarily caused by the lower *Rf* of that month (e.g., Murai 1970; Ward and Robinson 2000). *LAI* was greater in April than in the other months (Fig. 2c)

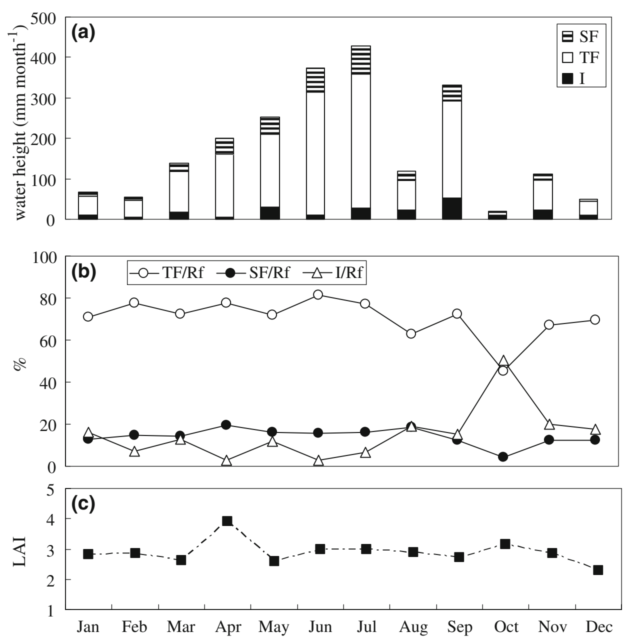

Fig. 2 Seasonal changes in: **a** rainfall (*Rf*), throughfall (*Tf*), stemflow (*Sf*), and interception (*I*); **b** *Tf/Rf*, *Sf/Rf*, and *I/Rf*; **c** leaf area index *LAI*. *LAI* was calculated by averaging 25 subplot values

because of leaf emergence in this month. The decrease in *LAI* in May was due to leaf fall. However, we did not observe greater *I/Rf* in April, indicating that seasonal *LAI* variation was not the primary factor determining *I/Rf*. Though Hattori and Abe (1989) also examined seasonal variations in *I/Rf*, they did not examine the relationship between *LAI* and *I/Rf*. In our study, the relationship between *LAI* and *I/Rf* suggested that seasonal *LAI* variation was not the primary factor determining *I/Rf*.

Comparison with other forest sites

Table 1 shows *I/Rf* values summarized from other published studies. The *I/Rf* values of natural and plantation forests ranged between 12.5 and 29.8% ($n = 19$). Many studies have shown that *I/Rf* is related to *Rf* as well as to forest properties (e.g., Suzuki et al. 1979; Ward and Robinson 2000; Komatsu et al. 2008b). Figure 3 shows the relationships between *Rf* and *I/Rf*. The *I/Rf* values of bamboo sites (our site and Hattori and Abe 1989) did not exceed those of other natural and plantation forests. The relatively low *I/Rf* value of our site was primarily caused by a relatively high *Sf/Rf* value. The *Sf/Rf* value of our site was higher than those of other forest sites, except for the two sites reported by Murai and Kumagai (1989) and Sato et al. (2002) (Table 1).

As noted above, the *Sf* data in our study represents an estimate based on three plants, rather than measurement of every bamboo plant in the study plot. Even so, our data indicate that the interception ratio of our plot did not exceed those of other natural and plantation forests despite the limited sample size used for *Sf* estimates. Various methods are used to estimate stand-scale stemflow. The true stand-scale stemflow amounts must exceed estimated values based on the following assumptions: (i) stemflow in bamboos in the DBH < 12.0 cm class were assigned a value of zero (note: our stemflow measurements were carried out on bamboo plants in the DBH = 12–14 cm class), and (ii) stemflow in bamboo plants with DBH > 12.0 cm were assigned the average value obtained from measurement of the three bamboo plants. Based on these assumptions, stand-scale stemflow was estimated to be 206 mm year^{-1}, which corresponds to 9.8% of annual rainfall. Thus, the interception ratio was calculated as

Table 1 *Tf/Rf*, *Sf/Rf*, and *I/Rf* of moso bamboo and other forest sites in Japan, where *Rf*, *Tf*, *Sf*, and *I* indicate rainfall, throughfall, stemflow, and interception, respectively

Species	Stand density (trees/ha)	Mean DBH (cm)	Mean annual rainfall (mm)	*Tf/Rf* (%)	*Sf/Rf* (%)	*I/Rf* (%)	References
Moso bamboo							
Phyllostachys pubescens	6,800	11.3	2,105	73.9	15.3	10.8	This research (exponential function)
Phyllostachys pubescens	7,200	9.6	1,398	72.6	15.2	12.2	Hattori and Abe (1989)
Natural							
Deciduous broadleaved forest	5,070	–	1,689	82.5	5.0	12.5	Park et al. (2000)
Deciduous broadleaved forest	3,502	–	1,621	66.5	9.9	23.8	Park et al. (2000)
Plantation							
Cryptomeria japonica	513	39	2,304	78.6	5.6	15.8	Tanaka et al. (2005)
Cryptomeria japonica	1,467	23	1,584	63.7	10.2	26.1	Sato et al. (2003)
Chamaecyparis obtusa	923	34	2,053	74.2	11.4	14.4	Tanaka et al. (2005)
Chamaecyparis obtusa	3,200	8	1,793	68.7	5.8	25.5	Iwatsubo and Tsutsumi (1967)
Chamaecyparis obtusa	2,051	16	1,543	67.7	11.0	21.3	Hattori et al. (1982)
Chamaecyparis obtusa	1,750	18	1,336	64.5	12.1	23.4	Hattori and Chikaarashi (1988)
Pinus densiflora	830	20	1,024	79.9	0.7	19.4	Murai (1970)
Pinus densiflora	1,575	12	1,513	83.0	3.0	14.0	Mitsudera et al. (1984)
Pinus densiflora	2,300	20	1,291	78.1	0.5	20.7	Taniguchi et al. (1996)
Pinus densiflora	1,700	20	1,291	68.9	1.2	29.8	Taniguchi et al. (1996)
Pinus thunbergii	3,326	5.5	2,876	50.4	27.3	22.2	Murai and Kumagai (1989)
Pinus thunbergii	3,895	8.5	2,876	65.5	6.6	27.9	Murai and Kumagai (1989)
Pinus thunbergii	3,810	7.5	2,876	60.5	15.5	24.0	Murai and Kumagai (1989)
Pinus thunbergii	3,222	5.5	2,847	72.2	5.9	21.9	Murai and Kumagai (1989)
Pinus thunbergii	2,376	10.5	2,847	72.8	5.7	21.5	Murai and Kumagai (1989)
Pinus thunbergii	1,614	9.5	2,847	76.3	4.0	19.7	Murai and Kumagai (1989)
Lithocarpus edulis	3,418	10.8	1,540	29.7	50.2	20.1	Sato et al. (2002)

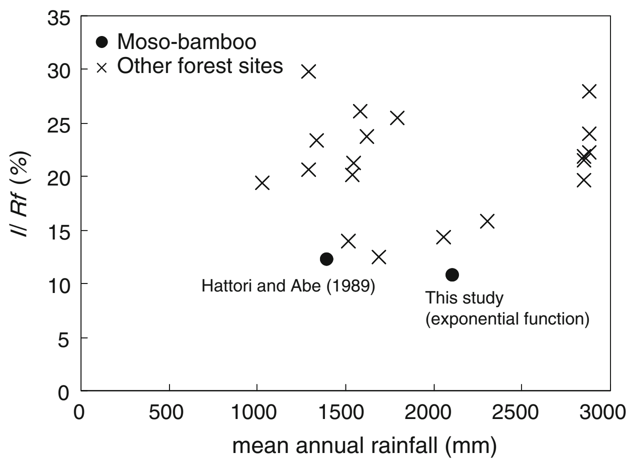

Fig. 3 Relationship between mean annual rainfall and interception ratio (interception/rainfall). Data from this study and from that of Hattori and Abe (1989) are shown

16.3%. This interception ratio did not exceed those of natural and plantation forests (Fig. 3).

We used an exponential function when calculating *Sf* (Eq. 2). When a linear function ($Sf = a \cdot \mathrm{DBH} + d$, where *c* and *d* are parameters) was applied instead of the exponential function, our conclusions remained the same. *Sf* and *I* during the measurement period were calculated as 258 and 291 mm, respectively. *Sf/Rf* and *I/Rf* were 12.3 and 13.8%, respectively. This interception ratio did not exceed those of natural and plantation forests (Fig. 3), indicating that our conclusions were not altered when the linear function was used. Note that the *I/Rf* value shown in Figs. 2 and 3 and Table 1 was based on the exponential function, because the correlation coefficient based on the exponential function was higher than that based on the linear function.

Hattori and Abe (1989) reported that the *I/Rf* value of a bamboo forest did not exceed those of other natural and plantation forests, and that this was due to the relatively high *Sf/Rf* of bamboo forests. Our results agreed with their findings in this respect. Hattori and Abe (1989) suggested that the relatively high *Sf/Rf* values of bamboo forests may be due to the structure of bamboo plants (i.e., a straight and smooth stem and widespread branches that would efficiently concentrate rainwater).

Our study contributes to the state of knowledge on rainfall interception in Japanese forests, not only by measuring rainfall interception at another bamboo forest site, but also because we extensively summarized rainfall interception data from various Japanese forests. In our study, we summarized 19 datasets from natural and plantation forests in Japan, adding to the previous summary of data from four other studies (Hattori and Abe 1989).

Ueda (1979) and Uchimura (1994) speculated that bamboo forests consume more water by evapotranspiration than natural and plantation forests. However, our results showed that the rainfall interception ratio of bamboo forests did not exceed those of other natural and plantation forests. As mentioned above, there have been no previous studies on the transpiration of moso bamboo forests. Transpiration within bamboo forests should be measured. Such information will help to predict changes in water resources that result from the replacement of forests by bamboo.

Acknowledgments This research was partly supported by a research grant from Munakata City and a Grant-in-Aid for Scientific Research (#17380096 and #20780119) from the Japanese Ministry of Education, Culture, Sports, Science and Technology. We thank Yoshinori Shinohara, Shoko Ikezaki, Jun'ichro Ide, Ryoko Maruno, and the Ecohydrology Laboratory at Kyusyu University Forest for their support and their help with our research. Thanks are also due to two anonymous reviewers, whose comments greatly improved this manuscript.

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