



## Characteristics of stemflow for tall stewartia (*Stewartia monadelpha*) growing on a hillslope

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### SUMMARY

The characteristics of stemflow were observed in a tall stewartia (*Stewartia monadelpha*) deciduous forest on a hillslope in central Japan, revealing new findings for a previously unreported type of deciduous forest. Using 2-year observations of 250 rainfall events, we analyzed seasonal and spatial variations in stemflow for several trees, and applied additional data sets of throughfall and plant area index (PAI) to produce a rough estimate of seasonal variations in rainfall redistribution processes and canopy architecture for a single tree. Compared to previous findings for other deciduous tree species, the ratios of throughfall, stemflow, and interception to open-area rainfall obviously varied with PAI changes for tall stewartia. Meteorological conditions of rainfall amount, rainfall intensity, wind speed, and wind direction had little effect on stemflow generation, which was mainly affected by variation in canopy architecture. Three novel characteristics of stemflow were identified for several tall stewartia trees. First, the yearly stemflow ratio at the forest-stand level for tall stewartia (12%) was high compared to previous findings on beech and oak stands, indicating tall stewartia has considerably high potential to generate a great amount of stemflow. Second, stemflow tended to be 1.3–2.0 times greater in the leafed period than in the leafless period. Third, the amount of stemflow was 12–132 times greater on the downslope side of the stem than on the upslope side. It likely caused by the uneven area between the upslope and downslope sides of the canopy and by asymmetrical stemflow pathways between the upslope and downslope sides of the trunk due to downslope tilting of the tree trunk.

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### Introduction

In rainfall redistribution processes in forest stands, a part of rainfall is intercepted by the canopy, while other parts are partitioned into throughfall and stemflow through the canopy as diffuse and point inputs to the forest floor, respectively. Therefore, the rainwater amount reaching the forest floor is considerably heterogeneous. Many studies have examined the effects of rainfall redistribution processes on soil water dynamics (e.g., Voigt, 1960; Durocher, 1990; Bouten et al., 1992; Keim et al., 2006; Liang et al., 2007). Most of these studies emphasized that the spatial distribution of throughfall mainly affects soil water dynamics. The low ratios of stemflow were usually disregarded, and interception was usually dealt with as the difference between gross and net rainfall (the sum of throughfall and stemflow). Throughfall reaching the forest floor either falls from foliage as foliage drip or passes directly through gaps within the canopy as direct throughfall;

these types of throughfall are mainly determined by the canopy architecture. Thus, previous studies reported various spatial distributions of throughfall. For example, higher throughfall was observed at the canopy perimeter in a Norway spruce (*Picea abies* [L.] Karst.) forest (Beier et al., 1993), at a middle position within the canopy of a black spruce (*Picea mariana* [Mill.] Britton, Sterns and Poggenburg) forest (Carleton and Kavanagh, 1990), and near the tree stems in a Sitka spruce (*Picea sitchensis* [Bong.] Carr.) forest (Ford and Deans, 1978), indicating large interspecies variations in spatial throughfall distribution, even within the same genus.

Although spatial variation in throughfall contributes to spatial variation in soil water, throughfall patterns may not necessarily be reflected in the soil moisture patterns (Pressland, 1976; Raat et al., 2002). Excluding spatial variability of soil thickness and physical properties, one explanation would be the influence of localized concentrations of stemflow input (Voigt, 1960; Keim et al., 2006). Although previous studies paid little attention to the effects of stemflow due to the low ratio of stemflow to precipitation reported in many forest stands (e.g., Bouten et al., 1992; Keim et al., 2006; Belk et al., 2007), the point input characteristic of stemflow may have major implications for soil water dynamics, even for tree species with a low ratio of stemflow to precipitation.

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Aboal et al. (1999) quantified the stemflow of 30 sample trees belonging to six different species in a laurel forest and found that precipitation could be concentrated up to 12.8 times in the infiltration areas of the trees by stemflow, even though the annual stemflow only represented 6.85% of the gross precipitation. Durocher (1990) recorded very rapid water movement beneath trees and suggested that this movement was caused by small-scale spatial variability in the water input to the soil surface by stemflow. In our previous study (Liang et al., 2007), we conducted detailed observations of soil water dynamics around a tree for many storm events, and observed that maximal soil water storage was more than 100–200% of the cumulative open-area rainfall at the points downslope from a tree stem on a hillslope; we attributed this to concentrated stemflow rapidly flowing into soil layers along the pathways around roots as bypass flow. Therefore, the stemflow infiltration process, differing from the throughfall infiltration process, has great implications for observations and simulations of soil water dynamics (Liang et al., 2009).

In addition to studies on soil water dynamics, research has focused on the relationship between global changes in climate and rainfall redistribution processes, which are expected to greatly and directly impact ecosystems. Under the climatic conditions found in Japan, the predicted change in forest stands from coniferous trees to broad-leaved evergreen trees, due to natural thinning but also to global warming, would cause significant changes in water movement and groundwater recharge processes (Tanaka et al., 2008). Iida et al. (2005) observed that during the period of forest stand succession from Japanese red pine to oak trees, there was a substantial increase in stemflow, essentially no change in throughfall, and a substantial decrease in interception. Therefore, clarifying the characteristics of stemflow in broad-leaved forests is important in light of the lack of previous research and potential succession from coniferous to broad-leaved forests in Japan caused by accelerating global climate change.

Except for the factors of forest types and locations, stemflow yield is greatly influenced by meteorological conditions such as rainfall amount, rainfall intensity, wind speed, and wind direction (Crockford and Richardson, 2000; Levia and Frost, 2003). Although Levia and Frost (2003) pointed out general tendencies of stemflow

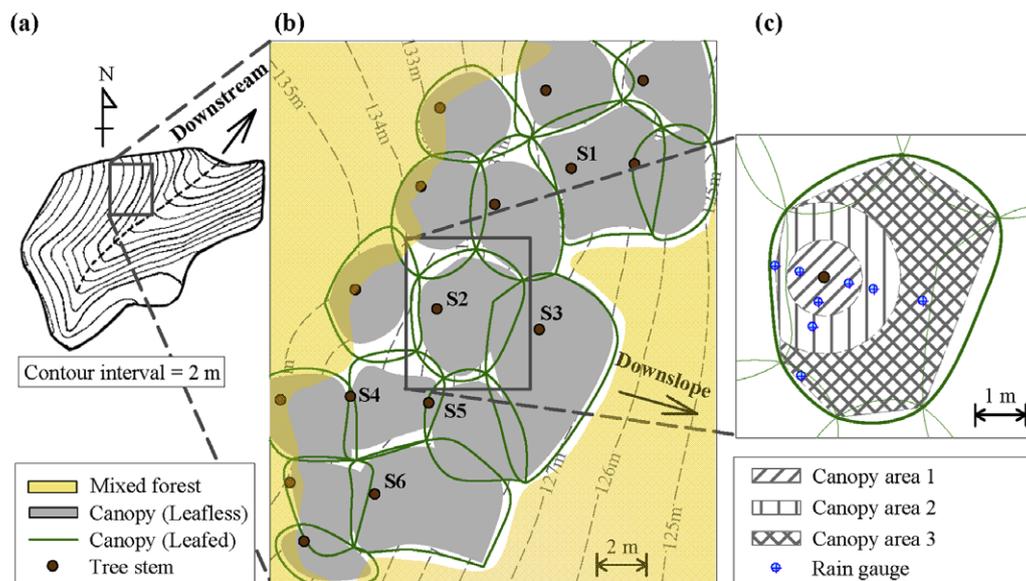
yield, which increased with the magnitude of a precipitation event and wind speed but decreased with rainfall intensity of incident gross precipitation, they also presented some study cases that contrasted with generally held assumptions, exemplifying the diverse relationship between stemflow yield and meteorological conditions. Moreover, characteristics of stemflow in deciduous forests should vary more than in other forest types because of changes in canopy architecture between leafed and leafless conditions. Although some studies have reported that throughfall and stemflow increased, and interception decreased, in the leafless period of deciduous forest stands (Helvey and Patric, 1965; Neal et al., 1993; Staelens et al., 2008), those studies mostly focused on beech or oak species; few studies have examined other deciduous tree species (Llorens and Domingo, 2007). Thus, stemflow studies conducted in beech or oak forests may be insufficient to represent the characteristics of stemflow in all deciduous forests.

The purpose of this study was to clarify the characteristics of stemflow in a type of deciduous forest that has not been reported on previously: tall *Stewartia* (*Stewartia monadelphica* Siebold et Zucc.). Using long-term observations of many rainfall events, we quantitatively analyzed the seasonal and spatial variations in stemflow for several trees. We also collected additional throughfall data to provide a rough estimate of seasonal variations in the ratios of stemflow, throughfall, and interception to open-area rainfall for a single tree. We compared the results observed in tall *Stewartia* with previously reported findings for other tree species.

## Methods and materials

### Study area

Observations were conducted on a hillslope at the Kamigamo Experimental Station of Kyoto University (Fig. 1a), located in southern Kyoto Prefecture, central Japan (35°04'N, 135°46'E). The climate of this area is warm-temperate. The mean annual air temperature for the 1976–2005 period was 14.7 °C, with highest and lowest monthly averages of 27.4 °C (August) and 2.4 °C (January), respectively (Kyoto Univ., 2007). The mean annual precipitation was 1523 mm. Rainfall was distributed year-round, with a peak



**Fig. 1.** (a) Map showing the small catchment area with a small channel (dashed line). (b) Topography of the observation area showing the locations of the tall *Stewartia* tree stems, and tree canopy projection areas in the leafed and leafless periods. (c) Setting points of rain gauges to estimate throughfall within radii of 0–75 cm (canopy area 1), 75–150 cm (canopy area 2), and farther (canopy area 3) from the stem of tree S2. The observation area shown in (b) was surrounded by a mixed conifer–broad-leaved forest; trees S1–S6 were selected to measure stemflow.

in summer and only a few centimeters of snow for a short time in winter.

The hillslope had a mean gradient of 28°, with brown forest soil classified as Cambisol underlain by sandstone and slate. It was predominantly covered with tall *Stewartia* (*S. monadelphica*), planted in 1956 and surrounded by a mixed conifer–broad-leaved forest. The genus *Stewartia* includes 21 species that are distributed throughout Japan, Korea, China, and eastern America (Li et al., 2002). Of these, tall *Stewartia* is widespread in natural forests in western and southern parts of Japan, classified in the US Department of Agriculture (USDA) hardiness zones of 6B through 8B. Like most species of *Stewartia*, tall *Stewartia* is a deciduous broad-leaved tree with upward-tilting branches (Fig. 2a) and smooth-exfoliated bark (Fig. 2b). Tall *Stewartia* exhibited leaf fall in November and regrowth in April in the study area. We separated canopy architecture into leafed and leafless periods based on field observations of the foliage states.

#### Observations of stemflow, throughfall, and canopy architecture for a single tree

To provide a rough estimate of the ratios of stemflow, throughfall, and interception to open-area rainfall for tall *Stewartia* growing on a hillslope, observations were conducted for a single tall *Stewartia*, tree S2 (Fig. 1b) during the observation period from July 2006 through August 2007.

To measure stemflow, we used two tubes cut longitudinally and wrapped spirally around the upslope and downslope sides of the trunk to collect separate samples of stemflow from the upslope (SF-up) and downslope (SF-down) sides of the trunk of tree S2. The flow rates of SF-up and SF-down were measured using tipping-bucket gauges that tipped at 4 ml (Davis, 7852 M) and 500 ml (Ikeda, TQX-500), respectively.

To estimate the amount of throughfall under the canopy of tree S2, we installed a tipping-bucket rain gauge (Davis, 7852 M; 0.2 mm per tip; water collection area, 200 cm<sup>2</sup>) at each of five points (TF-5p): 100 cm and 50 cm upslope from the tree stem, and 50 cm, 100 cm, and 200 cm downslope from the stem of tree S2 (Fig. 1c) during the observation period from July 2006 through April 2007. The canopy area of tree S2 was divided into three parts: annuli of 0–75 cm (canopy area 1: 1.74 m<sup>2</sup>), 75–150 cm (canopy area 2: 4.31 m<sup>2</sup>), and farther (canopy area 3: 9.73 m<sup>2</sup>) from the stem (Fig. 1c). Thus, rainwater collected by tipping-bucket gauges at 50 cm, 100 cm, and 200 cm from the stem were presumed to

represent throughfall amounts within canopy area 1, canopy area 2, and canopy area 3, respectively. Then, the average throughfall amount within the canopy of tree S2 could be estimated as an area-weighted mean for all measurement points. To increase the resolution of throughfall measurement, we additionally installed the same type of tipping-bucket rain gauge at each of three points (total was eight, TF-8p): 50 cm, 100 cm, and 200 cm laterally from the stem of tree S2 (Fig. 1c) during the observation period from May 2007 through June 2008. The relationship between TF-5p and TF-8p during this observation period was used to estimate TF-8p during the former observation period during which only TF-5p was measured. Although the sample size of throughfall was small in comparison to previously published studies (Staelens et al., 2006; Zimmermann et al., 2007), throughfall in our study was an additional data set that helped to provide a rough estimate of rainfall redistribution processes relating to seasonal changes in stemflow.

To estimate seasonal variations in canopy architecture, the plant area index (PAI) was measured monthly above TF-5p with an optical plant canopy analyzer (LI-COR, Inc., LAI-2000) using default parameters and calibration from 7 May 2006 through 21 April 2007. We used a 90° mask on the lens of the analyzer and conducted four measurements to estimate PAI over all azimuth angles at each point and to avoid contamination of the measurement by the instrument operator. Open-sky calibration measurement was conducted at an open site 200 m from the observation slope before PAI measurement at each point. Although the absolute value of PAI was influenced by the hillslope and adjacent coniferous forests for some azimuth angles, the average PAI for all measurement points could roughly represent the seasonal variations in canopy architecture in the study area. This measurement method for PAI has well applied in previous studies (Aboal et al., 2000; Deguchi et al., 2006; Kosugi et al., 2007).

#### Observations of stemflow for several trees

To verify general trends in stemflow generation, we selected four other tall *Stewartia* trees (S3–S6 in Fig. 1b) to measure stemflow during the observation period from June 2007 through June 2008. SF-up and SF-down were also separately collected for these trees. We used four 16-L containers with siphon drainage equipment to determine SF-down based on water-level changes in the containers (previously calibrated in the laboratory) and tipping-bucket gauges (Davis, 7852M) to measure SF-up. In our previous

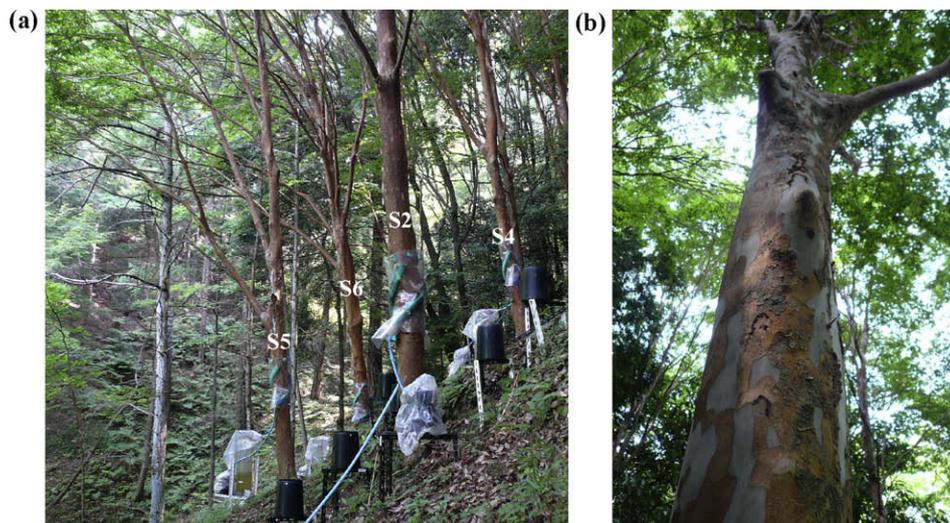


Fig. 2. (a) Upward branches and (b) smooth-exfoliated bark of tall *Stewartia*. Trees S2 and S4–S6 in (a) correspond to those shown in Fig. 1b.

study (Liang et al., 2007), we conducted detailed observations of soil water dynamics around tree S1 (Fig. 1b). From 1 April through 30 June 2008 (i.e., the leafed period only), we additionally measured SF-up and SF-down of tree S1 using the same method as described above for tree S2.

Table 1 provides information on observation trees S1–S6. We observed projection locations of canopy perimeter for 6–11 points, and then surveyed the points using an impulse (Laser Technology, Inc., 200LR) to estimate the canopy projection area for each tree in both leafed and leafless periods (Fig. 1b). The same impulse was used to measure tree height, calculated by the distance and angle from the impulse to the top and base of a tree. The canopy projection area determined during the leafed period was divided into the upslope and downslope sides from the trunk (Table 1); the overlapping areas were divided equally into adjacent canopies for each tree (Fig. 1b and c). The canopy projection areas of observation trees S1–S6 were not overlapped by the mixed conifer–broad-leaved forest (Fig. 1b).

During all observation periods, measurements of stemflow and throughfall were simultaneously and automatically recorded at 5-min intervals by a data logger (Campbell, CR-1000). Gross rainfall (open-area rainfall) data provided by the Kamigamo Experimental Station of Kyoto University was measured using a tipping-bucket rain gauge (Ikeda RH-5; 0.5 mm per tip, water collection area, 314.16 cm<sup>2</sup>) at an open site 112 m from the observation slope. Wind speed and wind direction data were provided by the Japan Meteorological Agency; these data were measured at a station approximately 6.6 km from the observation slope.

Data analysis

Meteorological data of open-area rainfall and wind were analyzed for each rainfall event. An individual rainfall event was defined as an amount more than 0.5 mm and separated from another event by six consecutive hours without rain. To provide a rough estimate of rainfall redistribution processes, we calculated the ratios of total stemflow, throughfall, and interception amounts to open-area rainfall in the leafed and leafless periods. Stemflow was determined by the sum of SF-up and SF-down per canopy projection area of tree S2, and interception was estimated as open-area rainfall minus the sum of throughfall and stemflow for each rainfall event.

To clarify how changes in canopy architecture affect rainfall redistribution processes, monthly average PAI values were compared to the monthly ratios of total throughfall, stemflow, and interception amounts to open-area rainfall for tree S2. We compared the results to those of three previous studies (Deguchi et al., 2006; Sraj et al., 2008; Staelens et al., 2008) that reported seasonal PAI changes and the ratios of throughfall, stemflow, and interception amount to gross precipitation in deciduous forests. As in our study, the three previous studies estimated interception as gross precipitation minus the sum of throughfall and stemflow.

To estimate stemflow yield on the forest-stand level for tall *Stewartia*, we calculated the ratio of total stemflow volume per total

canopy projection area of trees S1–S6 to open-area rainfall. We compared results to values reported in previous studies for beech (Giacomin and Trucchi, 1992; Chang and Matzner, 2000; Santa Regina and Tarazona, 2000; Mosello et al., 2002) and oak (Moreno et al., 2001; Silva and Rodriguez, 2001; Mosello et al., 2002; Holscher et al., 2003).

For the spatial variation in stemflow, we assumed that the stemflow production rate was identical in both upslope and downslope sides of the canopy, and then calculated stemflow supplies from the upslope and downslope sides of the canopy for each rainfall event,  $Sf_{up}^{supply}$  and  $Sf_{down}^{supply}$ , respectively, by

$$Sf_{up}^{supply} = (Sf_{up}^{yield} + Sf_{down}^{yield}) \times C_{up} / (C_{up} + C_{down})$$

$$Sf_{down}^{supply} = (Sf_{up}^{yield} + Sf_{down}^{yield}) \times C_{down} / (C_{up} + C_{down}), \tag{1}$$

where  $Sf_{up}^{yield}$  and  $Sf_{down}^{yield}$  correspond to SF-up and SF-down volumes, and  $C_{up}$  and  $C_{down}$  represent upslope and downslope canopy areas (Table 1), respectively. Then, we compared each of  $Sf_{up}^{supply}$  and  $Sf_{down}^{supply}$  to  $Sf_{up}^{yield}$  and  $Sf_{down}^{yield}$  to clarify the spatial variation in stemflow for trees growing on a hillslope.

Results and discussion

Seasonal variation in canopy architecture and open-area rainfall events

Average PAI for five measurement points was clearly larger in the leafed period than in the leafless period (Fig. 3). Average PAI values in the leafed and leafless periods were 3.7 and 2.2, respec-

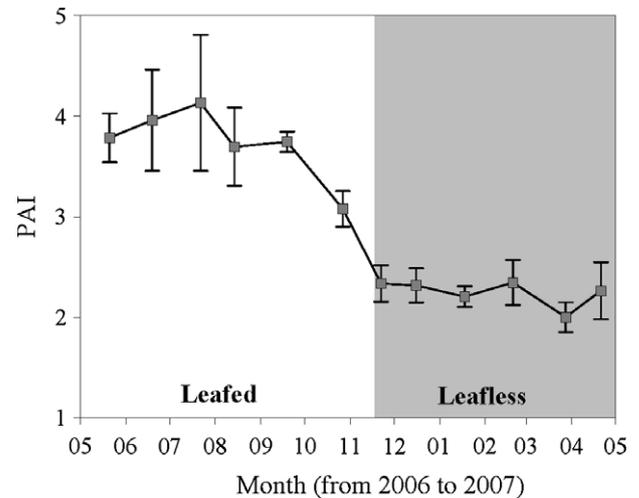


Fig. 3. Temporal variations in plant area index (PAI) from May 2006 to April 2007. Symbols are average PAI values for five measurement points (TF-5p), and error bars are standard deviations. The shaded area indicates the leafless period.

Table 1

Upslope, downslope, and total canopy projection area, height, diameter at breast height (DBH), and angle of downslope inclination of the study tree stems.

Tree	Canopy area (m <sup>2</sup> )			Height (m)	DBH (cm)	Angle of inclination (°)
	Upslope	Downslope	Total			
S1	3.63	16.74	20.38	17.5	22.3	5.4
S2	2.72	12.70	15.42	13.8	23.7	4.3
S3	8.21	18.18	26.39	13.5	29.1	1.6
S4	0.24	12.24	12.48	12.7	21.8	10.0
S5	0.05	11.03	11.08	12.1	20.3	5.8
S6	6.15	16.67	22.83	15.4	27.9	6.8

tively, for all measurement points, with a maximum of 4.1 measured in July and a minimum of 2.0 measured in March.

Fig. 4a shows meteorological data for open-area rainfall and wind speed measured in the whole observation period from 1 July 2006 through 30 June 2008, in which the two leafless periods were observed from 22 November 2006 to 1 May 2007 and from 20 November 2007 to 12 May 2008 (i.e., shaded areas). Excluding the failed observation period from 5 to 19 April 2007 (Fig. 4a), 250 rainfall events were observed. For each rainfall event in all observation periods, rainfall amounts ranged from 0.5 to 194 mm, average rainfall intensity ranged from 0.1 to 35 mm/h, and average wind speed ranged from 0.3 to 5 m/s. Although rainfall amount, rainfall intensity, and wind speed were slightly greater for

some events in the leafed period than in the leafless period (Fig. 4a) due to the intensive frontal rainfalls and convectional showers that occur in summer, those histograms showed similar frequency distributions in both leafed and leafless periods (Fig. 4b). Therefore, meteorological conditions differed only slightly between the leafed and leafless study periods.

*Comparison of how changes in canopy architecture affect seasonal variation in stemflow for tall stewartia and other deciduous tree species*

The amount of TF-5p and TF-8p differed slightly: TF-8p was 1.16 and 0.96 times TF-5p in the leafed and leafless periods,

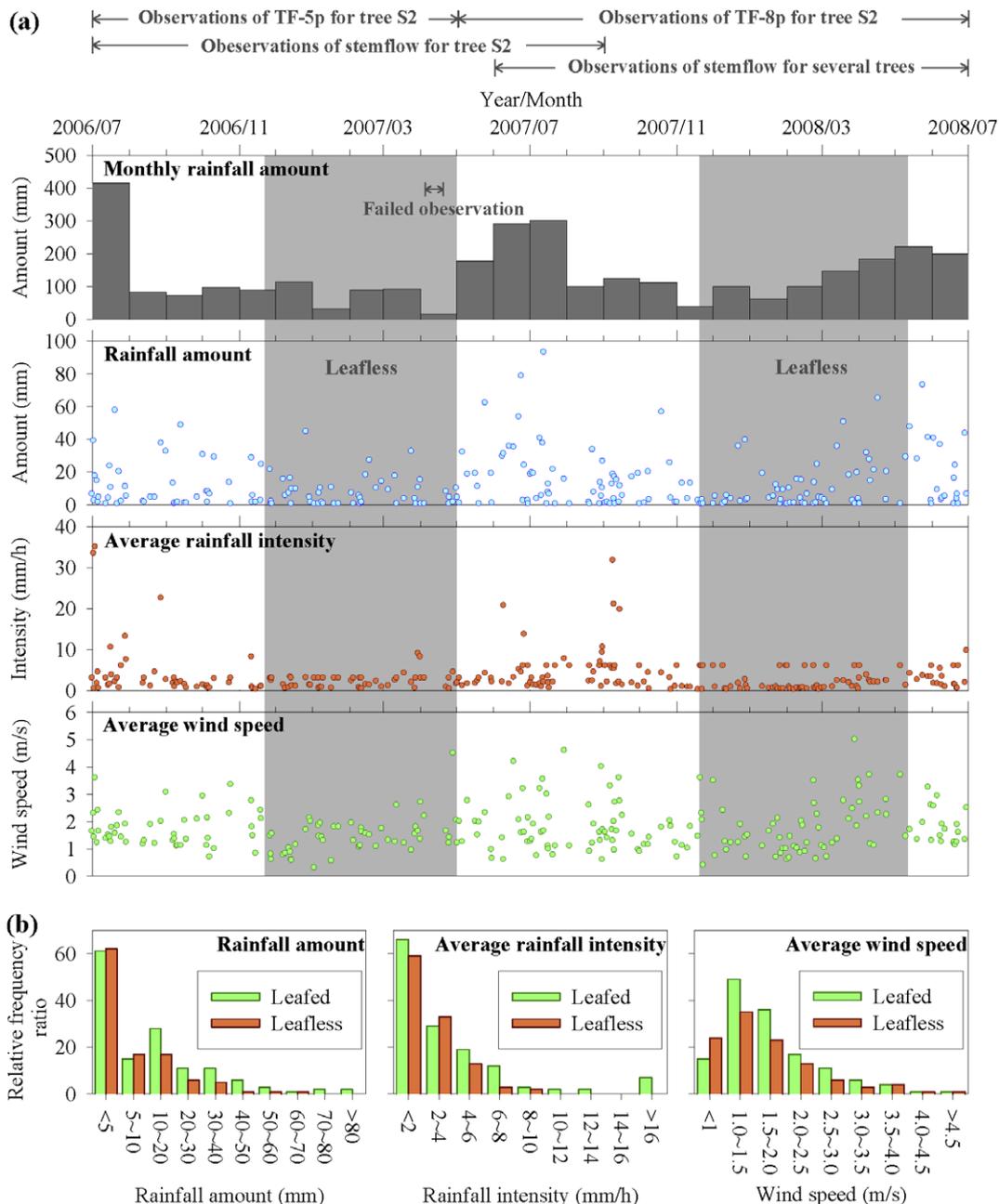
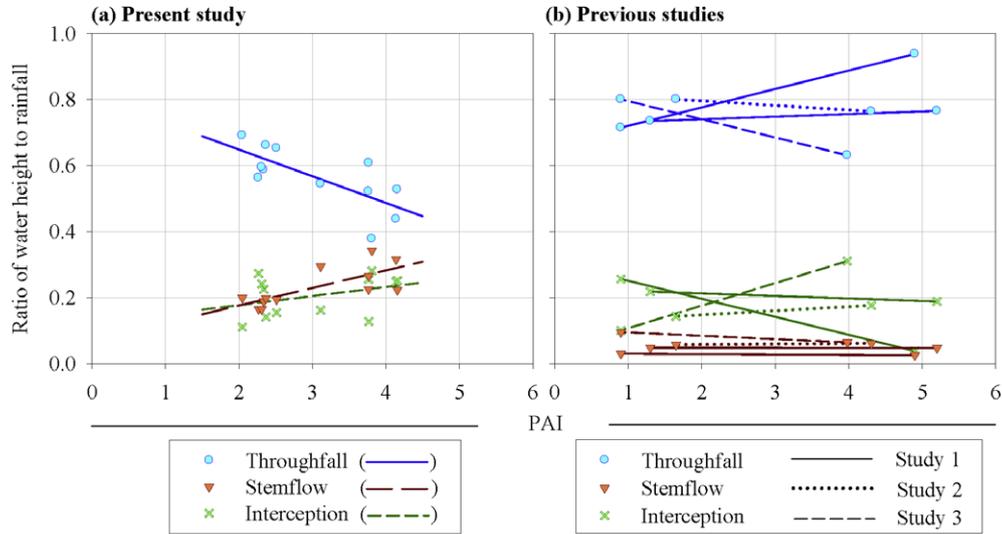


Fig. 4. (a) Cumulative open-area rainfall for each month, and rainfall amount, average rainfall intensity, and average wind speed for each rainfall event. (b) Histograms of rainfall amount, average rainfall intensity, and average wind speed for all observation periods. The arrows in (a) indicate the four observation periods for throughfall measured at five points (TF-5p) and eight points (TF-8p), stemflow measured for a single tree (S2) and for several trees (S1, S3–S6), respectively. Shaded areas indicate the leafless periods. Observations failed from 5 to 19 April 2007.



**Fig. 5.** Relationship between monthly average plant area index (PAI) and monthly average ratios of throughfall, stemflow, and interception to open-area rainfall (a) in the present study and (b) three previous studies: study 1 (Sraj et al., 2008), study 2 (Deguchi et al., 2006), and study 3 (Staelens et al., 2008, with data from Mussche et al., 2001). There were two data sets from two measurement plots in study 1.

**Table 2**

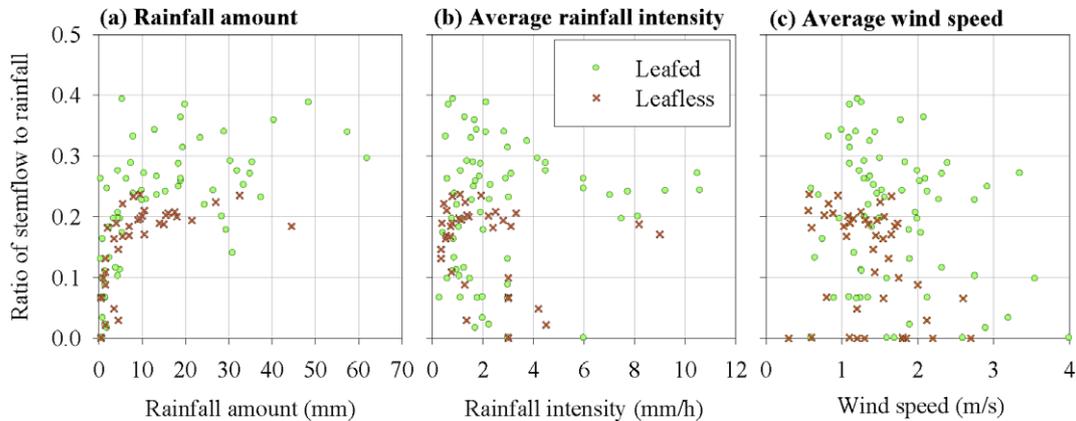
The ratio of stemflow to open-area rainfall for trees S1–S6 in the leafed, leafless, and yearly periods. Observation for tree S1 was only conducted in the leafed period.

Tree	Leafed (%)	Leafless (%)	Yearly (%)
S1	25.9	–	–
S2	28.1	19.1	26.0
S3	10.9	7.9	10.3
S4	17.2	8.8	14.7
S5	3.4	2.7	3.3
S6	7.6	4.6	6.6

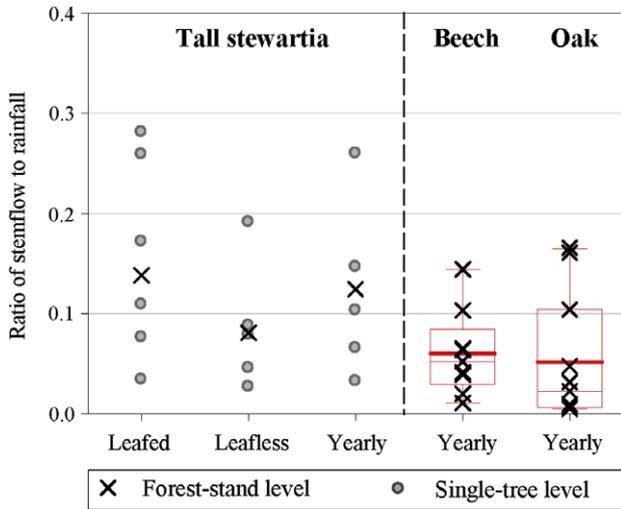
respectively. We used these relationships to estimate TF-8p when only TF-5p was measured. We observed significant seasonal variations: throughfall increased and stemflow and interception decreased from the leafed period to the leafless period. The ratios of stemflow, throughfall, and interception to open-area rainfall were 28%, 50%, and 22% in the leafed period, and 19%, 63%, and 18% in the leafless period, respectively.

Throughfall, stemflow, and interception ratios varied obviously with changes in PAI (Fig. 5a), showing a clear inverse correlation in throughfall versus PAI, and positive correlations in

stemflow and interception versus PAI. Fig. 5b shows the relationships between PAI and variations in rainfall redistribution reported in three previous studies. Study 1 (Sraj et al., 2008) used two data sets measured on the south- and north-facing slopes of a mixed deciduous forest. Throughfall was sampled using two large gutter collectors in combination with ten manual roving gauges; stemflow was measured for single ash and oak trees on each of two plots; PAI values were derived from hemispherical photography. Seasonal variations in rainfall redistribution processes were small; the higher throughfall ratio in the leafed period was attributed to the high intensity of precipitation in summer, and no seasonal variation was found in stemflow on either plot. Study 2 (Deguchi et al., 2006) sampled throughfall at nine points and measured stemflow for eight species in a multispecies forest predominantly covered with deciduous oak and Japanese *Clethra* trees, whereby PAI values were measured using a plant canopy analyzer (LAI-2000). That study showed that throughfall decreased and interception increased in the leafed period, but there was no seasonal variation in stemflow. In Study 3 (Staelens et al., 2008), throughfall was sampled at 20 points, and stemflow was measured for a single mature deciduous beech tree where PAI had been previously



**Fig. 6.** Relationship of stemflow ratios for tree S2 and (a) rainfall amount, (b) average rainfall intensity, and (c) average wind speed for rainfall events in the leafed and leafless periods.



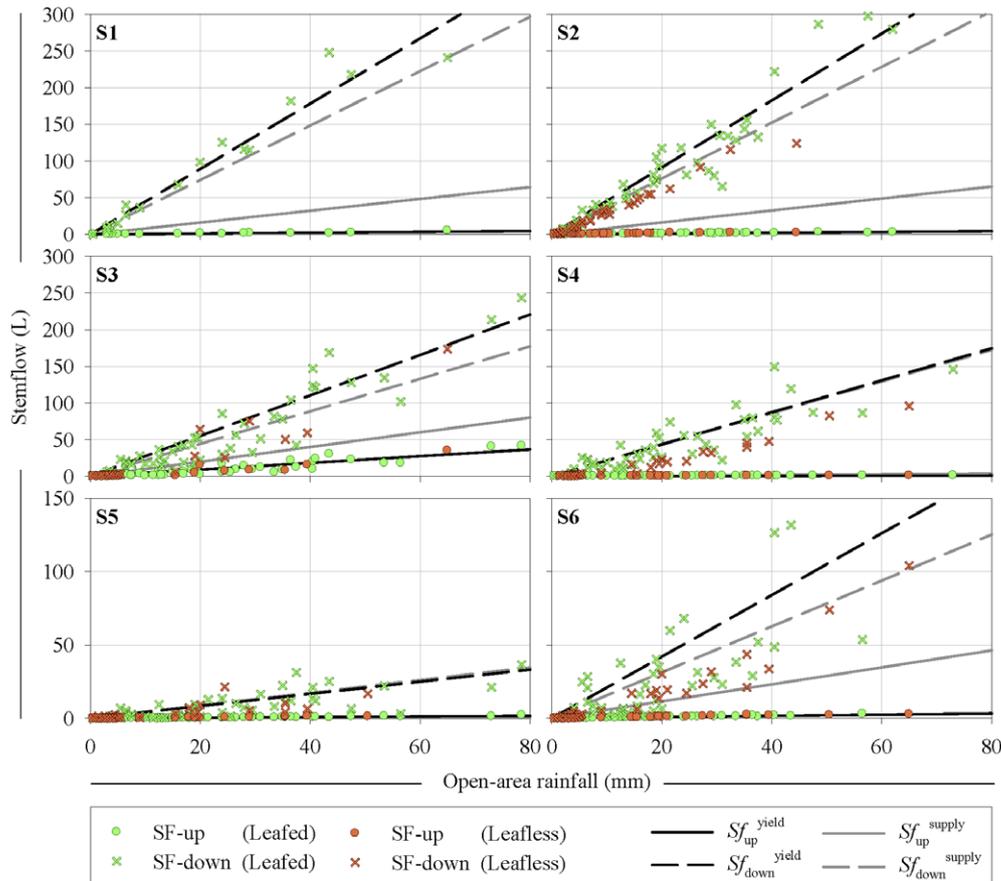
**Fig. 7.** Stemflow ratios at the forest-stand level and single-tree level (S1–S6) for tall Stewartia, and stemflow ratio at the forest-stand level for beech (Giacomin and Trucchi, 1992; Chang and Matzner, 2000; Santa Regina and Tarazona, 2000; Mosello et al., 2002) and oak (Moreno et al., 2001; Silva and Rodriguez, 2001; Mosello et al., 2002; Holscher et al., 2003). The stemflow ratio at the forest-stand level for tall Stewartia was calculated as the ratio of total stemflow per total canopy area of trees S1–S6 to open-area rainfall. Stemflow ratios for tall Stewartia were separated into leafed, leafless, and yearly periods. Boundaries of the box indicate the 25th and 75th percentiles, and the fine line within the box marks the median. The bold line marks the mean, and error bars indicate the 10th and 90th percentiles.

observed by Mussche et al. (2001) using a plant canopy analyzer (LAI-2000). The results showed that throughfall greatly de-

creased and interception greatly increased in the leafed period, but the stemflow ratio increased by only 3% from the leafed period to the leafless period.

In contrast to the results of these studies (Fig. 5b), our results indicated that the ratios of throughfall, stemflow, and interception to open-area rainfall greatly varied with changes in PAI values (Fig. 5a), indicating that changes in canopy architecture greatly affected rainfall redistribution processes for tall Stewartia. In particular, we identified a clear positive correlation between stemflow and PAI for tall Stewartia, which was a contrary trend to previous findings showing a nonobvious or inverse correlation in stemflow versus PAI. In addition to tree S2, greater stemflow in the leafed period was also found on the other tall Stewartia trees (Table 2). The ratio of stemflow to open-area rainfall was 1.3–2.0 times greater in the leafed period than in the leafless period for trees S3–S6. This suggests that greater stemflow in the leafed period than in the leafless period was a general trend for tall Stewartia.

Previous studies have recognized the tendency of stemflow in deciduous forest stands to be greater in the leafless period than in the leafed period (Helvey and Patric, 1965; Neal et al., 1993), mainly because of seasonal meteorological conditions and changes in canopy architecture (Crockford and Richardson, 2000; Levia and Frost, 2003). To clarify the effect of meteorological conditions on stemflow, the ratios of stemflow for S2 were compared to rainfall amount, average rainfall intensity, and average wind speed for rainfall events in the leafed and leafless periods (Fig. 6). With regard to the relationship between stemflow ratios and rainfall amount (Fig. 6a), we found that stemflow ratios significantly increased with the event amount for events <5 mm, but did not increase significantly for events ≥5 mm. It is likely that a greater



**Fig. 8.** Relationship between open-area rainfall and stemflow measured along the upslope (SF-up) and downslope (SF-down) sides of tree stems S1–S6 in the leafed and leafless periods. In each panel, four regression lines were derived from the relationships of each  $Sf_{up}^{yield}$ ,  $Sf_{down}^{yield}$ ,  $Sf_{up}^{supply}$ , and  $Sf_{down}^{supply}$  in Eq. (1) to open-area rainfall, respectively.

proportion of a tree stem is saturated with increasing rainfall input, so the area contributing to stemflow increases until a threshold rainfall input that saturates all areas capable of producing stemflow is reached (Carlyle-Moses and Price, 2006). We did not observe a significant tendency with regard to the relationship between stemflow ratios and average rainfall intensity (Fig. 6b). Although Crockford and Richardson (2000) indicated that stemflow production decreased with the intensity of incident gross precipitation because high intensity rainfall may produce branch flow that exceeds flow path capacity (Herwitz, 1987), this tendency was not significant in our study, even for events with an average intensity >3 mm/h. We also did not observe a significant relationship between stemflow ratio and average wind speed (Fig. 6c), although Levia and Frost (2003) indicated that a greater area of a tree's surface may be wetted during events with greater wind speeds, thus contributing to stemflow production. This result was likely due to that the events were mild (low wind speed and intensity) in this study compared to those previously found to affect stemflow. Overall, we found no clear influences of rainfall amount, rainfall intensity, or wind speed on the stemflow ratio, whereas our results clearly revealed differences in the stemflow ratio by leafed and leafless periods (Fig. 6). In addition to the result of slight differences in seasonal meteorological conditions (Fig. 4b), we suggest that the characteristic of greater stemflow in the leafed period for tall Stewartia was greatly affected by changes in canopy architecture rather than seasonal meteorological conditions.

Greater stemflow in the leafless period has been commonly explained by leaf abscission exposing a larger orthogonally projected branch area, which could capture more rainfall (Helvey and Patric, 1965). For example, Giacomini and Trucchi (1992) reported that stemflow in a beech coppice forest was always higher in the leafless period except for the small rainfall class (1–5 mm); they presumed that foliage prevented the branches from becoming wet and conducting water down the stem in the leafed period. However, rainwater intercepted by leaves would not only be detained on the leaf surface; it could also drip down as throughfall or flow to the stem via branches as stemflow. The increased throughfall ratio of 13% from the leafed to leafless periods could be considered an effect of leaves on rainfall redistribution processes, contributing 9% and 4% of rainfall to stemflow and interception in the leafed period, respectively. Therefore, we suggest that leaves have a positive effect on the generation of stemflow for tall Stewartia, in which a large part of rainwater intercepted by leaves would flow downward via upward-tilting branches to become stemflow (Fig. 2a); this would lead to greater stemflow in the leafed period than in the leafless period.

There are two reasons why the positive correlation between stemflow and PAI was not reported in previous studies. First, rainfall redistribution studies in deciduous forest stands have focused on a few tree species, mostly beech and oak (Llorens and Domingo, 2007); there has thus been little information on processes for other deciduous tree species. Second, as pointed out by Deguchi et al. (2006), most studies of deciduous forests have only included measurements from a single season, not both the leafed and leafless seasons. Therefore, we presume that the same seasonal trend in stemflow should exist in other tree species, especially those with a canopy or branch architecture similar to that of tall Stewartia.

#### Comparison of stemflow amount for tall Stewartia and other deciduous tree species

As shown in Fig. 5, tall Stewartia tree S2 showed greater stemflow than other deciduous tree species reported in the three previous studies, suggesting the capability of tall Stewartia forests to yield high stemflow. The yearly stemflow ratio at the forest-stand level for tall Stewartia (12%) was high compared to the ratios for

beech and oak forest stands in the previous studies (Fig. 7). Even in the leafless period, the smaller stemflow ratio at the forest-stand level for tall Stewartia was higher than the means of yearly stemflow ratios for beech (6%) and oak (5%). Additionally, Helvey and Patric (1965) reported average stemflow ratios of 4% in the leafed period and 6% in the leafless period for deciduous trees in the eastern United States. The ratios reported by Helvey and Patric (1965) were all lower than stemflow ratios in the tall Stewartia stand, for which we estimated ratios of 14% in the leafed period and 8% in the leafless period (Fig. 7). These results indicate that tall Stewartia has considerably high potential to generate a great amount of stemflow compared to other deciduous tree species reported in previous studies.

The large generation of stemflow by tall Stewartia is probably attributable to its branch architecture, which is also the main factor affecting intraspecific variability in stemflow production rates (Levia and Frost, 2003). Herwitz (1987) clarified the strong positive relationship between branch flow and branch inclination in a laboratory experiment. In that experiment, branch flow yields were more than 80% of simulated rainfall when branch inclination angles were greater than 60° above the horizontal. As shown in Fig. 2a, the branch inclination angles of the tall Stewartia were almost all greater than 60° above the horizontal and trained to a single trunk, which could have contributed to the generation of stemflow. Moreover, bark characteristics also affect the stemflow amount. In general, smooth bark has lower bark water storage capacity and contributes to the generation of a continuous flow path, which would increase stemflow yield (Levia and Herwitz, 2005). Helvey and Patric (1965) also attributed stemflow being greater in young stands than in old stands to the smoother bark with branches tending to grow upward rather than outward in young stands. Therefore, compared to some beech and oak species that exhibit drooping branches and rougher bark, it is reasonable that tall Stewartia with upward-tilting branches (Fig. 2a) and smooth bark (Fig. 2b) generated a greater amount of stemflow than beech and oak. Although bark water storage capacity is an important factor affecting stemflow yield, we did not obtain these data for tall Stewartia: bark water storage capacity is difficult to measure in the field and laboratory measurements involve many potential errors (Levia and Herwitz, 2005). Future studies should

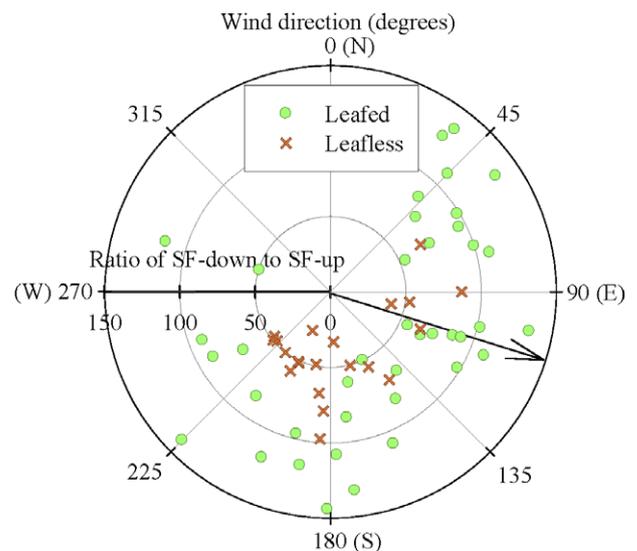


Fig. 9. Relationship between wind direction and the ratio of SF-down to SF-up volumes for tree S2. The arrow indicates the downslope direction of the hillslope (east-southeast) corresponding to that shown in Fig. 1b.

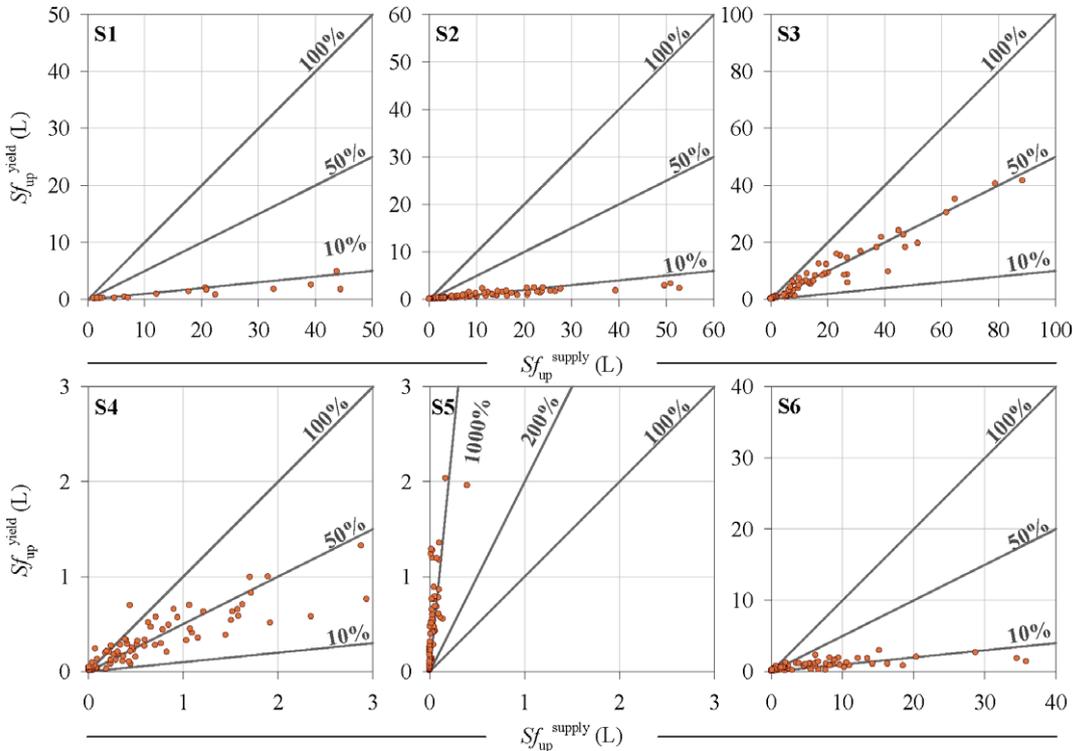
focus on improving estimation methods of bark water storage capacity in the field.

*Generation of stemflow along the upslope and downslope sides of the tree stems*

For each tree, the volume of SF-down was considerably greater than the volume of SF-up (Fig. 8). The maximum difference between SF-up and SF-down was measured for tree S4, for which the SF-down volume was approximately 132 and 78 times greater than the SF-up volume in the leafed and leafless periods, respectively. The minimum difference was measured for tree S5, for which the SF-down volume was approximately 19 and 12 times greater than the SF-up volume in the leafed and leafless periods, respectively. This result suggests that the concentration of stemflow to the downslope side of the tree stems, causing an asymmetrical spatial distribution of stemflow, was a general trend for tall *Stewartia* growing on the hillslope. Regarding seasonal variations, SF-down volume was greater in the leafed period than in the leafless period, whereas there were no obvious seasonal variations observed in the SF-up volume for trees S2–S6. The different trends in the seasonal variations of SF-down and SF-up are probably due to the generation of SF-up being small and thus not reflecting much seasonal variation.

There was an obvious seasonal distinction in the relationship between wind direction and spatial variation in stemflow (Fig. 9), in which SF-down volumes were approximately 90 and 50 times greater than SF-up volumes in the leafed and leafless periods, respectively; however, we found no clear correlation between wind direction and the ratio. In particular, the ratio did not increase when the wind came from the east–southeast, which could bring rainfall to the downslope side of the stems. The result indicates that the asymmetrical generation of stemflow (Fig. 8) was not explained by wind-driven rainfall in this study.

In general, unlike trees growing on flat land, trees growing on a steep hillslope incline toward the slope (Table 1) and are more or less “S”-shaped (Schweingruber, 1996, p. 276), causing an uneven canopy architecture. Thus, such large differences between SF-up and SF-down could be attributable to the uneven area between upslope and downslope sides of the canopy (Fig. 1b and Table 1). Fig. 8 shows that  $Sf_{down}^{supply}$  was greater than  $Sf_{up}^{supply}$ , indicating that a greater downslope canopy projection area was a reason for the generation of greater stemflow volume along the downside of the stem. Comparing  $Sf_{up}^{supply}$  and  $Sf_{down}^{supply}$  to  $Sf_{up}^{yield}$  and  $Sf_{down}^{yield}$ , we found no clear difference between  $Sf_{up}^{supply}$  and  $Sf_{up}^{yield}$  (or  $Sf_{down}^{supply}$  and  $Sf_{down}^{yield}$ ) for trees S4 and S5. However, for trees S1–S3, and S6,  $Sf_{down}^{supply}$  values were obviously greater than  $Sf_{down}^{supply}$ , and  $Sf_{up}^{yield}$  values were obviously smaller than  $Sf_{up}^{supply}$ . The difference between  $Sf_{down}^{supply}$  and  $Sf_{down}^{yield}$  (i.e.,  $Sf_{down}^{supply} - Sf_{down}^{yield}$ ) is identical to the difference between  $Sf_{up}^{supply}$  and  $Sf_{up}^{yield}$  (i.e.,  $Sf_{up}^{supply} - Sf_{up}^{yield}$ ) and represents the water volume that was supplied by the upslope side of the canopy and turned into the stemflow along the downslope side of the stem. This indicates the water volume transported from the upslope to the downslope sides of the stem. Fig. 10 shows the relationship between  $Sf_{up}^{supply}$  and  $Sf_{up}^{yield}$  for trees S1–S6 for each rainfall event.  $Sf_{up}^{yield}$  was approximately 10% of  $Sf_{up}^{supply}$  for trees S1, S2, and S6, and 50% of  $Sf_{up}^{supply}$  for S3 and S4. Thus, 90% of the stemflow supplied by the upslope side of the canopy would turn into the stemflow along the downslope side of the trunk for trees S1, S2, and S6. The ratio was 50% for trees S3 and S4. Therefore, in addition to the uneven area between the upslope and downslope sides of the canopy, asymmetrical stemflow pathways between the upslope and downslope sides of the trunk also contributed to the greater stemflow volume along the downside of the stem. We presumed that the asymmetrical stemflow pathways were caused by the tilt of the tree trunk toward the downslope direction as indicated in Fig. 2a and Table 1. In Fig. 10, tree S5 showed a different trend from the other trees; in tree S5,  $Sf_{up}^{yield}$  was ten times greater



**Fig. 10.** Relationship between  $Sf_{up}^{supply}$  and  $Sf_{up}^{yield}$  for trees S1–S6 for each rainfall event.  $Sf_{up}^{supply}$  calculated by Eq. (1) corresponds to the stemflow volume supplied by the upslope canopy, and  $Sf_{up}^{yield}$  is the stemflow volume measured on the upslope side of the trunk. The difference between  $Sf_{up}^{supply}$  and  $Sf_{up}^{yield}$  (i.e.,  $Sf_{up}^{supply} - Sf_{up}^{yield}$ ) represents the water volume that was supplied by the upslope side of the canopy and turned into the stemflow along the downslope side of the trunk.

than  $S_{up}^{supply}$ . This result was likely due to rainwater falling directly on the upslope side of the trunk. Greater  $S_{up}^{yield}$  than  $S_{up}^{supply}$  values were also measured at tree S4 for some rainfall events (Fig. 10). Therefore, the effect of asymmetrical stemflow pathways was not obvious for the tree with the small upslope canopy projection area; as a result, the stemflow volume supplied from upslope or downslope sides of the canopy was consistent with the stemflow volume yielded along the upslope or downslope sides of the stem (i.e., trees S4 and S5 in Fig. 8).

In our previous study (Liang et al., 2007), we found that asymmetrical and local generation of stemflow caused large and rapid increases in soil water content and frequent generation of a saturated zone at the soil–bedrock interface in the downslope region but not in the upslope region for tree S1. Such spatial variation in stemflow on a hillslope would not only have great implications for hillslope hydrological processes but also for spatial root development (Ford and Deans, 1977; Herwitz and Levia, 1997) and soil erosion-accelerated downslope trees (Herwitz, 1986). Moreover, these results are important for improving prediction accuracy for rainfall infiltration simulated on a forested hillslope, particularly in determining how to input stemflow into the calculation domain in a spatial model (Liang et al., 2009). Although some previous studies have measured stemflow on forested hillslopes (e.g., Park and Cameron (2008) conducted a study on rolling hills with slopes of up to 48%), the asymmetrical generation of stemflow upslope and downslope of tree stems has never been carefully measured. We presume that this asymmetrical generation of stemflow probably occurs in general with trees growing on a hillslope. Therefore, we suggest that future studies conducting observations of stemflow for trees growing on a hillslope should consider the spatial variation in stemflow.

## Conclusions

In this study, we clarified the characteristics of stemflow using long-term observations of many rainfall events for a previously unreported type of deciduous forest (tall *Stewartia*) on a hillslope. Three novel characteristics of stemflow were observed for several tall *Stewartia* trees.

1. Our observations suggested the potential for large amounts of stemflow generation. The yearly stemflow rate at the forest-stand level for tall *Stewartia* (12%) was high compared to those reported in previous studies for beech and oak forest stands. The high level for tall *Stewartia* is attributed to its upward-tilting branches and smooth bark.
2. Stemflow tends to be greater in the leafed period than in the leafless period, a feature that has not been revealed previously. We suggest that leaves have a positive effect on the generation of stemflow for tall *Stewartia*; a large part of rainwater, once intercepted by the leaves, would flow downward via upward-tilting branches to become stemflow, causing more stemflow in the leafed period than in the leafless period.
3. A greater amount of stemflow was generated on the downslope side of the stem than on the upslope side. Asymmetrical canopy projection area was a reason for such asymmetrical generation, but it was not enough to represent the amount of stemflow on the upslope and downslope sides of the trunk. The greater stemflow volume along the downside of the trunk was also attributable to asymmetrical stemflow pathways between the upslope and downslope sides of the trunk caused by the tilt of tree trunk toward the downslope direction. We presume that this asymmetrical generation of stemflow probably occurs in general on trees growing on a hillslope and thus has important implications for hillslope hydrological processes.

Most studies on stemflow generation have focused on few tree species (e.g., beech and oak) in flat forested stands, resulting in a lack of knowledge about stemflow characteristics in all deciduous forests, particularly for trees growing on a hillslope. Based on the understandings in this study, using the within-event method (Link et al., 2004) to estimate canopy capacity and the threshold amount of rainfall required before stemflow generated could be one direction for further studies, which would be helpful in understanding the dynamics and mechanisms of rainfall redistribution processes in the forest with high stemflow ratio.

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