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Abrupt changes in annual stemflow with growth in a young stand of Japanese cypress

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Abstract:

Stemflow was measured in a planted young stand of Japanese cypress for four years from ages 9 to 12. Canopy cover increased with growth from 55% to 94% during the measurement period. The ratio of stemflow SF to rainfall R, SF/R (the funneling ratio FR that represents the efficiency in collecting stemflow), was 5.9% (81.3) at age 9 on an annual basis; however, it abruptly fell to 2.8% (30.0) at age 10. Following the drop, SF/R recovered gradually with growth, reaching 3.8% at age 11 and 4.3% at 12, while FR remained almost constant at values of around 30. The relation between R and SF/R analyzed quarterly on a rain event basis revealed that changes in canopy structure and/or tree architecture caused the drop in SF/R in the April–June period at age 10. Saplings of the species must compete for light and water until canopy closure because their growth rate is slower than that of competitors. As stemflow effectively supplies rainwater into the soil around the root system, it can be hypothesized that large SF/R and FR at age 9, and probably younger ages, are a strategy to acquire water for juvenile unclosed stands in dry summers.

KEYWORDS Stemflow; forest hydrology; canopy structure; tree architecture; Hitachi Ohta Experimental Watershed

INTRODUCTION

Stemflow typically accounts for several percent of rainfall, and is often a minor component of the water budget in forest hydrology in comparison with throughfall, that amounts to 60 to 90% of rainfall. In some studies, stemflow is not considered because it is regarded as negligibly small. Even so, stemflow plays an important role as a point source of water input onto the forest floor or into soil: it accounts for a significant amount of groundwater recharge (Taniguchi *et al.*, 1996; Tanaka *et al.*, 1996), and affects soil moisture distribution (Durocher, 1990), soil chemistry (Matschonat and Falkengren-Grerup, 2000; Chang and Matzner, 2000), soil erosion (Herwitz, 1988) and the distribution of understory vegetation (Falkengren-Grerup, 1989; Andersson, 1991).

The amount of stemflow yield is influenced by tree architecture. Some studies found a positive correlation between stemflow on the one hand, and tree basal area (Crockford and Richardson, 2000) and stem angle (Martinez-Meza and Whitford, 1996) on the other. Seemingly, stemflow increases with tree size or canopy size, i.e. tree age, because larger and taller trees tend to have a greater catchment area for rainwater. However, Johnson (1990) found that stemflow yield decreased with tree age from 39% (age 14) to 2% (age 63) of total rainfall in five stands in the UK. Tree architecture, e.g. branch inclination angle (Návar, 1993; Martinez-Meza and Whitford, 1996), would vary with age and thus affect stemflow production.

The number of stemflow studies focusing on water budget is much lower than that of throughfall or canopy interception, especially studies on stemflow conducted over a full year or in a series of successive years, as pointed out by Levia and Frost (2003). The present study deals with four years of successive observations of stemflow in a young stand of Japanese cypress (*Chamaecyparis obtusa*), a major plantation species in Japan. The purpose of this study is to clarify variation in stemflow with canopy growth based on analyses on an annual and a quarterly basis.

STUDY SITE

A stemflow plot was set up in the Hitachi Ohta Experimental Watershed of the Forestry and Forest Products Research Institute, situated on the Pacific coast of eastern Japan (latitude 36°34’N, longitude 140°35’E) where an extensive study on forest hydrology has been carried out. It includes several forested catchments with gauging weirs and a meteorological station. At the site, throughfall has also been observed (Murakami, 2006; 2007), but the present study focuses only on stemflow. The elevation of the site is 320 m above sea level with average annual precipitation of 1467.7 mm (1991 to 2000). Winter is a dry season and precipitation during December, January and February accounts for only 9.1% of the annual total (1991 to 2000).

Stemflow measurement was conducted from 1997 to 2000 in a stand of *C. obtusa* planted in 1988. The stand structure is shown in Table I. Canopy cover was 55% in 1997, but it reached 94% and almost closed in 2000. Average tree height and DBH also grew larger during the measurement period. Leaf area index (LAI) measured by a LAI-2000 Plant Canopy Analyzer (LI-CO, Inc.,

Table I. Changes in stand structure. The stand density, 2944 tree ha^{-1}, was constant throughout the observation period. h: average tree height; DBH: average diameter at breast height; c: canopy cover; CPA: average canopy projection area.

Time of survey	Age (years)	h (m)	DBH (cm)	c (%)	CPA (m^2 tree^{-1})
July 1997[a]	9	4.7	5.8	55	1.8
April–May 1999	11	5.8	7.0	81	2.7
October 2000	12	6.3	8.1	94	3.1

[a] Values of h and DBH were measured in December 1997.

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Lincoln, NE, USA) varied from 3.9 to 5.2 in 2000 depending on the season, with a peak in summer.

METHODS

A stemflow collector was made from a polyurethane foam board with a thickness of some 4 cm, so that the board would deform in accordance with the growth of the tree. One of the long edges of the board was cut obliquely, and the board was fastened around a tree trunk using plastic ties. Rough, flaky bark of *C. obtusa* was scraped off to smooth the area for the sealant, which was filled between bark and the board. The collectors were installed on nine trees (Murakami (2006; 2007) had mistakenly described only eight trees). At a drain outlet of the stemflow collector, a coarse sponge was placed to prevent it getting clogged by litter. A plastic tube implanted in the collector drained stemflow water into a tank, and changes in water level were recorded with a resolution of 0.07 mm on paper. The tank was automatically drained if the water level reached the maximum. The plot area occupied 29.63 m^2: this covered all the canopy projection area of the trees on which stemflow collectors were installed. Using these data stemflow per unit ground area, i.e. total stemflow volume divided by the plot area, was calculated. The instruments worked without trouble through the measurement period, and there was no missing data for SF.

Two pairs of raingauges, consisting of a tipping bucket raingauge and a storage type one, were installed on the ground level in the watershed. One tipping bucket (0.1 mm per tip) was installed at the meteorological station, 20 m away from the stemflow site. The other had a resolution of 0.5 mm and was installed at a distance of 170 m from the stemflow plot. Both of the raingauge sites were established at clearings on ridges, to reduce the influence of the forest stand on rainfall measurements.

Measurements were taken at 10-minute intervals at the raingauge of 0.1 mm per tip, and every hour at the 0.5 mm per tip gauge. Each storage-type raingauge was measured every two weeks manually, and the rainfall measured by the tipping bucket raingauges was corrected by regarding the values obtained by the storage-type gauges as true. Separation time of a rain event was set at 6 hours: if no rainfall was observed for 6 hours after the cessation of the rainfall of interest, the storm was defined as a single rain event. For a rain event of 5.0 mm or more measured by the 0.1 mm per tip raingauge, the mean rainfall of the two tipping bucket raingauges was employed; otherwise, the value obtained by the raingauge with the resolution of 0.1 mm was adopted. At least one raingauge was operating throughout the measurement period; if one did not work data obtained by another was used. The stemflow data were analyzed on a rain event basis, with focus on annual and quarterly changes.

RESULTS

Annual precipitation, rainfall R, and stemflow SF are shown in Table II. Precipitation includes rainfall and snowfall, while R does not contain snowfall that can be distinguished from rainfall using solar radiation, air temperature, and precipitation data from the meteorological station and throughfall data. Precipitation and throughfall recorded with strong solar radiation or positive temperature followed by a cold wave often implies snowmelt: snow stored in the raingauges or the throughfall collectors thaws. Though SF observed in snow events was excluded from the analysis, it had little effect on the water balance in the stand as snowfall made up 3.7% or less of annual precipitation during the measurement period.

Table II. Annual precipitation, rainfall R, stemflow SF, the ratio of SF to R, the funneling ratio FR, the bark water storage S_t, and the canopy capacity per unit ground area S. R does not include snowfall.

Year	Precipitation (mm)	R (mm)	SF (mm)	SF/R (%)	FR[a]	S_t (mm)	S[b] (mm)
1997	1266.9	1259.7	73.7	5.9	81.3	0.18	-
1998	1566.7	1509.4	42.7	2.8	30.0	0.12	-
1999	1707.4	1673.2	62.9	3.8	31.4	0.19	0.41
2000	1452.4	1431.2	61.5	4.3	29.0	0.13	0.44

[a] For each year estimated DBH on July 1 was employed to calculate FR. Refer to the text in detail.
[b] Based on Murakami (2007).

The value of SF/R suddenly dropped from 5.9% in 1997 (age 9) to 2.8% in 1998 (age 10) followed by a gradual increase up to 4.3% in 2000 (age 12). This trend is also apparent in the analysis on a rain event basis (Figure 1). At age 9 (Figure 1(a)), SF/R increases with R rapidly and plateaus at around 9%. At age 10 (Figure 1(b)), the value of leveling off decreases to 7% with large variation; however, the value of the plateau is 5% if the data from the April–June period are excluded. At age 11 (Figure 1(c)), SF/R plateaus at 6% or less with smaller variation compared with age 10, and at age 12, the value of leveling off recovers up to 7%. It is apparent that the data for SF/R in the July–September period are at the lowest position throughout all four years. This trend is independent from rainfall amount, though rain events larger than 50 mm occurred in either the April–June or the July–September period throughout the four years except for one data set in 1997. Other than the July–September period, seasonal change was not clear.

The funneling ratio FR that represents the efficiency of funneling rainwater into the stem (Herwitz, 1986) was shown in Table II. For a single tree FR is defined as FR = V/(BG), where V is the volume of stemflow, B is the trunk basal area, and G is the depth of equivalent incident rainfall. The term BG is equivalent to the rainfall amount that would have been measured by the raingauge occupying the same area with the trunk basal area. In this study the total stemflow volume and the total basal areas for nine stems were used instead of V and B for a single tree, respectively. The values of DBH on July 1, the median of the day of year, were estimated using the regression line between Julian day and DBH ($r^2 = 1.000$). The estimated average DBH on July 1 was adopted for each year to calculate the total basal areas, since the measurements of DBH were conducted three times irregularly during April to December (Table I). The value of FR was 81.3 in 1997, while it diminished to around 30 and remained almost constant through 1998 to 2000.

DISCUSSION

Annual changes in SF

Canopy cover at age 9 was only 55% but it grew year by year up to 94% at age 12 (Table I). Although this trend indicates that the catchment area of individual trees grew, SF (FR) dropped abruptly from 5.9% (81.3) down to 2.8% (30.0) from age 9 to 10 (Table II), which

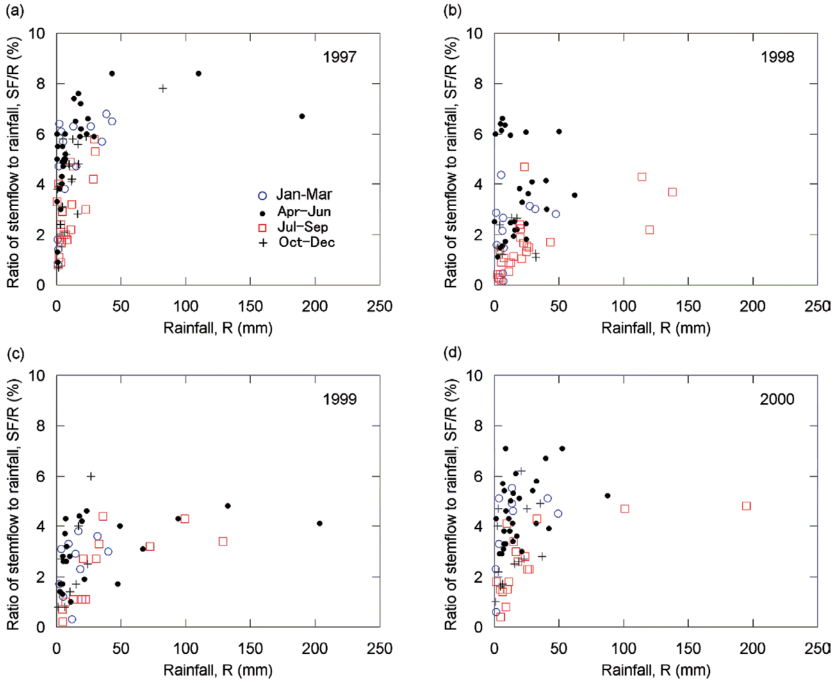

Figure 1. The ratio of stemflow SF to rainfall R on a rain event basis. (a) 1997, age 9; (b) 1998, age 10; (c) 1999, age 11; (d) 2000, age 12.

suggests drastic changes in tree architecture and/or canopy structure occurred between these ages. To unravel the mechanism, structural analysis of canopies that includes ages 9 to 10 is required on an annual basis, but that is out of the scope of the present study.

Nevertheless, there is a clue to the phenomenon in Figure 1(b): the data from the April–June period at age 10 demonstrate greater variation than during any other period. This trend implies that sudden morphological changes in trees and/or canopy occurred and were completed during that period. Gradual increase in SF following the drop is a natural trend, since more rainwater is collected with an increase in the catchment area by canopy growth. Constant values of FR following the drop imply that *C. obtusa* is a steady state in terms of the efficiency in stemflow collection that corresponds to the growth. In other words, *C. obtusa* funnels rainwater into stemflow in proportion with the trunk basal area, B.

At age 12 the canopy had almost closed and SF/R reached 4.3%. This is a comparable value to the approximately 5% of a ca. 70-year-old mature stand of the same species in the same watershed (unpublished). The canopy of the mature stand was closed with a stem density of 783 stems per hectare (Murakami *et al.*, 2000). However, it is premature to conclude that SF/R remains at a constant value of some 5% after canopy closure, i.e. age 12 or older. Levia and Herwitz (2005) pointed out that the dependence of stemflow yield on the stand age comprises of complicated processes in which bark water storage capacity plays a significant role. The bark water storage capacity increases with tree growth, which reduces stemflow amount for small rain events. On the other hand, once the storage capacity is reached, generally speaking, older and larger trees produce more stemflow than younger and smaller ones because of the greater catchment area as mentioned in the introduction. Changes in canopy storage capacity and tree architecture with growth also contribute to variations in stemflow yield that makes the entire process intricate. As for the present study, bark water storage S_t, defined as the y-intercept of the regression line between R and SF, and canopy storage capacity S are listed in Table II. The maximum difference in S_t in four years was 0.07 mm, and the variation in S between 1999 and 2000 was 0.03 mm. As these values are small, they do not seem to affect the annual variations in stemflow yield in the present study. However, in general, morphological information on bark, branches and canopy as well as the data on water storage for the trunk and the canopy is required to establish the dependence of SF/R and /or FR on the stand age.

Seasonal changes in SF

The values of SF/R in the July–September period were at the lowest position throughout the measurement period. Murakami (2006) displayed seasonal changes in canopy interception with a peak in summer. This reduces a percentage of rainwater partitioning into both throughfall and stemflow and explains the decrease in SF/R in the summer period.

Ecohydrological interpretation

Some studies have pointed out that SF is a strategy to acquire water, since it can directly supply rainwater into soil near the root system. This process is especially important in semi-arid environments. Nulsen *et al.* (1986) revealed that a canopy of mallee trees collects rainwater and redistributes it into deep soil through SF and soil-root interface pathways. The roots of mallees reach a depth of 28 m and it is postulated that the trees store water deep in the soil for use during the dry summer season.

Though *C. obtusa* is widely distributed in areas of sufficient rainfall, foresters do not plant the species near valleys as it is not considered to be 'the right tree for the site'; *C. obtusa* does not grow well in wet environments and prefers somewhat dry soil on the middle or upper part of a slope. This trend can lead to water shortage in a dry summer, especially for saplings of this species because of the competition with other species.

In plantations of *C. obtusa*, though the same is true for the other species for plantation, weeding in summer is essential for several years after the planting to help the saplings receive light and water. Without this silvicultural practice, *C. obtusa* either loses the survival game to other species or it takes longer to win the position of upper story tree. Weeding had been conducted at the *C. obtusa* stand at Hitachi Ohta for 6 years following the planting in 1988.

It can be hypothesized that large SF/R and FR at age 9 with unclosed canopy is a strategy to collect water effectively. At age 10, the canopy cover was not measured, but it occupied 55% at age 9 and 81% at 11 (Table I), and one could say the stand had almost established the position of upper story vegetation. At this age, *C. obtusa* can obtain enough light and water since the enlarged canopy keeps other species out, and the special strategy for water collection through canopy and stemflow is no longer needed.

Kobayashi *et al.* (2000) measured soil water potential around a stem in a 30-year-old stand of *C. obtusa* with almost closed canopy and poor understory vegetation. Under dry antecedent conditions, concentrated water input by stemflow was mainly consumed to compensate for water deficits near the stem regions in the soil, and recharge of ground water occurred only in areas far from the stem. This result implies the importance of SF under dry conditions for this species, and it is postulated that the competition for acquiring water must be harder when the canopy is unclosed.

The abrupt changes in SF and FR would influence the concentration of nutrients at the tree base, which might affect the growth of this species. For future stemflow research, the analysis of chemical composition as a function of age using enrichment ratios (Levia and Herwitz, 2000; André *et al.*, 2008), and the degree of the alternation of chemical composition between rainwater and stemflow, are useful to elucidate the ecohydrological perspective.

CONCLUSION

The specific mechanism of the drop in SF/R at age 10 is worth studying in terms of changes in canopy structure and tree architecture. Confirmation of whether the ecological interpretation of the phenomenon, the strategy for acquiring water, is valid or not will require years of observation of young stands that include the stage of transformation from unclosed to closed canopy.

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