Hydrological Research Letters **11**(4), 181–186 (2017)
Published online in J-STAGE (www.jstage.jst.go.jp/browse/hrl). DOI: 10.3178/hrl.11.181

Field estimation of interception in a broadleaf forest under multi-layered structure conditions

Yutaka Abe[1], Takashi Gomi[2], Norihisa Nakamura[1] and Noriko Kagawa[3]
[1]*Institute for Water Science, Suntory Global Innovation Center Ltd., Japan*
[2]*Department of International Environmental Agriculture Science, Tokyo University of Agriculture and Technology, Japan*
[3]*CSR Department, Corporate Communication Division, Suntory Holdings Ltd., Japan*

Abstract:

We performed a field experiment on throughfall, stemflow, and bamboo culm flow to estimate interception in a deciduous broadleaf forest with different stand structures by separately removing the overstory and understory vegetation. The study area is occupied by oak (*Quercus serrata*) and chestnut (*Castanea crenata*) with an understory of chino bamboo (*Pleioblastus chino*). We established three plots for vegetation control, including an overstory plot (removal of understory), a bamboo plot (removal of overstory), and a control plot (both overstory and understory remained). Throughfall amounts relative to precipitation were 61% in the control plot, 54% in the overstory plot, and 31% in the bamboo plot. Average stemflow in control and overstory plots was 3% of precipitation. The significant difference in throughfall for the bamboo plot may have been caused by the high density of understory vegetation. A large portion of intercepted water is transferred to the ground as bamboo culm flow in the understory beneath the canopy in the control plot and in the bamboo plot. Our experiment highlighted the significance of understory vegetation in altering hydrological processes from canopy to understory vegetation.

KEYWORDS interception; throughfall; stemflow; deciduous broadleaf forest; understory vegetation

INTRODUCTION

Throughfall and stemflow together make up an important component of the hydrological and geochemical cycles in forest environments, allowing transfer of water and chemical species from the canopy to the soil (Levia and Frost, 2006; Carlyle-Moses and Gash, 2011). Estimating throughfall and stemflow is essential for evaluating interception loss, which influences water yield in forests (Crockford and Richardson, 2000). A number of studies have reported the throughfall and stemflow in various types of forests. For example, in Japan, throughfall and stemflow in Japanese cedar and cypress forest ranged from 68 to 79% and from 3 to 10% of the rainfall, respectively (Katagiri, 2008; Tanaka *et al.*, 2005; Saito *et al.*, 2013), and those in broadleaf forest dominated by chestnut and oak ranged from 65 to 85% and from 5 to 10% (Park *et al.*, 2000; Katagiri, 2008), depending on stand condition. Komatsu *et al.* (2007) showed that interception loss in published studies varied with stand density in both deciduous and coniferous forests.

Stand structure, including canopy, shrubs, and understory vegetation, can influence hydrological processes in forested landscapes (Bellot and Escarré, 1991; Manfroi *et al.*, 2004; Iida *et al.*, 2005). Recently, several studies showed that understory vegetation is critical in surface hydrological processes in hillslope environments. For instance, Hiraoka *et al.* (2010) determined that the presence of understory vegetation induced a 5-fold greater infiltration capacity compared with a bare surface. The distribution of understory vegetation is also important for estimating the contribution of overland flow to total catchment storm runoff generation (Gomi *et al.*, 2010). These results suggest that understory vegetation and shrubs might affect both the pathway and amount of throughfall and stemflow.

Despite the complex stand structures in forested landscapes, hydrological processes across multiple forest structures have not been thoroughly examined. Most previous studies on throughfall examined interception by both the canopy and understory (Park *et al.*, 2000; Zimmermann *et al.*, 2007). In general, instruments for measuring throughfall can be placed at 20–50 cm in height, between the ground surface and shrub or understory vegetation (Keim *et al.*, 2005). Few studies have focused on interception loss by overstory and understory vegetation separately (i.e. Cantú and Okumura, 1996a; Ziegler *et al.*, 2009; Haga, 2011). For comprehensive investigations of hydrological processes in multiple forest structures from the soil surface to the canopy, the influence of understory vegetation on throughfall needs to be explicitly included in monitoring schemes. Therefore, we conducted a field experiment wherein we removed only the understory (mainly bamboo) or only the overstory vegetation to clarify the difference in interception with and without understory. The findings of this study can provide insights into the role of multi-layered vegetation in the interception of rainfall in a broadleaf forest.

Correspondence to: Yutaka Abe, Institute for Water Science, Suntory Global Innovation Center Ltd., Seikadai, Seika-cho, Soraku-gun, Kyoto 619-0284, Japan. E-mail: abe.yutaka.hydro@gmail.com

Received 22 August, 2017
Accepted 2 November, 2017
Published online 8 December, 2017

© The Author(s) 2017. This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

STUDY SITE AND METHODS

This study was conducted on a forested hillslope located in Tochigi, eastern Japan (latitude 36.42°N, longitude 139.70°E), which is approximately 80 km from the Tokyo metropolitan area. The site is mainly occupied by oak (*Quercus serrata*), sawtooth oak (*Quercus acutissima*), chestnut (*Castanea crenata*), and Korean hornbeam (*Carpinus tschonoskii*) trees 17 to 25 m in height. Stand density of the broadleaf forest in this area was approximately 1,100 stems/ha, excluding shrubs. Including overstory and shrubs, the stand density rose to 1,700 stems/ha. The dominant understory vegetation is chino bamboo (*Pleioblastus chino*) 3 to 4 m in height. Our experiment focused on understory chino bamboo because sasa and/or dwarf bamboo may become the dominant understory vegetation in broadleaf forests, suppressing other species and constituting an important issue in sustainable forest management (Suzaki *et al.*, 2005; Tsuchiya *et al.*, 2013). Mean annual precipitation and air temperature were 1,400 mm and 14°C, respectively, based on data from the Automated Meteorological Data Acquisition System (AMeDAS) at Tochigi, located 5.5 km south of the study site. The underlying geology of the area consists of a Mesozoic accretionary complex including sandstone and chert.

The amount of interception loss (*Ic*) was calculated based on the following water balance equation:

$$Ic = R - TF - SF - BCF \quad (1)$$

where rainfall (*R*), throughfall (*TF*), stemflow of the overstory (*SF*), and bamboo culm flow (*BCF*) are derived from observations for each plot. We established three plots characterized by different stand structures in March 2014 (Figure 1a). For plot T_o (6 × 15 m), all understory vegetation, which consisted mostly of chino bamboo, was removed for investigation of interception by overstory vegetation. Plot T_o had six stems of overstory, mainly consisting of oak and chestnut (17 to 25 m in height), along with two shrubs. We also developed a plot with overstory vegetation removed (plot T_s; 15 × 15 m) for investigating interception by chino bamboo understory vegetation (3 to 4 m in height). The control plot (plot C; 6 × 15 m) contained both overstory and understory bamboo. Eight stems of oak and chestnut (18 to 22 m in height) as well as ten shrubs were located in the control plot. Plots C and T_o, which had overstory vegetation, were located adjacent to each other. Plot T_s, with only chino bamboo, was located approximately 8 m north of plots C and T_o. We also established a climate monitoring station in an open area 400 m north of the observation plots to measure *R* (CTKF-1 with 0.5 mm resolution; CLIMATEC, Inc.). Leaf area index (LAI) was measured with a plant canopy analyzer (LAI-2200C; Li-Cor, Inc.) at three points in each plot on July 23, 2015. The biomass of understory vegetation was estimated by measuring the dry weight of chino bamboo sampled in three 50 × 50-cm areas adjacent to each plot of C and T_s on October 20, 2015.

We installed tipping bucket rainfall gauges (rain collector with 0.2 mm resolution; Davis Instruments, Co.) to measure *TF* in each plot. Eight gauges each in plots C and T_o were installed, as well as four gauges in plot T_s. Rain

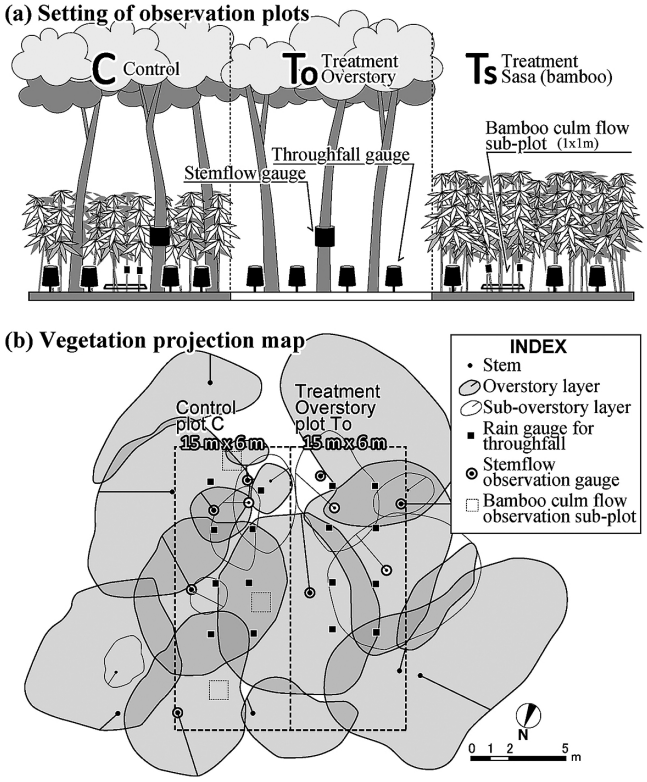


Figure 1. Study area and observational setting

gauges were located 2 to 3 m apart. We placed the top of the rain gauges approximately 100 cm from the ground surface to minimize rain-splash impact and capture *TF* from chino bamboo leaves. The number of tips for each gauge was recorded every 10 minutes using data loggers (OWL data logger, EME systems; UA-003-64 Hobo pendant event data logger, Onset Computer Co.). Error associated with *TF* measurement (ε) was calculated based on the following equation:

$$\varepsilon = \frac{t_{(\alpha, n-1)}\sigma}{\sqrt{n}} \quad (2)$$

where *n* is the number of *TF* gauges, *t* is the Student's t-value with confidence level (α) and degree of freedom ($n - 1$), σ is the standard deviation of the *TF* amount measured at all gauges (Carlyle-Moses *et al.*, 2004; Iida *et al.*, 2005; Inoue *et al.*, 2017).

Ten experimental stems were selected for the measurement of *SF* in plots C and T_o (Figure 1b). We selected two oaks, two sawtooth oaks, two chestnuts, two Korean hornbeams, and two shrub trees. Each sampled tree was equipped with a polyvinyl tube around the trunk at a height of approximately 1.3 m with a drain hole connected to a bucket of 70 to 120 L volume. To estimate water volume, the water level in the bucket was measured every 10 minutes using a capacitance water level sensor with a logger (Odyssey capacitance water level logger, Dataflow Systems, Ltd.). We converted the measured water volume of stemflow in each stem (S_{fv}) to water height using two methods. To estimate the plot-scale stemflow height (*SF*), we applied the following equation for plots C and T_o,

$$SF = \frac{\sum S_{fv}}{A} \quad (3)$$

where A is the area of the plot. To estimate S_{fv} of ungauged stems, we use the method proposed by Katagiri (2008), which consists of a multiple regression analysis with S_{fv}, crown areas of 10 measured stems and rainfall. We calculated the *SF* for a combined area of plots C and T_o because tree canopy cover extended over both plots. We then estimated crown-area stemflow height (S_c) based on crown projection area (C_a) of the given trees based on the following equation,

$$S_c = \frac{S_{fv}}{C_a} \quad (4)$$

This analysis permits us to examine the effectiveness of water capture by the forest canopy (Taniguchi *et al.*, 1996).

Bamboo culm flow (*BCF*) was measured in three sub-plots of 1 × 1 m within each plot, C and T_s. A cylindrical form was attached around the culm at a height of approximately 50 cm on three bamboo stems in each sub-plot. A drain tube was connected to a 5-L bucket. The mean diameter of the measured bamboo culms was 13 mm, with a range of 9 to 16 mm. The average and min-max range of *BCF* were estimated by multiplying the mean, minimum and maximum water volume by the mean density of bamboo stems in the sub-plots.

The monitoring period for *R*, *TF*, and *SF* was May 15 to October 20, 2015, and that for *BCF* was June 3 to 23, 2016. Despite the difference in measurement periods, this study focused on the relative contribution of *BCF* to the hydrological processes of multi-layered forest. Therefore, we estimated *BCF* and *Ic* as a percentage (%) of *R* rather than calculating the amount in water height (mm). We defined a single rainfall event as ≥5 mm of precipitation. A consecutive event was separated by a period that had no rainfall for more than 24 hours after the precipitation ceased. Rainfall events with missing data due to equipment malfunctions were excluded prior to this analysis.

RESULTS

Mean leaf area indices (LAI) and standard deviations (SD) of three measurement points in plots C, T_o, and T_s were 5.1 (SD: ±0.1), 2.1 (SD: ±0.3), and 7.0 (SD: ±0.1), respectively. The mean biomass of understory chino bamboo was 3.3 kg/m^2 (SD: ±2.8) in plot C and 4.7 kg/m^2 (SD: ±0.7) in plot T_s. The mean densities of chino bamboo in the sub-plots were 15.3 stems/m^2 stems in plot C and 18.7 stems/m^2 in plot T_s.

Based on AMeDAS data, precipitation during our monitoring period from May to October (1,327 mm) was approximately 15% greater than that in the average year (1,154 mm). We obtained complete sets of *TF* and *SF* measurements for 12 rainfall events, although 27 rainfall events occurred during our monitoring period. These 12 events ranged from 6.0 to 39.5 mm, for a total of 243.5 mm, with all 27 events ranging from 5.0 to 446.0 mm, with 1122.0 mm in total. The mean event rainfall amount (with standard deviation) was 22.1 mm (SD: ±11.5 mm) for the 12 events and 42.3 mm (SD: ±85.2 mm) for the 27 events. Twelve rainfall events were less than 40 mm, and three events of more than 40 mm occurred during the monitoring period. Therefore, this study only analyzed interception for small to moderate rain events (5 to 40 mm). The estimated error in *TF* measurements of 12 events using Equation (2) were 17.5% in plot C, 15.4% in plot T_o, and 35.3% in plot T_s. The equation for estimating *SF* of ungauged stems was S_{fv} (L) = 0.33 × C_a (m^2) + 0.66 × *R* (mm) – 14.29 (R^2 = 0.214, $p < 0.01$).

TF and *SF* associated with small (10.0 mm) and moderate (29.5 mm) rainfall events varied temporally with the *R* input (Figure 2). *TF* in all plots responded quickly to *R* for all rainfall events. Peak *TF* corresponded to the peak *R* input. Plot T_s tended to have smaller *TF* than the other plots. Unlike *TF*, *SF* did not respond to small events or the initial intense *R* of a moderate event, although significant *SF* was detected during the subsequent peak in *R* (Figure 2b).

The total amount of *TF* was greatest in plot T_o, at 149 mm (error: ±23 mm), followed by plot C at 131 mm (error: ±23 mm) and plot T_s at 76 mm (error: ±27 mm). *TF* was significantly correlated with *R* for all plots ($p < 0.01$) (Figure 3a). *TF* as a percentage of *R* was 54% (error: ±9%) in plot C, 61% (error: ±9%) in plot T_o, and 31% (error:

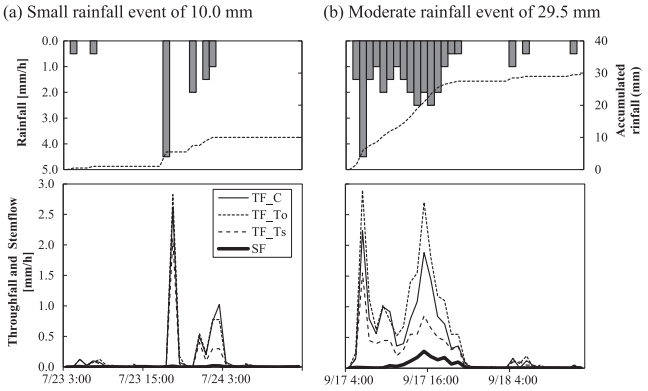
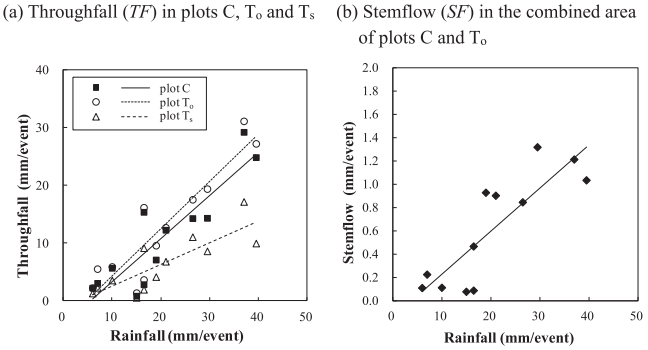


Figure 2. Temporal variation in rainfall (*R*), accumulated rainfall, throughfall (*TF*), and stemflow (*SF*) during small and moderate rainfall events



C: a = 0.74, R^2 = 0.79, $p < 0.01$
T_o: a = 0.82, R^2 = 0.83, $p < 0.01$
T_s: a = 0.38, R^2 = 0.68, $p < 0.01$

a = 0.04, R^2 = 0.65, $p < 0.01$

Figure 3. Relationships of rainfall and throughfall (*TF*) in each plot with stemflow (*SF*). Each value a is the slope of the regression line

Table I. Summary of observation and estimation data for interception in each plot. Values in parentheses are the error and range of the observed values. The *TF* values shown with ± are the error calculated by Equation (2). The range values for *BCF* and *Ic* are the minimum and maximum values. *BCF* is shown only as a percentage (%) because it was measured in a different period (June 3 to 23, 2016) from *TF* and *SF* (May 15 to October 20, 2015). *Ic* estimated using *BCF* is also shown only as a percentage (%).

Total amount of 12 events (mm) and percentage to rainfall (%)							
	Rainfall	Throughfall		Stemflow		Bamboo culm flow	Interception loss
	R (mm)	*TF* (mm)	*TF/R*	*SF* (mm)	*SF/R*	*BCF/R*	*Ic/R*
plot C	243.5	131 (± 23)	54% (± 9%)	7	3%	22% (13–29%)	21% (8–39%)
plot T_o	243.5	149 (± 23)	61% (± 9%)	7	3%	—	36% (27–45%)
plot T_s	243.5	76 (± 27)	31% (± 11%)	—	—	53% (6–91%)	16% (−33–74%)

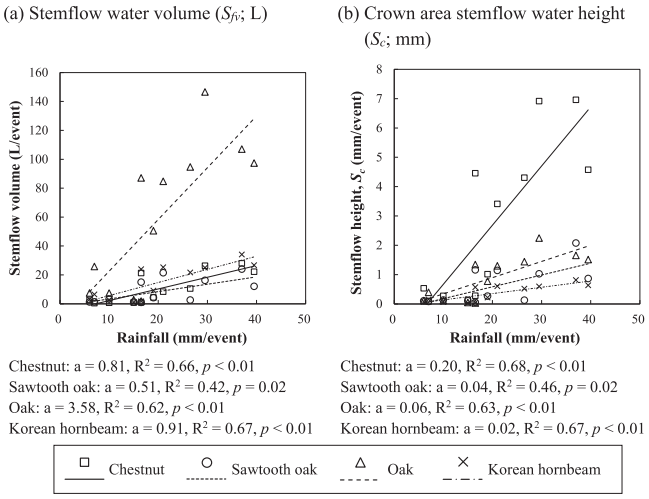


Figure 4. The relationship between rainfall and stemflow in each species (S_{fv} and S_c). Each value a is the slope of the regression line. The stemflow value of each species is the sum of two stems from the same species

±11%) in plot T_s (Table I). *SF* based on the combined area of plots C and T_o ranged from 0.1 to 1.3 mm, with a total of 7 mm (*SF/R* = 3%; Table I). *SF* was significantly correlated with *R* ($p < 0.01$) (Figure 3b).

Both S_{fv} and S_c varied substantially among tree species. These factors were correlated with *R* ($p < 0.01$) (Figure 4). For all events, S_{fv} in oak trees was consistently greater than that in the other tree species (Figure 4a). For example, S_{fv} during a 21.0-mm event on May 18 to 20 was 85 L in oak, while values in other species ranged from 8 to 25 L. Unlike S_{fv} the greatest S_c occurred in chestnut trees (Figure 4b).

The total amount of *R* over 20 days of the *BCF* measurement period was 102.5 mm. The water volume of culm flow in plot C and T_s ranged from 900 to 1900 mL and from 350 to 5000 mL, respectively. The estimated *BCF* as a percentage of *R* was 22% (range: 13–29%) in plot C, and 53% (range: 6–91%) in plot T_s. The average *Ic* as a percentage of *R* was 21% (range: 8–39%) in plot C, 36% (range: 27–45%) in plot T_o, and 16% (range: −33–74%) in plot T_s (Table I).

DISCUSSION

Our estimation of *TF/R* in the control plot C was smaller than values reported in previous studies focused on oak trees in Japan, while *SF/R* showed similar values (Table II). For instance, previously reported *TF/R* and *SF/R* in broad-leaved forest mainly consisting of oak, chestnut, and sawtooth oak were approximately 70 to 80% and 3 to 10%, respectively (Katagiri, 2008; Park *et al.*, 2000; Toba and Ohta, 2005). Tanaka *et al.* (2005) reported the ranges of *TF/R* and *SF/R* as 75 to 79% and 5 to 10%, respectively, in a Japanese coniferous forest. The reason for the smaller *TF/R* in our observations may be associated with our limited *R* observations. In general, rainfall events of less than 20 mm tend to have high *Ic/R* compared with events with high *R* (Cantú and Okumura, 1996a; Toba and Ohta, 2005). Furthermore, Haga (2011) reported that *TF/R* in rainfall events of less than 10 mm was as low as 60 to 75% in oak forest. Nevertheless, skewed data from the 12 storm events may have led to overestimation of *Ic* and thus provided lower *TF* values. Therefore, further analysis should be conducted using greater precipitation ranges.

Our estimated mean *Ic/R* in overstory canopy plots (plots C and T_o) ranged from 21 to 36% (Table I), which is approximately the same as the 14 to 31% reported in previous studies (Cantú and Okumura, 1996b; Park *et al.*, 2000; Toba and Ohta, 2005) in broadleaf forests in Japan. Hence, the estimated mean *Ic/R* in plot C tended to be smaller than in plot T_o. This differs from previous studies, which showed that *Ic* tended to have a positive relationship with vegetation biomass (Crockford and Richardson, 2000; Toba and Ohta, 2005). Higher interception is expected in plot C because the LAI in plot C was 2.4-fold greater than that in plot T_o. Among the factors in Equation (1) used to calculate *Ic*, the limited monitoring period and numbers of samples of bamboo culms probably resulted in relatively high uncertainty in the estimation of a representative *BCF*, and caused the underestimation of *Ic/R*.

Comparing *TF* in plots T_o and C, the *TF* in plot C tended to be smaller than plot T_o. Differences in intercepted rainfall between these two plots can be associated with water intercepted by chino bamboo beneath the overstory vegeta-

Table II. Throughfall and stemflow in plot C and previous studies in Japan

References	Forest type	*TF/R* [%]	*SF/R* [%]	Location
This study in plot C	Broadleaf forest of Chestnuts (*Castanea crenata*), Oak (*Quercus serrata*)	54	3	Tochigi pref. (36.42°N, 139.70°E)
Toba and Ohta (2005)	Sawtooth oak (*Quercus acutissima*)	72	3	Aichi pref. (35.17°N, 137.18°E)
	Oak (*Quercus serrata*)	79	3	Aichi pref. (35.15°N, 136.97°E)
Katagiri (2008)	Broadleaf forest of Chestnuts (*Castanea crenata*), Loose-flowered hornbeam (*Carpinus laxiflora*), Oak (*Quercus serrata*)	79	3	Shimane pref. (35.17°N, 132.62°E)
Park *et al.* (2000)	Mixture forest of Oak (*Quercus serrata*) and Red pine (*Pinus resinosa*)	66	10	Aichi pref. (35.20°N, 137.17°E)
	Mixture forest of Oak (*Quercus serrata*) and shrubs	82	5	Kyoto pref. (34.78°N, 135.85°E)
Tanaka *et al.* (2005)	Japanese cedar (*Cryptomeria japonica*)	79	5	Chiba pref. (35.20°N, 140.12°E)
	Japanese cypress (*Chamaecyparis obtusa*)	75	10	

tion. Similarly, Cantú and Okumura (1996a) showed that understory sasa alone (*Sasa paniculata*) under an oak forest intercepted 13.6% of rainfall. Based on the separate monitoring of *TF* under the oak canopy and understory sasa (*Sasa palmata*), Haga (2011) reported that water intercepted by understory sasa was approximately 20% during selected rainfall events of 20 mm. According to previous observations, intercepted water by bamboo or sasa underlying oak forest may range from 10 to 20% of *R*. Although these previous studies did not quantify *BCF*, our findings based on monitoring of *BCF* in plot C suggested that a large portion of the water intercepted by bamboo under overstory vegetation was redirected to culm flow. Further investigation is necessary to quantify interception by bamboo, including *TF* and *BCF*.

When we measured intercepted rainfall solely by understory chino bamboo in plot T_s, *TF/R* was reduced to 31% (i.e. 69% of *R* was intercepted) compared to levels in plot C. A large portion of *R* intercepted by bamboo leaves in plot T_s may be transferred to the bamboo culm because estimated *BCF* was 53%. The possible reasons for the large ratio of intercepted water and *BCF* in plot T_s include greater density and greater leaf coverage of chino bamboo compared with plot C. The biomass of bamboo in plot T_s was 1.4-fold greater than in plot C, and the LAI in plot T_s was 2.3-fold greater than that in plot C. After the experimental removal of overstory vegetation, the density and biomass of bamboo were elevated due to the increased availability of light. Thus, our observations suggest that high-density bamboo vegetation strongly intercepts rainfall, and large portions of intercepted rainfall were redistributed to *BCF* and transferred to the ground surface.

SUMMARY AND CONCLUSIONS

Our field experiment elucidated the water transfer from the canopy to the soil surface in a broadleaf forest with an understory of bamboo. In a multi-layered forest, we found that the proportion of interception loss (*Ic*), throughfall (*TF*), stemflow (*SF*), and bamboo culm flow (*BCF*) relative to rainfall (*R*) was 21%, 54%, 3%, and 22%, respectively. The estimated *BCF* under the overstory canopy suggests that a large portion of water, intercepted by bamboo, may transfer to the ground surface as *BCF*. In the bamboo plot, *Ic/R*, *TF/R* and *BCF/R* were 16%, 31%, and 53%, respectively. These findings strongly suggested that a large portion of the intercepted water, which is $(1 - TF/R) \times 100$, was transferred as *BCF* due to the high density of bamboo. The findings of this study provide insights useful for elucidating the complex hydrological processes involved in water transfer from the canopy to the soil surface in broadleaf forests, and may be used in the development of forest management strategies. For more comprehensive understanding of these phenomena, continuous monitoring combined with investigation of multiple flow pathways, including bamboo culm flow, is essential.

ACKNOWLEDGMENTS

This study was supported by the project “Suntory Natural Water Sanctuaries” and partly supported by a Grant-in-Aid for Scientific Research (A) (#16H02556) from the Japan Society for Promotion of Science. We thank all the members of the Tokyo University of Agriculture and Technology and Suntory group who assisted in this collaborative research, as well as Fumie Terashita of Regional Environmental Planning, Inc.

REFERENCES

Bellot J, Escarré A. 1991. Chemical characteristics and temporal variations of nutrients in throughfall and stemflow of three species in Mediterranean holm oak forest. *Forest Ecology*

and Management **41**: 125–135. DOI: 10.1016/0378-1127(91)90123-D.

Cantú SI, Okumura T. 1996a. Rainfall partitioning in mixed oak forest with dwarf bamboo (*Sasa paniculata*) undergrowth. *Journal of Environmental Hydrology* **4**: 1–16.

Cantú SI, Okumura T. 1996b. Throughfall, stemflow and interception loss in a mixed white oak forest (*Quercus serrata* Thunb.). *Journal of Forest Research* **1**: 123–129. DOI: 10.1007/BF02348189.

Carlyle-Moses DE, Flores Laureano JS, Prince AG. 2004. Throughfall and throughfall spatial variability in Madrean oak forest communities of northeastern Mexico. *Journal of Hydrology* **297**: 124–135. DOI: 10.1016/j.jhydrol.2004.04.007.

Carlyle-Moses DE, Gash JH. 2011. Rainfall interception loss by forest canopies. In *Forest Hydrology and Biogeochemistry*, Levia DF, Carlyle-Moses DE, Tanaka T (eds). 407–423. DOI: 10.1007/978-94-007-1363-5_20.

Crockford RH, Richardson DP. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes* **14**: 2903–2920. DOI: 10.1002/1099-1085(200011/12)14:16/17<2903::aid-hyp126>3.0.co;2-6.

Gomi T, Asano Y, Uchida T, Onda Y, Sidle RC, Miyata S, Kosugi K, Mizugaki S, Fukuyama T, Fukushima T. 2010. Evaluation of storm runoff pathway in steep nested catchments draining a Japanese cypress forest in central Japan: a geochemical approach. *Hydrological Processes* **24**: 550–566. DOI: 10.1002/hyp.7550.

Haga H. 2011. Characteristics of rainfall-runoff responses and open channel flows in a small headwater catchment covered by deciduous broad-leaved forest. In *Management and Utilization of Broad-Leaved Forests*, Furukawa I, Hioki Y. Yamamoto F. (eds). Kaiseisha, Otsu, 117–138 (in Japanese).

Hiraoka M, Onda Y, Kato H, Mizugaki S, Gomi T, Nanko K. 2010. Effects of understory vegetation on infiltration capacity in Japanese cypress plantation. *Journal of the Japanese Forest Society* **92**: 145–150. DOI: 10.4005/jjfs.92.145 (in Japanese).

Iida S, Tanaka T, Sugita M. 2005. Change of interception process due to the succession from Japanese red pine to evergreen oak. *Journal of Hydrology* **315**: 154–166. DOI: 10.1016/j.jhydrol.2005.03.024.

Inoue A, Nagano M, Sankoda K. 2017. Rainfall interception in an intensively managed low density stand of bamboo, *Phyllostachys pubescens*. *Journal of Forest Research* **22**: 53–60. DOI: 10.1080/13416979.2016.1273086.

Katagiri S. 2008. Studies on estimation of stem-flow in a deciduous broadleaved forest and a Sugi-Hinoki (*Cryptomeria japonica-Chamaecyparis obtusa*) stand. *Bulletin of the Faculty of Life and Environmental Science-Shimane University* **13**: 11–18 (in Japanese).

Keim RF, Skaugset AE, Weiler M. 2005. Temporal persistence of spatial patterns in throughfall. *Journal of Hydrology* **314**: 263–274. DOI: 10.1016/j.jhydrol.2005.03.021.

Komatsu H, Tanaka N, Kume T. 2007. Do coniferous forests evaporate more water than broad-leaved forests in Japan? *Journal of Hydrology* **336**: 361–375. DOI: 10.1016/j.jhydrol.2007.01.009.

Levia DF, Frost EE. 2006. Variability of throughfall volume and solute inputs in wooded ecosystems. *Progress in Physical Geography* **30**: 605–632. DOI: 10.1177/0309133306071145.

Manfroi OJ, Kuraji K, Tanaka N, Suzuki M, Nakagawa M, Nakashizuka T, Chong L. 2004. The stemflow of trees in a Bornean lowland tropical forest. *Hydrological Processes* **18**: 2455–2474. DOI: 10.1002/hyp.1474.

Park HT, Hattori S, Kang HM. 2000. Seasonal and inter-plot variations of stemflow, throughfall and interception loss in two deciduous broad-leaved forests. *Journal of Japan Society of Hydrology and Water Resources* **13**: 17–30. DOI: 10.3178/jjshwr.13.17.

Saito T, Matsuda H, Komatsu M, Xiang Y, Takahashi A, Shinohara Y, Otsuki K. 2013. Forest canopy interception loss exceeds wet canopy evaporation in Japanese cypress (Hinoki) and Japanese cedar (Sugi) plantations. *Journal of Hydrology* **507**: 287–299. DOI: 10.1016/j.jhydrol.2013.09.053.

Suzaki T, Kume A, Ino Y. 2005. Effects of slope and canopy trees on light conditions and biomass of dwarf bamboo under a coppice canopy. *Journal of Forest Research* **10**: 151–156. DOI: 10.1007/s10310-004-0123-x.

Tanaka N, Kuraji K, Shiraki K, Suzuki M, Suzuki M, Ohta T, Suzuki M. 2005. Throughfall, stemflow and rainfall interception at mature *Cryptomeria japonica* and *Chamaecyparis obtusa* stands in Fukuroyamasawa watershed. *Bulletin of the Tokyo University Forest* **113**: 197–240 (in Japanese).

Taniguchi M, Tsujimura M, Tanaka T. 1996. Significance of stemflow in groundwater recharge. 1: Evaluation of the stemflow contribution to recharge using a mass balance approach. *Hydrological Processes* **10**: 71–80. DOI: 10.1002/(SICI)1099-1085(199601)10:1<71::AID-HYP301>3.0.CO;2-Q.

Toba T, Ohta T. 2005. An observational study of the factors that influence interception loss in boreal and temperate forests. *Journal of Hydrology* **313**: 208–220. DOI: 10.1016/j.jhydrol.2005.03.003.

Tsuchiya K, Okuro T, Takeuchi K. 2013. The combined effects of conservation policy and co-management alter the understory vegetation of urban woodlands: a case study in the Tama Hills area, Japan. *Landscape and Urban Planning* **110**: 87–98. DOI: 10.1016/j.landurbplan.2012.10.013.

Ziegler AD, Giambelluca TW, Nullet MA, Sutherland RA, Tantasarin C, Vogler JB, Negishi JN. 2009. Throughfall in an evergreen-dominated forest stand in northern Thailand: Comparison of mobile and stationary methods. *Agricultural and Forest Meteorology* **149**: 373–384. DOI: 10.1016/j.agrformet.2008.09.002.

Zimmermann A, Wilcke W, Elsenbeer H. 2007. Spatial and temporal patterns of throughfall quantity and quality in a tropical montane forest in Ecuador. *Journal of Hydrology* **343**: 80–96. DOI: 10.1016/j.jhydrol.2007.06.012.