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

Yutaka Abe1, Takashi Gomi2, Norihsa Nakamura1 and Noriko Kagawa3

1Institute for Water Science, Suntory Global Innovation Center Ltd., Japan
2Department of International Environmental Agriculture Science, Tokyo University of Agriculture and Technology, Japan
3CSR 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 (Phleoblastus 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 induces 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.
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:

\[ Ic = R - TF - SF - BCF \]  

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 T1 (6 × 15 m), all understory vegetation, which consisted mostly of chino bamboo, was removed for investigation of interception by overstory vegetation. Plot T2 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 T3; 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 T1, which had overstory vegetation, were located adjacent to each other. Plot T2, with only chino bamboo, was located approximately 8 m north of plots C and T1. 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 T1 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 T1 were installed, as well as four gauges in plot T2. Rain 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 (\( \varepsilon \)) was calculated based on the following equation:

\[ \varepsilon = \frac{t(n-1)\sigma}{\sqrt{n}} \]  

where \( n \) is the number of TF gauges, \( t \) is the Student’s t-value with confidence level (\( \alpha \)) and degree of freedom (\( n-1 \)), \( \sigma \) 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 T1 (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 (\( S_{p} \)) to water height using two methods. To estimate the plot-scale stemflow height (SF), we applied the following equation for plots C and T1.
where $A$ is the area of the plot. To estimate $S_{c}$ of ungauged stems, we use the method proposed by Katagiri (2008), which consists of a multiple regression analysis with $S_{c}$, crown areas of 10 measured stems and rainfall. We calculated the $SF$ for a combined area of plots C and T, because tree canopy cover extended over both plots. We then estimated crown-area stemflow height ($S_{c}$) based on crown projection area ($C_{p}$) of the given trees based on the following equation,  

$$S_{c} = \frac{S_{fv}}{C_{p}}$$  

(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 $1 \times 1$ m within each plot, C and T. 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 $\geq 5$ 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, and T 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/m² (SD: ±2.8) in plot C and 4.7 kg/m² (SD: ±0.7) in plot T. The mean densities of chino bamboo in the sub-plots were 15.3 stems/m² stems in plot C and 18.7 stems/m² in plot T.

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) was 17.5% in plot C, 15.4% in plot T, and 35.3% in plot T. The equation for estimating $SF$ of ungauged stems was $S_{o}$ (L) = 0.33 × $C_{s}$ (m²) + 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 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, at 149 mm (error: ±23 mm), followed by plot C at 131 mm (error: ±23 mm) and plot T, 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, and 31% (error: ±9%) in plot T.

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

(a) Throughfall ($TF$) in plots C, T, and T

(b) Stemflow ($SF$) in the combined area of plots C and T

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 (%).

| Rainfall | Throughfall | Stemflow | Bamboo culm flow | Interception loss |
|----------|-------------|----------|------------------|------------------|
| R (mm)   | TF (mm)     | SF (mm)  | BCF/R            | Ic/R             |
| plot C   | 243.5       | 131      | 7                | 22%              |
|          | (±23)       | (±9%)    | 3%               | (13–29%)         |
|          | plot T_o    | 149      | 7                | 21%              |
|          | (±23)       | (±9%)    | 3%               | (8–39%)          |
|          | plot T_i    | 76       | --               | 36%              |
|          | (±27)       | (±11%)   | --               | (27–45%)         |

Total amount of 12 events (mm) and percentage to rainfall (%)

| Rainfall | Throughfall | Stemflow | Bamboo culm flow | Interception loss |
|----------|-------------|----------|------------------|------------------|
| R (mm)   | TF (mm)     | SF (mm)  | BCF/R            | Ic/R             |
| plot C   | 243.5       | 131      | 7                | 22%              |
|          | (±23)       | (±9%)    | 3%               | (13–29%)         |
|          | plot T_o    | 149      | 7                | 21%              |
|          | (±23)       | (±9%)    | 3%               | (8–39%)          |
|          | plot T_i    | 76       | --               | 36%              |
|          | (±27)       | (±11%)   | --               | (27–45%)         |

= 184 –

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 I). For instance, previously reported TF/R and SF/R in broadleaf 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-
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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, 137.71°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       | Aichi pref. (35.20°N, 140.12°E) |

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 \((1 - \frac{TF}{R}) \times 100\), 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.

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