Detached stemflow has been defined as rainwater that breaks away from the stemflow and falls around the trees as throughfall. Quantitative measurements of detached stemflow were taken for two sample broadleaf trees on the university campus. Zelkova, with smooth bark, has a tree structure that concentrates rainwater, producing a large amount of stemflow. A rainwater collection system installed around the trunk can capture large amounts of throughfall as detached stemflow. The detached stemflow amount had almost doubled in water height equivalent to throughfall at the tree stand. Therefore, some trees generate much throughfall in the forest near the trunk. In the case of the Katsura tree, however, the stemflow was low. The throughfall attributable to the detached stemflow was less than the average throughfall. This low stemflow generation was assumed to be due to the roughness of the Katsura bark. The rainwater which attaches to the trunk and branches breaks away easily. Presumably, the leaves near the trunk intercept raindrops and disperse the rainwater to the surroundings. The detached stemflow can constitute a large quantity. It can be expected to be related closely to the stemflow generation mechanism.

KEYWORDS funneling ratio; rainfall; branchflow; throughfall; tree shape

INTRODUCTION

Rainfall on a forest canopy reaches the forest floor via two paths: throughfall and stemflow. The generation of throughfall and stemflow is strongly related to each other (Levia et al., 2011). The rainwater detained by branches makes branchflow, and collection of branchflow makes stemflow (Herwitz, 1987). The canopy interception loss, which is important for evaluating available water resources, is calculated with the rainfall amount at open-sky places, throughfall, and stemflow.

Throughfall in a forest is widely recognized to have strong spatial distribution (e.g. Lloyd and Marques, 1988) because a forest crown system is complicated with water storage at the canopy and redistribution by rainwater moving with branch connections. To investigate the throughfall amounts accurately, Lloyd and Marques (1988) reported that relocated rainfall collection would be necessary for a tropical rainforest. Furthermore, Konishi et al. (2006) used one hundred rainfall collectors to observe throughfall in a lowland tropical rainforest. To explain how the spatial distribution of throughfall is generated, Loescher et al. (2002) observed 56 points of rainfall around a tree and verified the relation among the nearest leaf distance and the throughfall amount. However, the generation mechanism of spatial distribution of throughfall was not clarified quantitatively. Nanko et al. (2011) reported precise observations of throughfall distribution using a single transplanted tree and described a tendency by which a lower throughfall amount was observed at the middle part of the crown canopy than at inner or outer parts of the crown.

Factors that decide stemflow generation have also been analyzed (Levia and Germer, 2015). Funneling systems of branches gather rainwater. The degree of bark relief is regarded as important for ascertaining the stemflow amount, because rougher-barked trees show higher bark water storage capacities, resulting in the reduction of branchflow or stemflow (Levia and Germer, 2015).

Herwitz (1987) conducted laboratory tests with a rainfall simulator in order to quantify how much rainwater was detained by branches with changing branch inclination, with results showing that the branches of higher inclination above the horizontal gathered more branchflow.

The throughfall and stemflow partitioning interaction was also considered. Staelens et al. (2008) examined partitioning of throughfall and stemflow during leaf period and no-leaf period and concluded that the leaf condition decided their portioning ratio. Those findings reflected a strong relation between throughfall and stemflow.

By changing a view into a real situation, one can sometimes see water flow from a tree branch or stem during a rain event. During heavy rainfall, we could sometimes see massive downward rainwater flow from the bending points of branch or bole (Figure S1). It is detached from branches or stem by some triggers such as stem bark undulation, fragments of bark (Crockford and Richardson, 2000), or an overly great amount of stemflow that a stem is unable to hold. These “drips” are said to be one reason that throughfall has strong spatial distribution (Levia et al., 2011). Although one might readily imagine that these drips around the stem would be outstanding because funneling branches have a function of concentrating rainwater to the main
stem, a few reports have described an evaluation of the drip amounts around (or very near) the stem. As described herein, we defined these drips as “detached stemflow.” Nanko et al. (2011) measured throughfall near the stem, but the nearest distance was 0.4 m apart from the stem surface. Herwitz (1987) measured and compared throughfall near trunk (within 1 m from the trunk) and throughfall near the perimeter of the crown for 50 trees and with results showing that the maximum as well as the minimum throughfall were found in the near-trunk throughfall, and the near-trunk throughfall showed higher variation. These papers provided us useful information for the throughfall near the trunk, but the quantitative analysis has still been insufficient.

In order to quantify the detached stemflow, we specifically examined and measured the throughfall very near to the trunk, with a newly established wide-area water pool system which can collect all rainwater in the near trunk region. We selected two broadleaf trees for preliminary observation. We also analyzed their relationship with rainfall conditions. This study is believed to be the first to examine and quantify the throughfall including detached stemflow. The aim of this study is to evaluate the actual and on-site characteristics of detached stemflow. Although the characteristics of tree species should be an important factor to evaluate the detached stemflow amount, this paper does not cover the species factor, because the sample number has been limited.

For supplementation of the definition of the detached stemflow, detached stemflow from bole is categorized into throughfall near trunk because it is not stemflow. It is difficult to distinguish the source of throughfall into detached stemflow, branchflow, throughfall that was not touching to leaves or branches, and throughfall that was once detained to leaves or branches. The amount and ratio of detached stemflow are expected to be important to elucidate throughfall and stemflow generation and canopy interception loss during rainfall.

METHODS

Study site and target trees

The study plot was set at a small tree stand inside a university campus (E 139.48°, N 35.68°). The plot is flat, with altitude of about 64 m above sea level. Some trees are planted and maintained to produce a campus garden (Figure 1b). Dead branches on trees are extracted artificially but overall tree shapes have retained their natural growth. The study plot comprises Zelkova (Zelkova serrata) and Japanese Katsura (Cercidiphyllum japonicum) trees, as presented in Figure 1a. Figure 1a shows three Zelkova (designated as Z1–Z3) and four Katsura (C1–C4) trees. This report specifically describes the Z3 and C4 trees. The tree heights, diameter at breast height (DBH), and crown projection areas are presented in Table I. Bark relief of the Zelkova is smooth, whereas that of Katsura is rough (Figure S2).

Rainfall observation

Open-sky rainfall has been observed at approximately 200 m away to the southeast of the study plot at the Automated Meteorological Data Acquisition System (AMeDAS) Fuchu weather station of the Japan Meteorological Agency. We could obtain 10 minute interval rainfall data through the internet.

Throughfall observation

Before this study, throughfall distribution was examined during April 8th, 2018 through December 11th, 2018. Throughfall at the study plot was measured in two ways. One automatic recording tipping bucket rain-gauge (Type OW-34-BP, 0.5 mm resolution; Ota Keiki Co.) was installed inside the plot. Then 20 funnels of 0.205 m diameter were used to measure throughfall. The tipping bucket rain-gauge recorded continuously with a 10 min temporal

![Figure 1](image)

**Figure 1.** Locations and features of and around the target trees: (a) canopy projection map and (b) photograph image. (a) Canopy projection map. Blue circle represents the 0.5 mm rain-gauge. Blue crosses represent the 20 funnels used for rainfall collectors. Blue lines show the outline of the canopy. (b) Photograph of C4 and Z3 trees (taken from north)

| Tree ID | Species             | Tree height (m) | DBH (m) | Crown projection area (m²) | A stem*1 (m²) | A pool*1 (m²) | FR.stem*2 (S.D.) | FR.pool*2 (S.D.) |
|---------|---------------------|-----------------|---------|-----------------------------|---------------|---------------|------------------|------------------|
| C4      | *Cercidiphyllum japonicum* | 19.7            | 0.38    | 37.9                         | 0.165         | 2.10          | 1.75 (0.82)      | 0.43 (0.15)      |
| Z3      | *Zelkova serrata*    | 26.7            | 0.48    | 35.6                         | 0.245         | 1.51          | 36.67 (9.38)     | 1.43 (0.59)      |

*1 area of stemflow collector and water pool system, see Figure 2b
*2 funnelling ratio of stemflow and near the stem, see Equations (1) and (2)
resolution using a pulse logger (UIZ5061; UIZIN Co.). Ten funnels out of 20 were connected using a vinyl hose (Figure S3). The collected throughfall was measured using two handmade tipping bucket flow meters (Shiraki et al., 2019). The handmade tipping bucket flow meter outputs approximately one pulse per 160 mL. Each handmade tipping bucket flow meter was calibrated by laboratory testing. These two tipping bucket flow meters were recorded with 10 min resolution using pulse loggers (UIZ5061; UIZIN Co.). During May 31st, 2018 to July 27th, 2018, 20 water bottles were installed to collect throughfall from each funnel individually to check the spatial distribution of throughfall.

Stemflow and detached stemflow observation system

The stemflow and detached stemflow was observed during April 16th, 2020 to December 5th, 2020. This period was leaf exhibition time. Stemflow was observed separately by binding a vinyl hose with silicone sealant around the stem, and with a transparent PVC sheet to make a barrier for the water path. The height of the stemflow collector was about 1.1 m above the ground. The drained water was measured using a handmade tipping bucket flow meter as described above (Figure 2).

A water pool made of a 1.83 m diameter vinyl sheet (merchandise catalog specification as a water pool, Snapset Pool Ocean; INTEX Co.) was used to collect throughfall near trunk. The rainwater collected by this pool system consisted of various components of water source such as detached stemflow, detached branchflow, throughfall that directly flows in, and throughfall that was once detained by leaves or branches. This water pool system can measure only the total amount of rainwater dripped in the collecting area. The vinyl water pool was cut and notched to fit it to the tree stem. It was fixed with a wood stage or supporting bars. The lengths between the stem surface to the outer periphery of the water pool were approximately 0.68 m and 0.49 m, respectively, for C4 and Z3. The height of the water pool bottom was about 0.7 m above the ground. The water collection area of the water pool collection system “A pool” (Figure 2b) was calculated by subtracting the stem area from the pool area, with 2.10 m² and 1.51 m², respectively, for C4 and Z3. The water pool size should be determined based on the definition of “near” a stem together with consideration of each tree size. We tentatively used this water pool size, because the definition of “near” must be discussed further with the use of the accumulated observation samples. Those specifications, including DBH are presented in Table 1.

**Analysis of funneling ratio**

The concentration of rainfall by tree branches has been analyzed using a funneling ratio value (Herwitz, 1986; Germer et al., 2010; Van Stan et al., 2016). Herwitz (1986) defined the funneling ratio of stemflow (FR.stem) as

\[
FR_{stem} = \frac{SF}{(P \times BA)} \times 10^{-3}
\]

where \(SF\) represents stemflow volume in milliliters, \(P\) denotes the gross rainfall (open-sky rainfall) amount in millimeters, and \(BA\) stands for the stem basal area in square meters. This value represents the degree of concentration of rainfall, with \(FR_{stem} = 1\) showing stemflow volume equal to the gross rainfall that would fall at the basal area. It is larger than one in cases where the stemflow concentrates the rainwater. In this paper, we use the value of “A stem” in Table 1 as \(BA\) in Equation (1). “A stem” is the summation of the basal area and the area of the vinyl hose tube width, presented in Figure 2b because they constitute the actual water collection area.

Here we define the new coefficient \(FR_{pool}\), which provides a ratio of throughfall volume that includes detached stemflow near the stem, to gross rainfall. That is

\[
FR_{pool} = \frac{PF}{(P \times PA)} \times 10^{-3}
\]

where \(PF\) denotes the volume in milliliters which is collected with a water pool in Figure 2; also, \(PA\) represents the water collection area of a water pool, that is “A pool” in Figure 2b and in Table 1 in square meters.

The funneling ratio of throughfall (average of 20 funnels throughfall) is calculated simply by dividing throughfall by gross rainfall. That is, funneling ratio and throughfall ratio are synonymous in this case.

**RESULTS**

**Throughfall**

The results of the earlier study showed that the average of funneling ratio for 20 funnels throughfall was 0.77 when the gross rainfall amount exceeded 10 mm. That means the average throughfall was 77% of gross rainfall. The distribution of 20 funneled rainfall meters, observed individually during June 6th, 2018 to July 28th, 2018, indicated that the total mean throughfall value in this period and the standard deviation were, respectively, 159.3 mm and 18.6 mm. Furthermore, the maximum and minimum throughfall were found respectively as 187.1 mm and 121.5 mm (92.2% and 59.8% of rainfall).
Funneling ratio of stemflow and throughfall near stem

We were able to divide 58 rainfall events by separating rainfall events by 12 h no-rainfall period during the analysis period. To calculate the funneling ratio of FR.stem and FR.pool of C4 and Z3, 27 events in which the gross rainfall amount exceeded 10 mm were selected, as depicted in Figure 3. The funneling ratio of the Z3 stem showed a higher value than others. Figure 3b shows details of data that did not exceed the funneling ratio of 5.

The funneling ratios of both the stem and pool fluctuated by the event rainfall.

The average values of the funneling ratios of Z3 stem and C4 stem were, respectively, 36.67 and 1.75 (Table I). Levia and Germer (2015) reviewed earlier stemflow research and reported that the average funneling ratios of various trees were 3–37. They also described that the funneling ratios of some tree species were greater than 100 during the storm rainfall event. The average funneling ratio of Z3 stem was high but fell within the range shown in previous studies. That of C4 stem was low compared to the summary given by Levia and Germer (2015).

The average funneling ratio of the Z3 pool, the funneling ratio for the neighborhood of a tree, is 1.43. That means throughfall near the Z3 tree showed almost double the amount of throughfall to the average, as the funneling ratio of throughfall was 0.77. However, the funneling ratio of C4 pool was 0.43, which indicates that throughfall near the C4 tree was less than average throughfall and that the divergence movement of rainwater would be functioning.

DISCUSSION

Detached stemflow

It is readily apparent that the Z3 tree concentrates the rainwater through the funneling function of branches and trunks. Detached stemflow generates high-intensity throughfall near the stem. Actually, these detached stemflows were checked visually by field observations during rainfall. The FR.pool of Z3 recorded double the average throughfall.

The FR.pool of C4 was below 1.0, whereas the FR.stem of C4 exceeded 1.0. Therefore, the C4 tree concentrated the rainwater by branches. Presumably, the detached stemflow was low. It is considered that the throughfall near the stem was intercepted by leaves surrounding the stem and was divergent out of the pool system (Figure 1b).

Stemflow generation

A remarkable difference was found between the funneling ratios of stemflow Z3 and C4. Levia et al. (2015) examined various parameters for generating stemflow such as the trunk lean angle, trunk diameter, branch angle, and total branch count. Although the tree structure of Z3 and C4 has a similar conical shape that opens upward, Z3 has more branches. In this case, from the on-site observation during a storm rainfall event, we made a hypothesis that the bark characteristics are assumed to be an important parameter that differentiates the stemflow generation. The Z3 tree, a zelkova tree, has a smoother surface on its branch and trunk (see Figure S3). Then it is apparent that detained rainwater on branches produce branchflow on the underside of the branch (Herwitz, 1987) and the branchflow flows down in an orderly and continuous manner along the inclined branches (Figure 4a). However, the C4 tree, Japanese Katsura, has a rougher trunk surface. The hangnail or fragmented bark provides many opportunities for detaching the branchflow generated on the underside of the branches. Previous studies, e.g. Van Stan et al. (2016), described the importance of bark structure characteristics for the bark water storage capacity and funneling ratio. Comparing the higher funneling ratio and lower bark water storage capacity by a smooth bark tree, Van Stan et al. (2016) inferred that the bark water capacity as a major parameter affecting stemflow generation. That finding is consistent with results of this study showing that the smooth bark tree (Z3) has higher funneling ratios than that of the rough bark tree (C4). The difference in stemflow amount, however, was so outstanding that we are unable to explain them solely by the differences of their respective bark water capacities. The converting function from stemflow to throughfall

Figure 3. Funneling ratios of target trees, both stemflow and near the stems, and throughfall. The vertical axis scales differ for (a) and (b)

Figure 4. Illustration of hangnail effect and flow line of rainwater on the underside of inclined branches: (a) C4 and (b) Z3
PRELIMINARY OBSERVATION OF DETACHED STEMFLOW

Figure 5. Illustration of the rainwater pathway with different bark surfaces: (a) C4 and (b) Z3. (a) Rough bark surface, C4 tree. Easy detachment and some branches and leaves make an interception of raindrops. (b) Smooth bark surface, Z3 tree. Stemflow is concentrated with branches which Crockford and Richardson (2000) have mentioned is considered to be more influential to the stemflow generation. It can be explained well if we suppose that the converting function or hangnail effect changes with the bark roughness as illustrated in Figure 4.

Figure 5 portrays diagrams illustrating the possible generation hypotheses of branchflow, stemflow and detached stemflow. The bark surface would create functions as a hangnail effect with fractures, fragmentation, or slight relief of the bark surface as illustrated in Figure 4. These hangnails would break away rainwater detained on the branches or trunks and make dripping throughfall.

Figure 5b shows the Z3-type tree structure. The bark surface is smooth, with few chances to detach. Branches and trunks are assumed to be effective at concentrating rainwater adhering to them. A small undulation of the stem produces a detached pathway of stemflow and a massive throughfall spot near the stem. These hypotheses are consistent with the results obtained for $FR_{stem}$ and $FR_{pool}$ of Z3, and tree shape observed as presented in Figure 2b. By observation during heavy rainfall, we could witness detach- ing stemflow from the Z3 bole and flowing into the pool system. Such a massive throughfall spot is assumed to be difficult to observe unless one uses a collector that has a wide-area water catchment because these dripping points are easily changeable depending on the rainfall intensity and changes of surface features.

The C4-type tree structure is presented in Figure 5a. The large number of hangnail effects with a rough bark surface would be possible to have frequent chances for detachment. Therefore, the rainwater concentration is rather small. In addition to it, the C4 tree has many leaves around the stem (Figure 1b), they will cause intercept and divergence of dripping rain. Actually, the height of the lowest live branches of C4 are 1.4 m above the ground, while that of Z3 are 9.3 m. These mechanisms can give a good explanation for the results of $FR_{stem}$ and $FR_{pool}$ of C4.

The ratio of detached as well as detained rainwater with the degree of bark roughness can be an important index.

Tree structure including branch and trunk connections and inclination features will need to be analyzed in detail in order to investigate the generation mechanisms of both throughfall and stemflow.

CONCLUSION

Choosing two broad leaf trees as samples, we elucidated quantitatively the actual characteristics of throughfall near trunk including detached stemflow. Detached stemflow produces concentrated throughfall near the stem for a tree with a smooth bark surface. The amount of throughfall near that tree showed double the average of throughfall. Another tree sample, however, showed decreased throughfall near the stem. The reasons for these are not certain but there is a consistency if we assume the hangnail effects of rough bark surface and interception of rain drops by lower branches.

Detached stemflow is not negligible to analyze the rainwater budget at the tree canopy, especially for a dense forest, because its amount is abundant. Together with a proper definition of a certain distance as “near” the stem, the detached stemflow characteristics should be examined further.

SUPPLEMENTS

Figure S1. Example picture of massive downward waterflow detached from a tree bole during heavy rainfall: At a zelkova tree on the same university campus as the research plot (photo was taken on July 18th, 2017)

Figure S2. Bark surface of (a) C4 – Katsura and (b) Z3 – Zelkova

Figure S3. Throughfall measurement with 20 funnels, 10 of which were connected and measured with a handmade tipping bucket flow meter

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