Relationship between stand structures and rainfall partitioning in dense unmanaged Japanese cypress plantations

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Abstract

The research on the relationship between stand structures and rainfall partitioning (RP) of gross rainfall (GR) into throughfall (TF), stemflow (SF), and interception loss (IL) was conducted in the two dense unmanaged Japanese cypress plots at an age of 33 years with stand density of 2500 stems ha⁻¹, and the results were compared with the previous studies. The results showed that (1) TF/GR significantly decreased, but SF/GR and IL/GR significantly increased with increasing stand density, which confirms that stand density is an informative stand structure factor for all the RP components in coniferous plantations. In addition to stand density, canopy cover ratio and storage capacity could also be influential stand structure factors for RP. (2) Having the highest stand density, TF/GR were the lowest class and SF/GR and IL/GR were the highest class in the two study plots. In detail, however, the plot with smaller stand with denser and thicker dead branch layers had the exceptionally low TF/GR compared with the other plot, but SF/GR in both plots were almost identical. (3) TF/GR decreased with increasing number of dead branches possibly because of increasing rainwater interception by dead branches, while it increased with increasing vertical dead branch space possibly because of increasing rainwater splash by dead branches. SF/GR could increase by dead branches possibly because of the additional gain of rainwater by the dead branches. However, the number of dead branches did not affect SF/GR possibly because the dead branches generating SF could be limited to the upper dead branches. These findings will contribute new information to the studies on RP in coniferous plantations and guide better silvicultural practices for effective forest ecological services.

Key words: Dead branch, Interception loss, Stand density, Stemflow, Throughfall

1. Introduction

Rainfall partitioning (RP) plays an important role in ecological, hydrological, and biogeochemical functions of forests (e.g., Llorens and Domingo, 2007; Sadeghi et al., 2018). When gross rainfall (GR) begins, the initial interaction occurs at forest canopy. GR is partitioned into (1) throughfall (TF) freely falling through the gaps and dripping and splashing from the canopy (2) stemflow (SF) flowing down the stem, and (3) interception loss (IL) once retained in the canopy and evaporating back to the atmosphere (Levia et al., 2017). TF is a primary component of RP portioning from 60.0% to 85.0% of GR in coniferous forests (Sun et al., 2014). Although SF/GR accounts for less than 10% on average, it is highly dependent on tree species and their structure (Levia and Frost, 2003; Levia and Germer, 2015). IL amounts from 9% to 48% of GR (Hörmann et al., 1996). Since RP has such a great influence on forest water budget, an understanding of characteristics of each component of RP is important for balancing silvicultural practices and forest ecosystem services.

Previous studies addressed that RP is a complex process controlled by various factors such as meteorological conditions (e.g., evaporation rate, rainfall intensity and rainfall amount; Gash, 1979; Llorens et al., 1997; Komatsu et al., 2008) and stand structures (e.g., stand density (SD), basal area (BA) and canopy cover (CC); Teklehaimanot et al., 1991; Komatsu et al., 2007, 2015; Molina and del Campo, 2012; Sun et al., 2015; Sun et al., 2017). The examination of RP in the regions where climate conditions (e.g., annual precipitation and seasonality of precipitation) are comparable, however, could reduce the effects of climate conditions and enable us to investigate the effects of forest structures with similar leaf phenology on RP (Komatsu et al., 2007, 2015; Sun et al., 2017).

In Japan, 67% of the land is covered by forest, of which 41% is occupied by plantations (Japan Forestry Agency, 2017). Japanese cedar (Cryptomeria japonica D. Don) and Japanese cypress (Chamaecyparis obtusa Endl.) are two dominant coniferous tree species occupying 44% and 25% of the plantations, respectively. A substantial number of these coniferous plantations have not been managed on account of the economic recession on forestry since the 1980s (Onda et al., 2010). As a result, these coniferous plantations have been kept under high SD and densely covered by canopies, which could intercept more rainwater at the canopies and thus reduce water supply to the forest floor (Kuraji, 2003; Sun et al., 2015; Shinohara et al., 2015). Since the awareness on the adverse effects of these unmanaged coniferous plantations has been increasing, effective forest management for solving such problems and enhancing forest ecosystem services has become a pressing issue. Komatsu et al. (2015) highlighted the usefulness of SD as a key forest inventory data for estimating IL of these coniferous plantations in Japan. Sun et al. (2017) evaluated SD, CC, and BA as the useful stand structure factors also obtained from
the forest inventory to estimate $TF$ in these coniferous plantations in Japan, among which $SD$ was most highly correlated with $TF$.

Although the dataset of previous studies on RP in the above-mentioned coniferous plantations includes the data with various SD, there are few data with a $SD$ of 2500 – 3000 stems ha$^{-1}$, which is a typical planting density for these coniferous species (Japan Forestry Agency, 2017). Shinohara et al. (2010) addressed that there was a possibility of appearing new stand structure factors affecting RP such as leaf area and dead branches in dense unmanaged coniferous plantations other than $SD$. Therefore, finding the relationships between all the components of RP and key stand structure factors in addition to $SD$, $CC$ and $BA$ including the data with a $SD$ of 2500 stems ha$^{-1}$, or more is required for better understanding of RP and better silvicultural practices for effective forest ecological services.

In this study, we observed all the components of RP and various stand structure factors in two nearby plots in a dense unmanaged Japanese cypress plantation with a $SD$ of 2500 stems ha$^{-1}$ and set the following objectives:

(1) to see the difference of RP with the data reported in previous studies with a $SD$ ranging 300 – 2400 stems ha$^{-1}$,

(2) to see the difference of RP in the dense unmanaged coniferous plantations with the same $SD$ but different stand structures,

(3) to see the new stand structure factors affecting RP in the dense unmanaged coniferous plantations.

### 2. Materials and methods

#### 2.1 Site description

This study was conducted in an unmanaged 33-year-old Japanese cypress (Chamaecyparis obtusa Endl.) plantation at the Takada Experimental Site in the Kasaoka Research Forest, Kyushu University, Fukuoka, Japan (33°37′58″ N, 130°31′48″ E, ca 100 m a.s.l.). The plantation has not been managed since planting with a $SD$ of 2500 stems ha$^{-1}$ in 1985. The soil type is brown forest soil originated from serpentine bedrock (Kinoshita and Takimoto, 1936). The mean annual temperature and the mean precipitation were 17.1°C and 1634.3 mm, respectively, recorded from 1986 to 2015 at a meteorological station 9 km southwest of the study site. Rainy season is from June to September, and snowfall rarely occurs.

Two 20 m × 10 m study plots were established (Fig. 1, Table 1). They were approximately 50 m apart (hereafter P1 and P2). Both plots were relatively steep with slopes of 26 degrees. $SD$ of each plot was 2500 stems ha$^{-1}$, containing 50 trees of Japanese cypress among which five trees had no leaves due to self-thinning (Fig. 1).

The stand structures are summarized in Table 1. The recommended $BA$, relative spacing ($Rs$), and relative yield index ($Ry$) indicating status of stocking for silvicultural practice of Japanese cedar and cypress plantations in Japan are 50 m$^2$ ha$^{-1}$, 20%, and 0.7, respectively (Tange and Koike, 2016). Those variables in the plots were 65 – 85 m$^2$ ha$^{-1}$, 13 – 16%, 0.88 – 0.95, respectively, which implies that both plots were overstocked. $CC$ and plant area index ($PAI$), the variables indicating the status of canopy coverage by leaves, branches, and stems, were 99.3 – 99.6% and 5.6 – 6.4 m$^2$ m$^{-2}$, respectively, which implies that both plots were almost fully covered by the canopies.

| Stand structures | P1 Average ± S.D. | P2 Average ± S.D. |
|------------------|------------------|------------------|
| The number of trees ($N_{tr}$) | 50 ± 4 | 50 ± 4 |
| Tree age (years) | 33 ± 1 | 33 ± 1 |
| Stand density (SD, stems ha$^{-1}$) | 2500 ± 300 | 2500 ± 300 |
| Diameter at breast height (DBH, cm) | 17.7 ± 1.5 | 17.7 ± 1.5 |
| Tree height (H, m) | 12.7 ± 2.0 | 12.7 ± 2.0 |
| Stand volume ($SV$, m$^3$ ha$^{-1}$) | 286.7 ± 84.1 | 286.7 ± 84.1 |
| Basal area (BA, m$^2$ ha$^{-1}$) | 64.9 ± 8.2 | 64.9 ± 8.2 |
| Relative spacing index ($Rs$, %) | 15.8 ± 10.0 | 15.8 ± 10.0 |
| Relative yield index ($Ry$) | 0.88 ± 0.10 | 0.95 ± 0.10 |
| Crown projection area (CPA, m$^2$) | 4.8 ± 1.8 | 4.8 ± 1.8 |
| Canopy cover ratio (CC, %) | 99.3 ± 0.1 | 99.6 ± 0.1 |
| Plant area index (PAI, m$^2$ m$^{-2}$) | 5.6 ± 0.2 | 6.4 ± 0.2 |

S.D. denotes standard deviation. $Rs$ indicates that the ratio of the mean distance between trees to the mean dominant tree height of the stand.

Considering these variables, P2 was slightly denser than that of P1 (Fig. 1, Table 1). Tree height and diameter at breast height (DBH), the variables indicating tree size, were 19 – 20 m and 13 – 15 cm, respectively, which indicates the tree size in P2 belongs to the highest class and that in P1 belongs to the middle class in the stand of their age in this area (Japan Forestry Agency, 1957).

The crown and live branch structures are given in Table 1 and Fig. 2. The average crown projection area (CPA) was 4.8 m$^2$ in P1 and 4.7 m$^2$ in P2 and the average crown length was 2.8 m in P1 and 3.0 m in P2. The average number of live branches ($N_{l}$) and thickness of live branch layer were 15.7 branches (21.8% of the total number of branch) and 2.8 m (22.3% of the tree height) in P1 and 14.7 branches (23.6% of the total number of branch) and 3.0 m (19.5% of the tree height) in P2, respectively. The average number of live branches per unit length ($\bar{N}_{l}$) and vertical live branch space ($\bar{x}_{sl}$) were 5.6 branches m$^{-1}$ and 0.18 m in P1 and 4.9 branches m$^{-1}$ and 0.20 m in P2, respectively. The results show that the crown and live branch structures were almost identical.

The dead branch structure is shown in Fig. 2. Since the trees in the plantation have not been pruned and dead branches of Japanese cypress tend not to fall naturally (Otuke et al., 2007), the dead branches were densely distributed from the base of the crown to the nearby forest floor in each plot. The average number of dead branches ($N_{d}$) and length of dead branch layer were 56.3 branches (78.2% of the total number of branch) and 7.9 m (62.1% of the tree height) in P1 and 47.4 branches (76.4% of the total number of branch) and 10.6 m (68.8% of the tree height) in P2, respectively. The average number of dead branches per unit length ($\bar{N}_{d}$) and vertical dead branch space ($\bar{x}_{sl}$) were 7.1 branches m$^{-1}$ and 0.14 m in P1 and 4.5 branches m$^{-1}$ and 0.22 m in P2, respectively. The results show that the dead branches in P1 were more densely and closely distributed than those in P2, despite the fact that the canopy in P1 was slightly sparser than that in P2 (Table 1).

### 2.2 Measurements

#### 2.2.1 Stand structure measurements

$CC$ and $PAI$ were measured using a pair of LAI-2000 plant canopy analyzers (Li-COR Inc., Lincoln, NE, USA) and FV2000 (LI-COR). The measurements were conducted on an overcast...
The free $TF$ coefficient ($C_{TF}$) was calculated using the following equation (Carlyle-Moses and Price, 1999; Shinohara et al., 2015):

$$C_{TF} = 1 - CC$$

Fig. 1. Photos and measurement designs of the (a) study plot 1, and (b) study plot 2. The solid circles indicate trees, the diamonds shapes indicate stemflow measurement, and the open circles indicate funnel-type throughfall collectors. The dash lines denote the borders of the subplot of $5 \, m \times 5 \, m$.

Fig. 2. Schematic diagrams of branch distribution in the study plot 1 (P1) and study plot 2 (P2). $N_L$ and $N_D$ denote the number of live branches and dead branches, respectively. Each number indicates the average ± standard deviation of the number of branches and thickness of layers with their percentage of the total number of branches or tree height.

In this study, we regarded the visually detectable branches longer than about 50 cm with leaves as live branches and those without leaves as dead branches. Branch distribution was observed by counting the number of live and dead branches using a telescope and measuring the heights of tree top, lowest

day to avoid the disturbance from direct sunlight.
live branch, and lowest dead branch using a hypsometer (Haglöf Vertex IV-360, Haglöf Inc., Madison, MS, USA).

2.2.2 Hydrometeorological measurements

GR was measured using a funnel-type rain collector (funnel diameter = 210 mm) and a HOBO RG3-M tipping bucket rain gauge with a resolution of 0.2 mm (diameter = 154 mm, Onset Computer, Bourne, MA, USA) connected to an Onset HOBO Event data logger installed at a 2 m tower in an open space approximately 50 m apart from each plot. The funnel-type GR was measured on a weekly basis and was strongly correlated to that of the tipping bucket rain gauge ($R^2 = 0.999, p = 0.000$); thus, data from the funnel-type rain collector were used in this study.

TF was measured using 30 funnel-type rain collector same for GR in each plot. They were randomly allocated on the forest floor and maintained throughout the study period (Fig. 1). TF (mm) was calculated as follows:

$$TF = \frac{\sum TF_i}{n_i}$$ (2)

where $TF_i$ is the throughfall (mm) of TF collector $i$ and $n_i$ is the number of TF collectors. The data from two TF rain collectors in P1 that normally exceeded GR were excluded for analysis because these TF collectors were placed ≤10 cm from the inclined stems with rough bark and collected not only TF but also separating SF (Leiva et al., 2010; Saito et al., 2013). Thus, $n_i$ for P1 and P2 were 28 and 30, respectively. The standard relative errors of mean TF estimated using the following equation (Kimmins, 1973; Saito et al., 2013; Shinohara et al., 2013; Sun et al., 2014) for P1 and P2 were 5.0% and 5.4%, respectively:

$$e = (t \times CV)/\sqrt{n_i}$$ (3)

where $e$ is the standard relative error of mean $TF$, $t$ is the Student’s t-value for a significance level ($p = 0.05$), and $CV$ is coefficient of variation of $TF$.

SF was measured for nine trees to cover the DBH class at each plot (Fig. 1). Two plastic flexible ducts (diameter = 22 mm) with wires were fixed in two lines around the stem at a height of about 1.5 m to trap SF. About 30 mm of both ducts at the same vertical position were cut and a kitchen hose (diameter = 30 mm) was attached in the section to collect $SF$ and drain it to the $SF$ collector. Then, the ducts and part of the hose were surrounded with a transparent vinyl sheet of about 20 cm width. Silicon sealant was applied on the stem, ducts, hose and vinyl sheet to prevent the leakage of $SF$. The hose was connected to the $SF$ collector made of two connected 90 L tanks. $SF$ (mm) was calculated as follows:

$$SF = \frac{\sum SFV_i}{n_{rec}} \times \frac{N_{rec}}{P_A}$$ (4)

where $SFV_i$ is the $SF$ volume (L) of the $SF$ observed trees, $n_{rec}$ and $N_{rec}$ are the numbers of $SF$ observed trees (9) and total trees in the plot (50), respectively, and $P_A$ is the plot area (200 m$^2$).

$IL$ (mm) was calculated using the following canopy water balance equation:

$$IL = GR - TF - SF$$ (5)

Stemflow funneling ratio ($FR$), the ratio of the volume of stemflow of an individual tree to the gross rainfall delivered on the $BA$ of the tree, was calculated using the following equation (Hewitt, 1986):

$$ FR = \frac{SFV}{j \times (GR \times BA)} $$ (6)

where $SFV_j$ is the volume of $SF$ of an individual tree (L) and $BA$, is the basal area of the tree ($m^2$).

The study was conducted from April to October 2017 during the growing season. During the study period, precipitation amount was 1076.9 mm which accounted for 65.9% of the mean annual precipitation. Data were collected once a week. Of 29 data collections, there were no rainfall event for four weeks, a single rainfall event for six weeks, and multiple rainfall events from two to five events for 19 weeks.

2.3 Data analysis

First, the relationships between $TF/GR$, $SF/GR$, $IL/GR$ and $SD$ were examined with the data in this study with those of 30 data in the previous studies of Japanese coniferous plantations (Japanese cedar and Japanese cypress). We selected the dataset of previous studies in accordance with the five criteria: (1) data of the plantations of Japanese cedar and Japanese cypress in Japan because no essential difference between the two tree species was detected when developing estimation models for $IL$ (Komatsu et al., 2015) and $TF$ (Sun et al., 2017), (2) data supplying all the components of RP, (3) data showing $SD$, (4) data including the typical rainy season of Japan from May to October to avoid substantial variations resulted from a short observation period in RP (Komatsu et al., 2015; Sun et al., 2017), and (5) data without snowfall to exclude the snow partitioning processes. The mean ± S.D. (range) of the dataset of $SD$ and tree age were 1221 ± 648 (355–2500) stems ha$^{-1}$ and 52 ± 21 (29–92) years, respectively (Table S1).

The amount of $GR$ has a significant influence on RP (Staelens et al., 2006; Sun et al., 2015). Thus, the relationships between $GR$ and $TF$, $SF$, and $IL$ on a weekly basis in P1 and P2 were examined using the least-squares method. Then, $GR$ on a weekly basis was grouped into four classes (<10, 10 to <25, 25 to <50, and ≥50 mm) and the difference of $TF/GR$, $SF/GR$, and $IL/GR$ between P1 and P2 ($\Delta TF/GR$, $\Delta SF/GR$, and $\Delta IL/GR$) in each $GR$ class were examined using the Wilcoxon-Mann-Whitney nonparametric test.

The canopy storage capacity ($S$, mm), the amount of gross rainfall to fully saturate the canopy, is one of the most important eco-hydrological parameters in RP (Leyton et al., 1967; Link et al., 2004; Sun et al., 2015). Thus, we estimated $S$ using Leyton’s method (Leyton et al., 1967). We drew the line with slope $(1−SF/GR)$ in the scattered graph of $GR$ versus $TF$ (3.0 mm < $GR$ < 50 mm) and shifted it to envelop the graph (Shinohara et al., 2013). The $S$ value was obtained from the negative intercept on the $TF$ axis for the upper envelop line (Leyton et al., 1967; Wallace and McNamet, 2006; Shinohara et al., 2013; Saito et al., 2013; Iida et al., 2017).

Finally, we divided each plot of a 20 m × 10 m into eight sub-plots of 5 m × 5 m (Fig. 1) and examined the relationship between the dead branch structures and $TF/GR$ using the least-squares method.

Confidence intervals were established at a 0.05 probability level for all statistical analyses with SPSS version 18.0.
3. Results

3.1 Relationships between SD and RP

The cumulative GR during the study period was 1076.9 mm. The cumulative TF, SF, and IL and their percentage of GR were 493.0 mm (45.8%), 251.1 mm (23.3%), and 332.8 mm (30.9%) in P1, respectively and 570.4 mm (53.0%), 236.1 mm (21.9%), and 270.3 mm (25.1%) in P2, respectively. Although SF/GR in the two plots were almost the same (1.4 percentage points), TF/GR in P1 is appreciably smaller than that in P2, resulting in a larger IL/GR in P1 than that in P2 (5.8 percentage points).

Fig. 3 shows a comparison of TF/GR, SF/GR, and IL/GR against SD obtained in this study with those of 30 data in the previous studies of Japanese coniferous plantations (n = 32 including the data in this study). TF/GR decreased but the SF/GR and IL/GR increased with increasing SD (Fig. 3). All the components of RP were significantly correlated to SD: TF/GR ($R^2 = 0.764$, $p = 0.000$), SF/GR ($R^2 = 0.670$, $p = 0.000$), and IL/GR ($R^2 = 0.516$, $p = 0.000$), which confirms that SD is an informative stand structure factor for all the RP components in coniferous plantations. Having the highest SD in this study (Fig. 3), TF/GR were very low: 45.8% in P1 (lowest) and 53.0% in P2 (second lowest), SF/GR were very high: 23.3% in P1 (highest) and 21.9% in P2 (second highest), and IL/GR were high: 30.9% in P1 (highest) and 25.1% (considerably high).

3.2 Relationships between GR and RP on a weekly basis

Fig. 4 shows the relationships between GR and RP. Weekly GR ranged from 1.7 mm to 125.2 mm with a mean of 43.1 ± 36.3 mm. As with the results of previous studies (e.g., Sun et al., 2015; Shinohara et al., 2015), all the components of RP linearly increased with increasing GR on a weekly basis as follows:

\[
\begin{align*}
TF_1 &= 0.52 \text{ GR} - 2.45 \ (R^2 = 0.97) \\
TF_2 &= 0.58 \text{ GR} - 2.33 \ (R^2 = 0.99) \\
SF_1 &= 0.26 \text{ GR} - 1.17 \ (R^2 = 0.97) \\
SF_2 &= 0.23 \text{ GR} - 0.48 \ (R^2 = 0.92) \\
IL_1 &= 0.23 \text{ GR} + 3.62 \ (R^2 = 0.81) \\
IL_2 &= 0.19 \text{ GR} + 2.80 \ (R^2 = 0.83)
\end{align*}
\]

where subscript of 1 and 2 indicates study plots of P1 and P2, respectively.

![Fig. 3.](image)

Fig. 3. Relationships between the stand density (SD) and the ratios of each component of RP to gross rainfall in this study with previous studies of Japanese coniferous plantations (n = 32): (a) TF/GR, (b) SF/GR, and (c) IL/GR. The triangles, open circles, and solid circles indicate the ratios in previous studies, the ratio in study plot 1, and the ratio in study plot 2, respectively. The solid lines are the regression lines determined by the least-squares method.

![Fig. 4.](image)

Fig. 4. Relationships between gross rainfall (GR) and each component of RP on a weekly basis: (a) TF, (b) SF, and (c) IL. Open and solid circles indicate the data from the study plot 1 (P1) and study plot 2 (P2), respectively. The solid and dashed lines indicate the linear regression lines of P1 and P2 determined by the least-squares method, respectively.
Table 2. The differences of $\Delta TF/GR$, $SF/GR$ and $IL/GR$ ($\Delta TF/GR$, $\Delta SF/GR$, and $\Delta IL/GR$) between plot 1 (P1) and plot 2 (P2) for four $GR$ classes and total $GR$. Positive values indicate that the ratio in P1 was larger than that in P2 and vice versa.

| $GR$ (mm) | No. of sampling | $\Delta TF/GR$ (%) | $p$-value | $\Delta SF/GR$ (%) | $p$-value | $\Delta IL/GR$ (%) | $p$-value |
|-----------|----------------|-------------------|-----------|-------------------|-----------|-------------------|-----------|
| <10       | 3              | −2.1              | 1.000     | 0.0               | 1.000     | +2.1              | 1.000     |
| 10 to <25 | 7              | −4.2              | 0.259     | +3.7              | 0.383     | +0.5              | 1.000     |
| 25 to <50 | 6              | −6.9              | 0.132     | −0.2              | 0.937     | +7.1              | 0.180     |
| 50 ≤      | 9              | −7.8              | 0.014*    | +1.5              | 0.666     | +6.2              | 0.136     |
| Total     | 25             | −7.2              | −         | +1.4              | −         | +5.8              | −         |

Asterisk denotes $p < 0.05$.

Fig. 5. Relationships between gross rainfall ($GR$) and throughfall ($TF$) on a weekly basis in the (a) study plot 1 and (b) study plot 2, respectively. The solid lines are the upper envelope lines for estimating canopy storage capacity ($S$).

Table 2 shows the difference of ratios of RP to $GR$ between P1 and P2 ($\Delta TF/GR$, $\Delta SF/GR$, and $\Delta IL/GR$) in the different rainfall classes on a weekly basis. A positive difference means that the ratio in P1 was larger than the ratio in P2 and vice versa. $\Delta SF/GR$ was nearly negligible regardless of the amount of $GR$. On the other hand, $\Delta TF/GR$ was negative indicating $TF/GR$ in P1 was smaller than that in P2 while $\Delta IL/GR$ was positive indicating $IL/GR$ in P1 was larger than that in P2 in each $GR$ class. The absolute values of $\Delta TF/GR$ and $\Delta IL/GR$ increased with increasing $GR$. However, the difference of $\Delta TF/GR$ between P1 and P2 was significant only when $GR \geq 50$ mm ($p = 0.014$, Mann-Whitney U test).

3.3 Canopy storage capacity

Fig. 5 shows the relationship between $GR$ ranging 3−50 mm and $TF$ on a weekly basis. The solid lines are the upper envelope line for estimating $S$.

$$TF_1 = (1 - \frac{SF_2}{GR}) \times GR - S = 0.77 \times GR - 2.63$$

$$TF_2 = (1 - \frac{SF_2}{GR}) \times GR - S = 0.78 \times GR - 2.51$$

From these equations, $S$ values were obtained as 2.63 mm for P1 and 2.51 mm for P2, respectively. Compared with $S$ values of the previous studies on Japanese coniferous plantations ($n = 13$) (Table S1), $S$ values of P1 and P2 were the highest and the second highest, respectively.

3.4 Relationship between dead branches and RP

The dead branches in P1 outnumbered those in P2 (Fig. 2, Fig. 6a). The relationship between the average number of dead branch per stem ($N_{db}$) and $TF/GR$ in the subplots of P1 and P2 (Fig. 6a) indicates that $TF/GR$ significantly decreased with an increase in $N_{db}$. In the subplots where $N_{db}$ ranged from 45 to 60 branches, however, $TF/GR$ in P2 tended to be larger than $TF/GR$ in P1 despite the fact that $N_{db}$ was within the same range (Fig. 6a).

The dead branches in P1 were more densely distributed than those in P2 (Fig. 2), and thus the average vertical dead branch space ($\overline{SDb}$) in P1 was shorter than $\overline{SDb}$ in P2. The relationship between $TF/GR$ and $\overline{SDb}$ in the subplots of P1 and P2 (Fig. 6b) indicates that $TF/GR$ significantly increased with an increase in $\overline{SDb}$.

Since it was difficult to obtain the representative $SF$ in each subplot, the relationship between the individual number of dead branches and $SF$ funneling ratios ($FR$) of the sample trees were examined. Clear relationships were found neither between the number of dead branches and $FR$ (Fig. 7) nor between individual vertical dead branch spaces and $FR$.

4. Discussion

4.1 Stand structures in the dense unmanaged Japanese cypress plantations

The stem of Japanese cypress is round and grows vertically straight, and its branches grow whirly in a radial direction. Hayashi and Takahashi (1997) measured the directions of branches of 18 Japanese cypress trees at an age of 11 years and reported that the horizontal distribution of the branches was omnidirectional. The average ratio of branch biomass to stem biomass of Japanese cypress ($14.2\%$, $n = 356$) was relatively larger compared with those of Japanese cedar ($7.9\%$, $n = 532$) and Japanese larch ($Larix kaempferi$ (Lamb.) Carrière) ($10.4\%$, $n = 128$) (Hosoda and Ichara, 2010). The branches of Japanese cypress.
cypress have long life spans with unexpectedly long stunted periods. Fujimori (1993) measured the dynamics of crown structure and stem growth of a Japanese cypress tree at an age of 51 years without artificial pruning and found that the life span of branches was about 16 years on average: nine years of growing period and seven years of stunted period. In addition to the long life span of branches, the dead branches of Japanese cypress tend to stay on the stem while those of Japanese cedar tend to naturally drop. Otake et al. (2007) measured the canopy structures of four cut trees of Japanese cypress with different ages of 19–34 years and heights of 7.0–15.3 m and reported that (1) the vertical space between the branches were consistently about 5 cm from top of the trees to the lowest dead branches near the forest floor, and (2) the lengths of branches ranged up to 3 m and its average vertical distribution was approximated by the quadratic equation having its vertex at half the tree height. Moreover, the branches tend to stay longer in dense Japanese cypress stands possibly because the wind speeds within the canopy in dense coniferous plantation were weaker than those in sparse plantations (Suzuki et al., 2010). Based on the results of Inagaki et al. (2010) investigating the effects of typhoons on the branch falls of Japanese cypress plantations at an age of 23 years with some 46 years-old trees, the branch falls in the control plot without thinning with a SD of 1700 stems ha$^{-1}$ was about 1/3 of that in the thinning plot with a SD of 850 stems ha$^{-1}$. These results imply that the dense and thick dead branch layers from the base of the crown to near the forest floor are common features of unmanaged Japanese cypress plantations.

SD studied in most of the previous studies on RP of two dominant coniferous plantations in Japan (Japanese cedar and Japanese cypress) ranged less than 2000 stems ha$^{-1}$ (Fig. 3). These stands should be thinned once or more because SD was less than the general planting density, which implies that these stands should be pruned during the course of silvicultural practice with thinning. Consequently, there are very few studies on RP in dense unmanaged coniferous plantations in Japan despite the fact that they are widely distributed in Japan. Conversely, the stands in this study have the typical stand structures of unmanaged Japanese cypress plantations as mentioned above and thus could contribute new information to the studies on RP in coniferous plantations.

The stands in this study were almost fully covered with canopies where CC were 99.3% in P1 and 99.6% in P2 (Table 1), which indicates that the free throughfall was negligible in each plot: free TF coefficients ($C_{VT}$) were 0.7% in P1 and 0.4% in P2. Consequently, most of the rainwater in this study should be at least once re-intercepted (Nanko et al., 2008b, 2011) and RP should occur not only in the crown composed of leaves and live branches but also in the thick and dense dead branch layers below the crown.

4.2 Comparison of RP in coniferous plantations in Japan with the previous studies

For all the RP components, SD was a significantly informative stand structure factor (Fig. 3). However, there could be other stand structure factors influencing RP in addition to SD.
There are studies reported that SD, CC, BA, and PAI were the dominant stand structure factors affecting TF and IL (Teklehaimanot et al., 1991; Toba and Ohta, 2002; Molina and del Campo, 2012; Komatsu et al., 2015; Sun et al., 2017). S was also considered as an informative factor on TF and IL under the different stand structures of SD and CC (Leyton et al., 1967; Link et al., 2004; Saito et al., 2013; Sun et al., 2015). SD in this study were the highest (2500 stems ha$^{-1}$) among the previous studies on RP in coniferous plantations in Japan (Fig. 3). On the other hand, S in P1 was higher than that in P2 though the both S values in this study were very high compared with the previous reported values: 2.63 mm in P1 (highest) and 2.51 mm in P2 (Table S1). BA is the factor representing the stem area measured by DBH, and CC and PAI are factors representing the canopy coverage and plant area measured by the light transmittance of the canopy, respectively. Therefore, these factors are indirectly related to RP but cannot directly represent the RP. On the other hand, S was calculated by the measured RP data and thus directly related to RP. We obtained the significant relations between RP and S from the data in Table S1 as follows: (1) TF/GR; $R^2 = 0.662$, $p = 0.001$; (2) SF/GR; $R^2 = 0.356$, $p = 0.031$; (3) IL/GR; $R^2 = 0.676$, $p = 0.001$. Therefore, the lowest TF/GR, the highest SF/GR and the highest/considerably high IL/GR in this study could be explained by the virtually full CC and highest S values in addition to the highest SD. Although the stand structure of thick and dense dead branch layers in P1 and P2 could also cause the extreme ratios of RP to GR (low TF/GR, high SF/GR, and high IL/GR) in this study, discussions on this possibility by comparing with the previous studies cannot be conducted because there have not been any studies on the effects of dead branches on RP at the stand scale.

4.3 Comparison of RP between the two dense unmanaged Japanese cypress plots

P1 and P2 had the trees at the same age of 33 years with the same SD of 2500 stems ha$^{-1}$ and the similar extreme ratios of RP to GR (low TF/GR, high SF/GR, and high IL/GR) compared with the previous studies (Fig. 3). In detail, however, the stand structures and the ratios of RP to GR in P1 and P2 were slightly different. Since all the components of RP and overall stand structure factors including dead branch distributions were measured in this study, comparisons of the stand structure and RP between P1 and P2 could contribute new knowledge to the studies on RP in coniferous plantations.

4.3.1 TF in dense unmanaged Japanese cypress plantations

TF/GR in P1 and P2 were 45.8% and 53.0%, respectively. Although they were the lowest and second lowest compared with TF/GR in the previous studies, the difference was considerably large as TF/GR in P1 was 7.2 percentage points lower than that in P2 (Table 2). Although TF/GR in P2 followed the relationship between TF/GR and SD in the previous studies, that in P1 was exceptionally low (Fig. 3a). TF/GR in P2 was estimated by the TF model for coniferous plantations in Japan using SD, BA, and CC (Sun et al., 2017) with an estimation error of 1.6 percentage points. On the other hand, the estimation error of TF/GR in P1 was 6.1 percentage points lower, which exceeded the relative error of the TF model (3.2 ± 2.4%). The results imply that there could be some stand structure factors other than the common stand structure factors such as SD, CC, and BA for estimating TF/GR (Molina and del Campo, 2012; Sun et al., 2017) in dense unmanaged coniferous plantations.

The free throughfall, drip, and splash from the crown should be similar in each plot because the crown and live branch structures in P1 and P2 were almost the same (Table 1, Fig. 2). However, RP below the crown should be different between P1 and P2 because the dead branch structures were considerably different (Fig. 2). The parts of raindrops could be re-intercepted, re-captured, re-dripped, and splashed by the dead branches. In this study, P2 had approximately 0.8 times less $\overline{N_b}$ and 1.6 times longer $\overline{S_b}$, respectively. TF/GR in P2 was larger than that in P1 possibly because of less re-interception of raindrops by the less $\overline{N_b}$ and more splash generation induced by the longer $\overline{S_b}$ (Fig. 6). Splash occurred in the canopy contributes not only to TF (Nanko et al., 2006; Levia et al., 2017) but also to IL transferred into the atmosphere (Murakami, 2006; Saito et al., 2013). However, the splash occurred on the dead branches under the crown in the dense stands could contribute mostly to TF but not to IL because wind speed within the canopy in the dense stands are very weak compared with the wind above the canopy (Nakai et al., 2008; Kitagawa et al., 2010; Suzuki et al., 2010). Thus, the dead branch structures could be other informative factors for TF/GR in addition to SD, CC, BA, and S in dense unmanaged coniferous plantations, especially in Japanese cypress plantations.

There were several studies on the relationship between live branches and TF supporting the above-mentioned discussion. Staelens et al. (2006) found that the branch cover was correlated to TF during a leafed period in a beech (Fagus sylvatica L.) stand and the TF decreased with increasing branch cover. He et al. (2014) found that plant area (leaf area plus wood area) rather than leaf area alone affected TF. Nanko et al. (2008b) conducted the pruning experiment on TF of Japanese cypress and reported that the thicker canopy had higher possibility for re-interception and splash by lower canopy layers. Nanko et al. (2011) reported that spatial distribution of TF was dominated by the canopy structure and position of branches inside the canopy. There were also several studies on the relationship between dead branches and TF supporting the above-mentioned discussion. Hutchings et al. (1988) found that the dead branches under the canopy stayed on the lower part of the stems had approximately 17% of total S for Sitka spruce (Picea sitchensis (Bong.) Carr.), which implies that the dead branches could recapture decent amount of rainwater. Nanko et al. (2008a) suggested that drips could be generated not only from the leaves on living branches but also from the dead branches in a mature Japanese cypress plantation based on the results that some drips had lower velocity/kinetic energy than those of expected drip falling from the crown-base height, which implies that the dead branches played a role in re-capture and re-drip. Shinohara et al. (2018) found that the drop velocity/kinetic energy decreased with decreasing in height of the lowest dead branch in Japanese cypress plantations, which implies that the shorter falling distance could decrease splash generation. Therefore, the results of the present study with these previous studies suggest that the dead branches should play an important role in TF generation.
4.3.2 SF in dense unmanaged Japanese cypress plantations

SF/GR in P1 and P2 were exceptionally high compared with SF/GR in the previous studies (Fig. 3b): 23.3% in P1 (highest) and 21.9% in P2 (second highest). They were about three times higher than the average of previous SF/GR (Fig. 3b) and about two times higher than average SF/GR reviewed by Levía and Frost (2003) and Levía and Germer (2015).

SF and TF generated in the crowns should be similar in P1 and P2 because the crown structures were almost the same. However, their process under the crown could be different. SF from the crown could flow on the stems and reach to the forest floor without obstacles. On the other hand, TF from the crown could be intercepted by the dead branches while falling (Shinohara et al., 2018). When the intercepted TF accumulates enough to saturate the branches, subsequently rainwater flows from the branches to the stems could be generated (Nanko et al., 2011) in addition to the drip and splash. This additional SF generated by the dead branches could be the predominant reason why SF/GR in this study were exceptionally high because of a number of dead branches.

However, the SF funneling ratios (FR) had no clear relationship with Nbr of each SF measured tree while TF/GR in the subplots had a clear positive relationship with Nbr. Moreover, SF/GR in P1 and P2 were almost identical regardless of GR class while the difference of TF/GR between P1 and P2 increased with increasing GR (Table 2).

Sufficient rainwater is necessary to generate SF at the dead branches because the rainwater movement in the canopies generally occurs in the sequence of saturation, dripping, and flowing (Nanko et al., 2011). The higher dead branches could intercept and store the rainwater composed of raindrops, drips, and splash more easily and thus get wetter than the lower dead branches because the rainwater in higher position has smaller kinetic energy with slower falling velocity (Nanko, 2013). Therefore, the dead branches generating SF should be limited to the upper dead branches, and the lower dead branches could not accumulate enough TF to generate rainwater flow at the branches regardless of the number of branches. These discussions could be the influential reason why the relationship between FR and Nbr was not clear (Fig. 7) and SF/GR in P1 and P2 were almost identical (Table 2). These results suggest that the dead branches under the crown could increase SF but the dead branches generating SF could be limited to the upper dead branches.

There were several previous studies on the relationship between SF and the branch structures supporting the above-mentioned discussions. There were reports mentioning that SF increased with increasing the number of branches using 12 European beech saplings (Levia et al., 2015), 30 shrubs belonging to three species (Návar, 1993), 14 shrubs belonging to two species (Yang et al., 2008), and 129 trees belonging to 33 species (Honda et al., 2015), which corresponds with our results although the branches of these studies were alive. There were reports mentioning that SF was larger during the leafless season than during the leaved season using eight beech trees and 6–11 oak (Quercus petraea Liebl.) trees (André et al., 2008), seven deciduous trees (Muzýlo et al., 2012), and a cylindrical lath-turned pine post with a diameter of 75 mm and length of 1.2 m having the branches with a diameter of 8, 16, and 25 mm and length of 22 cm (Dunkerley, 2014), which implies that not only leaves but also woody parts of the tree including branches plays an important role in generating SF. Karaji et al. (2001) measured the crown-only SF and stem-only SF of a Japanese cypress tree at an age of 70 years and with a height of 28.8 m and found that stem-only SF increased with increasing GR up to about 20% of the whole SF, which implies that a relatively large SF can be generated below the crown. SF increased with increase in steepness of the branch angle toward the sky (Levia and Frost, 2003; Futatsuka, 2008; Levía et al., 2015; Levía and Germer, 2015). Most of the branches of Japanese cypress were up-facing (Nanko et al., 2011; Kawatani et al., 2012), but the branch angle gradually decreased from the higher canopy to the lower canopy and some of the branches in the lower canopy were down-facing (Nanko et al., 2011), which implies that SF on the dead branches could occur mostly in the upper dead branches. Therefore, the results of the present study with these previous studies suggest that the dead branches should play an important role in SF generation.

5. Conclusion

We observed all the components of rainfall partitioning (RP) into throughfall (TF), stemflow (SF), and interception loss (IL), and all stand structure factors including the dead branch structures in the two dense unmanaged Japanese cypress plots with the same stand density (SD) of 2500 stems ha⁻¹, and the results were compared with the previous studies on RP in two dominant coniferous plantations (Japanese cedar and Japanese cypress) in Japan. The relationships between stand structures and RP in coniferous plantations obtained in this study were as follows:

5.1 Relationship between SD and RP in coniferous plantations

TF/GR significantly decreased with increasing SD while SF/GR and IL/GR significantly increased with increasing SD, which confirms that SD is an informative stand structure factor for all the RP components in coniferous plantations. Having the highest SD, TF/GR were the lowest and second lowest, SF/GR were the highest and second highest, and IL/GR were the highest and considerably high in the two study plots. In addition to SD, canopy cover ratio (CC) and storage capacity (S) could also be influential stand structure factors for RP.

5.2 Difference of RP in the two dense unmanaged coniferous plantations

Although the two study plots had the same SD and the similar extreme ratios of RP to GR (low TF/GR, high SF/GR, and high IL/GR) compared with the previous studies, the stand structures and the ratios were slightly different. The plot with smaller stand with denser and thicker dead branch layers had exceptionally low TF/GR compared with the other plot, but SF/GR in both plots were almost identical and exceptionally high.

5.3 New stand structure factors affecting RP in coniferous plantations

TF/GR decreased with increasing average number of dead branches (Nbr) possibly because of increasing interception by dead branches, while it increased with increasing average dead branch space (sdb) possibly because of increasing splash by dead branches. SF/GR could increase by dead branches possibly because of the
additional gain of rainwater by the dead branches. However, \( N_{ab} \) did not influence \( SF/GR \) possibly because the dead branches generating \( SF \) could be limited to the upper dead branches.

The above-mentioned findings on the relationship between stand structures and RP will contribute new knowledge to silvicultural practices for effective forest ecological services. Pruning experiment and measuring raindrop diameter will be helpful to confirm the findings.

**Acknowledgements**

We acknowledge the staffs of Kasuya Research Forest of Kyushu University and the faculties and students of the laboratory of forest ecosystem management for their help for measurement. We also thank Drs. Yoshihori Shinohara (Miyazaki University) and Akio Inoue (Prefectural University of Kumamoto) for their fruitful advice and comments. This study was partly supported by JSPS KAKENHI Grant number JP26292088, JP18H04152.

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