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

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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 Kasuya 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.

Table 1. Stand structures of plot 1 (P1) and plot 2 (P2).

Stand structures	P1	P2
	Average ± S.D.	Average ± S.D.
The number of trees (N_{tree})	50	50
Tree age (years)	33	33
Stand density (SD , stems ha^{-1})	2500	2500
Diameter at breast height (DBH , cm)	17.7 ± 4.1	20.4 ± 4.1
Tree height (H , m)	12.7 ± 2.0	15.4 ± 2.0
Stand volume (SV , $m^3 ha^{-1}$)	286.7	453.6
Basal area (BA , $m^2 ha^{-1}$)	64.9	85.2
Relative spacing index (Rs , %)	15.8	13.0
Relative yield index (Ry)	0.88	0.95
Crown projection area (CPA , m^2)	4.8 ± 1.8	4.7 ± 1.9
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 ($\bar{N}_{lb}$) 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 ($\bar{n}_{lb}$) and vertical live branch space ($\bar{s}_{lb}$) 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 (Otake *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 ($\bar{N}_{db}$) 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 ($\bar{n}_{db}$) and vertical dead branch space ($\bar{s}_{db}$) 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

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 $5\text{ m} \times 5\text{ m}$.

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

day to avoid the disturbance from direct sunlight. The free TF coefficient (C_{FTF}) was calculated using the following equation (Carlyle-Moses and Price, 1999; Shinohara *et al.*, 2015):

$$C_{FTF} = 1 - CC \quad (1)$$

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

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:

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

where TF_i is the throughfall (mm) of *TF* collector i and n_c 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* (Levia *et al.*, 2010; Saito *et al.*, 2013). Thus, n_c 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:

$$\varepsilon = (t \times CV) / \sqrt{n_c} \quad (3)$$

where ε 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:

$$SF = \frac{\sum SFV_i}{n_{tree}} \times \frac{N_{tree}}{PA} \quad (4)$$

where SFV_i is the *SF* volume (L) of the *SF* observed trees, n_{tree} and N_{tree} are the numbers of *SF* observed trees (9) and total trees in the plot (50), respectively, and PA is the plot area (200 m²).

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

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

Stemflow funneling ratio (FR_i), 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 (Herwitz, 1986):

$$FR_i = SFV_i / (GR \times BA_i) \quad (6)$$

where SFV_i is the volume of *SF* of an individual tree (L) and BA_i is the basal area of the tree (m²).

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 $\pm$ 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 $50 \leq$ 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* ($3.0 \text{ mm} < GR < 50 \text{ mm}$) and shifted it till it enveloped 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 McJannet, 2006; Shinohara *et al.*, 2013; Saito *et al.*, 2013; Iida *et al.*, 2017).

Finally, we divided each plot of a 20 m $\times$ 10 m into eight sub-plots of 5 m $\times$ 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 of difference), *TF/GR* in P1 is appreciably smaller (7.2 percentage points) than the one 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:

$$TF_1 = 0.52 GR - 2.45 \quad (R^2 = 0.97) \quad (7)$$

$$TF_2 = 0.58 GR - 2.33 \quad (R^2 = 0.99) \quad (8)$$

$$SF_1 = 0.26 GR - 1.17 \quad (R^2 = 0.97) \quad (9)$$

$$SF_2 = 0.23 GR - 0.48 \quad (R^2 = 0.92) \quad (10)$$

$$IL_1 = 0.23 GR + 3.62 \quad (R^2 = 0.81) \quad (11)$$

$$IL_2 = 0.19 GR + 2.80 \quad (R^2 = 0.83) \quad (12)$$

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

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. 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 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 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 .

$$TF_1 = (1 - \frac{SF_1}{GR}) GR - S = 0.77 GR - 2.63 \quad (13)$$

$$TF_2 = (1 - \frac{SF_2}{GR}) GR - S = 0.78 GR - 2.51 \quad (14)$$

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 ($\overline{N}_{db}$) and TF/GR in the subplots of P1 and P2 (Fig. 6a) indicates that TF/GR significantly decreased with an increase in $\overline{N}_{db}$. In the subplots where $\overline{N}_{db}$ ranged from 45 to 60 branches, however, TF/GR in P2 tended to be larger than TF/GR in P1 despite the fact that $\overline{N}_{db}$ 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 ($\overline{s}_{db}$) in P1 was shorter than $\overline{s}_{db}$ in P2. The relationship between TF/GR and $\overline{s}_{db}$ in the subplots of P1 and P2 (Fig. 6b) indicates that TF/GR significantly increased with an increase in $\overline{s}_{db}$.

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_i) of the sample trees were examined. Clear relationships were found neither between the number of dead branches and FR_i (Fig. 7) nor between individual vertical dead branch spaces and FR_i .

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

Fig. 6. Relationships (a) between the average number of dead branches ($\overline{N_{db}}$) and the ratio of throughfall to gross rainfall (TF/GR) and (b) between the average dead branch space ($\overline{s_{db}}$) and TF/GR for the 16 subplots, respectively. The open and solid circles indicate the data in the study plot 1 and study plot 2, respectively. The solid line indicates the regression line determined by the least-squares method.

Fig. 7. The relationship between the number of dead branches (N_{db}) and the individual funneling ratio (FR_i). The open and solid circles indicate the study plot1 and study plot2, respectively.

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_{TF}) 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 ($3.2 \pm 2.4\%$). 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 $\bar{N}_{db}$ and 1.6 times longer $\bar{s}_{db}$, respectively. *TF/GR* in P2 was larger than that in P1 possibly because of less re-interception of raindrops by the less $\bar{N}_{db}$ and more splash generation induced by the longer $\bar{s}_{db}$ (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 Levia and Frost (2003) and Levia 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_i) had no clear relationship with N_{db} of each *SF* measured tree while TF/GR in the subplots had a clear positive relationship with $\overline{N_{db}}$. 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_i and N_{db} 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 (Muzylo *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*. Kuraji *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; Levia *et al.*, 2015; Levia 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 ($\overline{N_{db}}$) possibly because of increasing interception by dead branches, while it increased with increasing average dead branch space ($\overline{s_{db}}$) 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_{db} 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 the studies on RP in coniferous plantations and guide better silvicultural practices for effective forest ecological services. Pruning experiment and measuring raindrop diameter will be helpful to confirm the findings.

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