Experimental study on canopy interception using artificial Christmas trees to evaluate evaporation during rainfall and the effects of tree height and thinning

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Abstract:

Canopy interception (I) was measured using artificial Christmas trees that were set on three trays under natural rainfall. Tree heights were 65 cm, 110 cm and 240 cm, with two of the higher stands thinned after three months. Gross rainfall (P_G) and water storage on a single tree of 65 cm high and 240 cm were measured, which enabled calculation of I not only on a per rain event basis but also over shorter time periods. Canopy interception rate (I/P_G) was comparable with that in the actual forest. The value of I/P_G tended to increase with tree height, while it increased or decreased after thinning depending on the forest structure. Evaporation during rainfall (I_R), during storm break time (I_{Sbt}) and after the cessation of rainfall (I_{Aft}) was calculated on a sub rain event basis at a resolution of 5 minutes. A sub rain event was defined when rainfall broke for more than 20 minutes during the rain event. Among the three evaporation components, I_R constituted nearly all of the total I, with I_{Sbt} close to zero and only a small contribution from I_{Aft}. The model forest appears useful for studying the mechanisms of I that are unexplainable using conventional approaches.

KEYWORDS   canopy interception; evaporation during rainfall; thinning; tree height; artificial Christmas tree

INTRODUCTION

Gross rainfall (P_G) in a forest stand can be partitioned into throughfall and stemflow that reach the forest floor, evaporation during rainfall, and canopy storage. Canopy storage at the time of rainfall cessation evaporates back into the atmosphere. Canopy interception (I), the sum of canopy storage at the time of rainfall cessation and evaporation during rainfall, is a major component of evapotranspiration from forested areas and accounts for 9% to 48% of annual rainfall (Hörmann *et al.*, 1996). This explains why forests are the largest evaporative surface on the planet. However, the mechanism of I has not been clarified, though the phenomenon seems to be a simple process of evaporation from the canopy surface, because there are some inexplicable observations related to I. Firstly, some studies show that vast amounts of evaporation by I, e.g. 13 mm h^{-1} for hourly rainfall of 58 mm h^{-1}, occur during a rain event when water vapor in the air is nearly at saturation and that hourly I is proportional to hourly rainfall (Tsukamoto *et al.*, 1988;

Murakami, 2006; Hashino *et al.*, 2010). Secondly, a massive amount of evaporation during a rain event is not explainable in terms of heat budget, since the source of latent heat of vaporization cannot be found (Murakami, 2006). Thirdly, I seems to be evaporation from the canopy surface, but a reduction in I due to thinning is much less than decreases in canopy area (Hattori and Chikaarashi, 1988; Teklehaimanot *et al.*, 1991) or the amount of leaves in the leafless season for deciduous forests (Deguchi *et al.* 2006; Mużyło *et al.* 2012). Fourthly, in theory I increases with tree height (h), but observational facts do not support such a relationship (Murakami, 2008).

To elucidate the mechanism of I the hypothesis of splash droplet evaporation was proposed (Murakami, 2006). The hypothesis assumes that splash droplets produced upon raindrops hitting the canopy evaporate, and that this can qualitatively explain the proportional relationship between hourly P_G and hourly I. Since the number of raindrops per unit volume and their size increase with rainfall rate, the production rate of splash droplets grows, and thus I increases, with increasing rainfall. Nonetheless, there is no appropriate method to prove the hypothesis. If one focuses on micrometeorological measurements it is difficult to determine how and what should be measured in or above the forest canopy during a rain event. The mysterious phenomena mentioned above have been observed using water budget methods, and we thus assume that traditional volume balance approaches are sound means of elucidating the mechanism of I. Investigating the dependence of forest structure, e.g. h, stand density, and leaf amount, on I would provide some indirect information on mechanisms. For this purpose we used artificial Christmas trees that allow easy alteration of the forest structure. Toba and Ohta (2008) conducted an experimental study on I using artificial Christmas trees, but they measured I using artificial rainfall under cloudy weather. Instead, this present study measured I under natural rainfall. The objective of the present study was to (1) observe the magnitude of I using artificial Christmas trees, (2) assess how I responds to changes in h and thinning, and (3) evaluate the amount of evaporation in a rain event during rainfall, during storm break times, and after the cessation of rainfall.

METHOD

Site, trees and trays

The experiment was conducted under natural rainfall at the clearing at Tohkamachi Experimental Station, Forestry

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and Forest Products Research Institute, Tohkamachi, Japan (37°07'53"N, 138°46'00"E), from May 24 to October 30, 2012.

Two kinds of artificial Christmas trees were employed. One was 65 cm in original height with a maximum canopy diameter of 30 cm (hereafter 'small tree'), and another was 150 cm in original height with a maximum canopy diameter of 75 cm ('large tree'). Both trees were made of polyvinyl chloride leaf and wire. On Tray #1 small trees with original heights were deployed, but on Tray #2 (small trees) and #3 (large trees), h was increased to 110 cm and 240 cm, respectively, using a plastic rod with a diameter of 1.2 cm for small trees and a metal pipe 2.8 cm in diameter for large trees (Table I). Two experimental runs, Run A (24 May to 23 August, 92 days) and B (24 August to 30 October, 68 days), were conducted, during which time the h in each tray was constant. Tray #1 was a control with a constant number of trees (41 trees per tray) in both Runs, but on Tray #2 and #3 the number of trees was changed from 41 trees per tray in Run A to 25 trees per tray in Run B to evaluate the effect of thinning (Table I).

Tray #1 and #2 were made of coated plywood with an external dimension of a 180-cm square (Figure 1a). The catchment area was smaller, being a 122.4-cm square (Figure 1a), to avoid the possibility of a decrease in rainfall capture rate at the edge of the trays, since trees along the edge of

Table I. Stand structures of each tray.

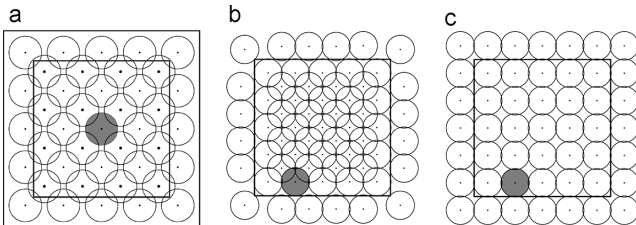|		Tray #1 Small tree	Tray #2 Small tree	Tray #3 Large tree
Tree height h	(cm)	65	110	240
Run A May 24 to Aug. 23, 2012				
Tree density	(trees tray^{-1})	41	41	41
Canopy closure	%	96	96	94
Plant area index	(m m^{-1})	5.1	5.1	5.9
Run B Aug. 24 to Oct. 30, 2012				
Tree density	(trees tray^{-1})	41	25	25
Canopy closure	%	96	58	79
Plant area index	(m m^{-1})	5.1	1.8	2.9

Figure 1. Arrangements of Christmas trees on trays. (a) Tree arrangement for Tray #1 and #2. Trees with large central dots were thinned on Tray #2 in Run B. The gray color tree was weighed. (b) Tree arrangement on Tray #3 in Run A. The tree arrangement pattern outside the tray differed from that on the tray, as trees could not be placed on the edge of the tray. (c) Tree arrangement on Tray #3 in Run B

the tray might let rainwater go out of the tray. This tray design is modeled after Toba and Ohta (2008). The trays for small trees (Tray #1 and #2) were set 1.2 m above ground level. The tray for large trees (Tray #3) was a lysimeter made of wood and plastic sheet with a catchment area of a 3.6-m square (Figure 1b, c) installed at ground level. Additional trees were placed along the outside of Tray #3 to avoid reduction in the rainfall capture rate presumably caused by the outer edge of the trees of the catchment area. Plant area index of each tray was measured by LAI-2000 (LI-COR, NE, USA) as listed in Table I.

Instrumentation and calculation of evaporation during rainfall

Gross rainfall, P_G, was measured using three kinds of raingauges at the clearing. A tipping bucket raingauge with a 0.5-mm tip was used as a main pluviometer, and a storage type raingauge was employed to complement the 0.5-mm gauge (the manufacturer and type of each raingauge is listed in Supplement Table SI). The rainfall measured by the storage type gauge was regarded as true values and the rainfall measured by the 0.5-mm gauge was corrected (the difference in total rainfall of the two gauges throughout the experiment was 0.2%). A tipping bucket raingauge with a 0.1-mm tip, which tended to underestimate P_G, was also used to detect small rainfall (<0.5 mm) and to determine the start and the end of a rain event. Each individual rain event was separated when no rainfall was observed for 6 hours or longer after the cessation of rainfall. In this case 6 hours is defined as the separation time (*ST*).

Net rainfall (rainfall on the trays under trees, P_N) drained into a tipping bucket flowmeter. For Tray #1 and #2 flowmeters with a 500-ml tip were used that had an accuracy of 0.333 mm. For Tray #3 a flowmeter with a 2000-ml tip was employed with a resolution of 0.154 mm. Canopy interception, I, was derived as the difference between P_G and P_N.

$$I = P_G - P_N \tag{1}$$

One of the trees on Tray #1 and #3 (Figure 1) was weighed to estimate water storage (S) on the canopies. An electric balance was set under the tray for Tray #1 to measure S of the single tree, while a digital push-pull gauge was placed over the tree for Tray #3. We did not measure the weight of all trees on Tray #1 or #3. This could be a source of error in estimating S, because the weight of the single tree is not necessarily representative of all trees (cf. RESULTS section). Water storage of any tree on Tray #2 was not measured, and it was assumed to be the same as the tree on Tray #1. Wind speeds were measured at 10.5 m above the ground. Those data were recorded in data loggers with a 1-minute or a 5-minute interval (Supplement Table SI).

Considering P_G as being partitioned into P_N, evaporation during rainfall, and S, P_G can be written as follows.

$$P_G = \int_0^t R\,dt = \int_0^t D\,dt + \int_0^t E\,dt + \Delta S \tag{2}$$

The start and end time of the rain event are 0 and t, respectively, where R is rainfall rate, D is drainage rate from the tray, E is evaporation rate during rain event (during rainfall and storm break time, *Sbt*), and $\Delta S = S_t - S_0$. Storm

break time is defined as the portion of the time within a rain event with no rainfall (Zeng *et al.*, 2000). Assuming that rainfall starts at $t = t_0 (= 0)$ and stops temporarily at $t = t_1$ followed by *Sbt* from t_1 to t_2 and that this pattern is repeated *n* times one can divide a rain event into *n* smaller sub rain event using *Sbt* as a delimiter. Rainfall was observed from $t = t_{2i-2}$ to $t = t_{2i-1}$ ($P_{G2i-1} > 0$) and not observed from $t = t_{2i-1}$ to $t = t_{2i}$ ($P_{G2i} = 0$), where *i* is positive integer. Storm break time satisfies $Sbt < ST (= 6 \text{ hours})$, but if $Sbt \geq ST$ the rain event is separated as an independent rain event. As a result the total number of sub rain event and *Sbt* is *n* times and $n - 1$ times, respectively. Referring to Equation (2) total evaporation of *I* during sub rain events is,

$$I_R = \sum_{i=1}^{n} \int_{t_{2i-2}}^{t_{2i-1}} E\,dt$$

$$= \sum_{i=1}^{n} \left[\int_{t_{2i-2}}^{t_{2i-1}} R\,dt - \int_{t_{2i-2}}^{t_{2i-1}} D\,dt - \Delta S_{2i-1} \right] \quad (3)$$

Where $\Delta S_{2i-1} = S_{2i-1} - S_{2i-2}$, and the *i*-th component of I_R is expressed as $I_{R_{2i-1}}$. Total evaporation of *I* during *Sbt* is,

$$I_{Sbt} = \sum_{i=1}^{n-1} \int_{t_{2i-1}}^{t_{2i}} E\,dt = -\sum_{i=1}^{n-1} \left[\int_{t_{2i-1}}^{t_{2i}} D\,dt + \Delta S_{2i} \right]$$

$$n \geq 2 \quad (4)$$

As water storage at the time of the cessation of rainfall ($\Delta S = S_{2n-1} - S_0$) is partitioned into evaporation after the stop of the rainfall (I_{Aft}) and drainage, I_{Aft} is written as,

$$I_{Aft} = \Delta S - \int_{t_{2n-1}}^{t_{2n}} D\,dt \quad (5)$$

Each term on the right-hand side in Equation (3) to (5) can be calculated from *R*, *D* and *S*. Canopy interception *I* for a rain event can be expressed as the sum of I_R, I_{Sbt} and I_{Aft},

$$I = I_R + I_{Sbt} + I_{Aft} \quad (6)$$

RESULTS

The relationship between P_G and *I* on a rain event basis is shown in Figure 2. Data for Tray #2 indicated by two large arrows were considered outliers and not used for later analyses including the calculation of regression lines (Figure 2a). Data for Tray #1 and #3 (small arrows) that correspond to the rain events for the two outliers were also excluded. Both outliers represented showers that fell for a short time accompanied by strong wind (> 3 m s^{-1}, 10 min. average), presumably leading to the capture rate of rainwater by raingauges and/or trays being reduced or boosted. The measurement accuracy for those rain events were thus considered low. Besides the outliers, only Tray #2 included missing data in Run B for two rain events, $P_G = 33.3$ mm and 5.6 mm. Cumulative $P_G - I$ relationships are shown in Figure 3. In Figure 3a (Figure 3b) the two outliers (two missing data) along with the corresponding data for Tray #1 and #3 were excluded.

Canopy interception rate (I/P_G) was in the range of 13.3% to 22.0%, which is consistent with values for actual forest stands in the temperate zone (Iida, 2009). Like *I* in actual forests, there is a proportional (to be exact, linear) relationship between P_G and *I* throughout the experiments. We selected the largest and the second largest rain events in each Run and calculated I_R using Equation (3). There is also a proportional relationship between P_{G2i-1} and I_{R2i-1} on a sub rain event basis (Figure 4). Storm break time was set at 20 minutes or longer, because the values of the determination coefficient (r^2) diminished with *Sbt* of shorter than 20 minutes (time resolution was 5 minutes). The other components of *I*, I_{Sbt} and I_{Aft} were also calculated using Equations (4) and (5), respectively. The result is shown in
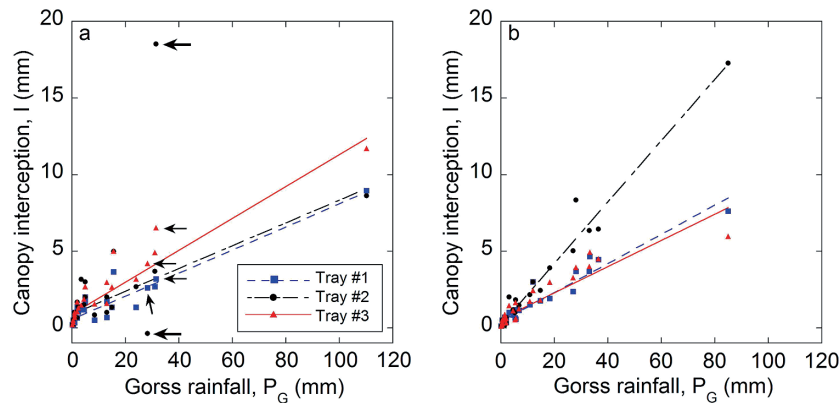

Figure 2. Gross rainfall P_G and *I* on a rain event basis. (a) Run A with total P_G of 263.7 mm. Canopy interception *I*, the regression equation and the determination coefficient r^2 for Tray #1, #2 and #3 were 36.4 mm (13.8%), $I = 0.075P_G + 0.551$, $r^2 = 0.880$, 46.4 mm (17.6%), $I = 0.075P_G + 0.891$, $r^2 = 0.755$, 54.7 mm (20.7%), $I = 0.104P_G + 0.909$, $r^2 = 0.897$, respectively. (b) Run B with total P_G of 342.9 mm for Tray #1 and #3 and 304.0 mm for Tray #2. Canopy interception *I*, the regression equation and the determination coefficient r^2 for Tray #1, #2 and #3 were 45.7 mm (13.3%), $I = 0.095P_G + 0.409$, $r^2 = 0.933$, 66.8 mm (22.0%), $I = 0.201P_G + 0.192$, $r^2 = 0.971$, 48.2 mm (14.1%), $I = 0.086P_G + 0.589$, $r^2 = 0.850$, respectively
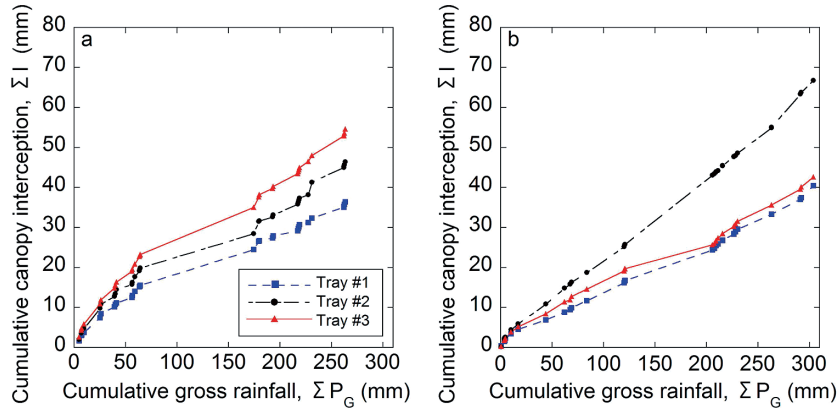
Figure 3. Cumulative gross rainfall ΣP_G and cumulative canopy interception ΣI. (a) Run A with the total P_G of 263.7 mm. The values of I for Tray #1, #2 and #3 were the same as those in Figure 2(a). (b) Run B with the total P_G of 304.0 mm. The values of I for Tray #1, #2 and #3 were 40.5 mm (13.3%), 66.8 mm (22.0%) and 42.7 mm (14.0%), respectively
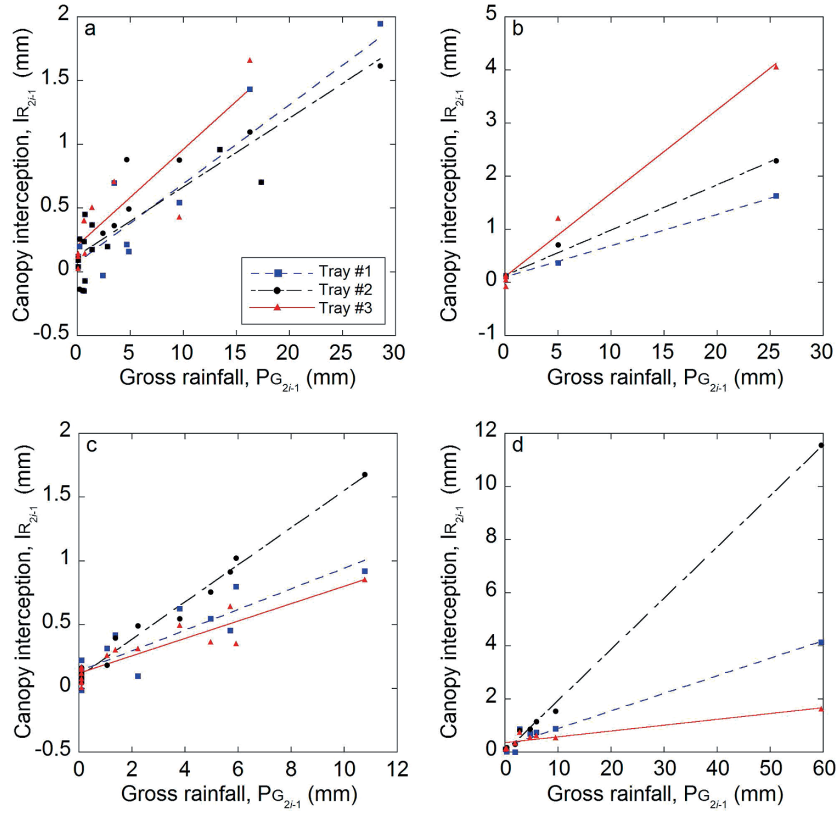

Figure 4. Gross rainfall P_{G2i-1} and canopy interception I_{R2i-1} on a sub rain event basis. (a) the rain event of 6 to 8 July with determination coefficients for Tray #1, #2 and #3 of $r^2 = 0.814$, 0.786 and 0.751, respectively. Some data for Tray #3 was missing. (b) the rain event of 13 to 14 August, $r^2 = 0.999$, 0.994 and 0.988, (c) the rain event of 24 September, $r^2 = 0.801$, 0.984 and 0.851, (d) the rain event of 30 September to 1 October, $r^2 = 0.966$, 0.998 and 0.843

Table II along with I estimated using Equations (1) and (6), respectively. Generally, the values of I calculated by Equation (1) and Equation (6) were not the same. Equation (1) does not include S, and I is calculated as the difference between P_G and P_N, while Equation (6) includes not only P_G and P_N but also the sum of ΔS that sometimes have large errors due to gusts of wind. As described in the section *Instrumentation and calculation of evaporation during*

rainfall, S was estimated based on weighing of a single tree. Gusts of wind can shake off water stored on upwind trees while water on downwind trees can be retained, which makes inhomogeneous distribution of water on trees over a tray. As a result the weight of a single tree is not necessarily representative of all trees. Thus, I calculated by Equation (6) that includes S derived from weighing of the single tree sometimes has large errors. The difference in the two values

Table II. Canopy interception and the components for four large rain events.

		Tray #	Run A		Run B	
			6 to 8 Jul.	13 to 14 Aug.	24 Sep.	30 Sep. to 1 Oct.
P_G	(mm)		110.2	31.0	36.4	84.9
Duration of the rain event	(hours)		52.2	11.3	18.3	22.8
Total *Sbt*	(hours)		16.3	5.9	9.8	8.8
Number of sub rain event *n*			22	6	14	8
$I = I_R + I_{Sbt} + I_{Aft}$ ($I = P_G - P_N$)	(mm)	1	9.0 (9.0)	2.6 (2.7)	3.4 (4.4)	7.9 (7.6)
		2	8.4 (8.6)	3.6 (3.7)	6.1 (6.4)	17.5 (17.3)
		3	—	4.8 (4.9)	4.3 (4.5)	6.1 (6.0)
I_R	(mm)	1	8.4	2.5	4.8	7.5
		2	8.8	3.5	6.6	16.6
		3	—	5.5	4.1	4.8
I_{Sbt}	(mm)	1	−0.5	−0.6	−1.3	0.3
		2	−1.2	−0.6	−0.3	0.5
		3	—	−0.4	0.0	0.4
I_{Aft}	(mm)	1	1.1	0.7	−0.1	0.1
		2	0.8	0.7	−0.2	0.4
		3	—	−0.3	0.2	0.9
$\bar{R}_R$	(mm h^{-1})		3.07	5.74	4.28	6.06
$\bar{E}_R$	(mm h^{-1})	1	0.25	0.48	0.40	0.56
		2	0.23	0.67	0.72	1.25
		3	—	0.89	0.51	0.44

for *I* was 0.3 mm or less for Tray #1 and #2 (except for Tray #1 on 24 September) and 0.2 mm for Tray #3, respectively, which is the same magnitude as the accuracy of the flowmeters, i.e. 0.333 mm per tip and 0.154 mm per tip, respectively. This implies that the total water balance is in most cases nearly equal to the measurement limit. Almost all evaporation seems to occur during rainfall on each tray, since *I* was nearly equal to I_R. Usually, a value of I_{Sbt} must be positive but there were some negative values estimated due to errors. The smallest value of I_{Sbt} is −0.6 mm for Tray #1 and #2 (except for Tray #2 on 6 to 8 July and Tray #1 on 24 September) and −0.4 mm for Tray #3, which are twice or three times larger than the measurement limit. Similarly, I_{Aft} contains some negative values, but the fact remains that *I* is nearly equal to I_R. In each Run average *E* during rainfall ($\bar{E}_R = I_R/(t_{2n-1} - t_0 - Sbt)$) tends to increase with average *R* during rainfall ($\bar{R}_R = P_G/((t_{2n-1} - t_0 - Sbt)$ except for the rain event on Tray #3 on 30 September to 1 October (Table II). Hourly *I* increased with hourly P_G as shown by Tsukamoto *et al.* (1988), Murakami (2006) and Hashino *et al.* (2010).

In Run A the regression lines indicate that the amount of *I* increased sequentially from Tray #1 to #3 (Figure 2a), and this was more noticeable for the cumulative $P_G - I$ relationship (Figure 3a). This indicates that *I* increased with increasing *h*. The only difference in the stand structure between Tray #1 and #2 was *h*, which also supports *h* as a major governing factor of *I*. After thinning, I/P_G in Tray #2 unexpectedly increased from 17.6% to 22.0%. On the contrary, in Tray #3 I/P_G diminished from 20.7% to 14.1% in Figure 2b (14.0% in Figure 3b). In Tray #1, the control, I/P_G changed little, from 13.8% to 13.3%.

DISCUSSION

This study showed for the first time that I/P_G of artificial Christmas trees is in the same range of that in actual forest stands. Experiments with artificial Christmas trees enable detailed analysis of water balance, because one can measure *S* on small trees which is challenging in actual forest stands. As a result, it was demonstrated for the first time that *I* is nearly equal to I_R and that evaporation during *Sbt* contributes little to *I* based on direct measurement of the water balance. The driving force of I_R seems to be rainfall itself, in combination with canopy structure; net radiation and water vapor deficit, which are the main driving forces of evaporation in terms of the heat budget, are in general larger during *Sbt* than during rainfall but what is happening is opposite, i.e. $I_{Sbt} < I_R$. There is a clear difference in the slopes among regression lines in Figure 4, which suggests *I* on a tray differs by rain event. The slopes in Tray #1 (#2, #3) in Run A for the rain event on 6 to 8 July, and 13 to 14 August were 0.062 (0.054, 0.076) and 0.059 (0.086, 0.157), respectively, while in Run B for the rain event on 24 September, and 30 September to 1 October they were 0.081 (0.146, 0.068) and 0.066 (0.193, 0.022), respectively. The difference in the slopes was likely caused by hydrometeorological variables that were not measured. As it is easier to make detailed micrometeorological measurements around small trees than in actual forest stands, the present approach has the potential to clarify the reasons for the difference in slopes in relation to micrometeorology, including raindrop size which is related to the splash droplet evaporation hypothesis.

Another remarkable result of the present study is the increase in I/P_G by thinning. This observation implies that turbulent mixing in the canopy, under the canopy, or vertical mixing through the canopy may boost *I*, and thus *h* is not

necessarily a major parameter to determine I, though specific mechanisms are unknown. Nakayoshi *et al.* (2009) conducted an experiment on I using an outdoor urban-scale model that consisted of cubic concrete blocks 1.5 m high and 1.5 m wide, but they could not find a correlation between P_G and I. Their experiment was conducted under the extreme condition that no ventilation occurs under the canopy. Their result also suggests that ventilating space in the canopy is an important parameter to increase I as Dunkerley (2009) pointed out.

The weakness of the present study is that the stands were a "model forest", which differs from an actual forest in two respects. First, the area of the model forest was smaller than that of an actual forest, suggesting higher inhomogeneity of the turbulence in the model. Second, the material of the model trees was obviously different from that of an actual tree, suggesting differences in splash and dripping rates and reflectivity. Even for actual forests we have little knowledge on how those parameters influence I and a comparative study between a model and actual forest is required.

CONCLUSION

There were three new findings in this experimental study: (1) I/P_G of artificial Christmas trees with $h \leq 2.4$ m was comparable with that of actual forest stands, (2) I was proportional to P_G and direct measurements revealed that I_R accounts for most of I, and (3) contrary to conventional results, an example was shown where I was increased by thinning.

ACKNOWLEDGEMENT

SUPPLEMENT

Supplement Table SI. Instruments and interval of measurements.

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