Chapter 5

Influence of canopy structures for throughfall drop generation: An indoor experiment with a transplanted Japanese cypress tree

5.1 Introduction

Spatial variability of throughfall: When considering soil surface erosion and crusting processes in forests with little surface cover, it is necessary to evaluate throughfall erosivity because these processes are triggered and dominated by raindrop impacts on the soil surface (Ellison, 1944; van Dijk et al., 2002). However, the inhomogeneous spatial distribution of throughfall makes field observations of throughfall amount and throughfall energy difficult. Researchers have not yet agreed on a single theory to explain the spatial distribution of throughfall. Various studies, as noted by Tanaka et al. (2005a), have examined the throughfall amount relative to the distance from the trunk and canopy edges. However, results have varied. Largest throughfall amounts were measured around the canopy edge (Johnson, 1990; Hansen, 1995), near the trunk (Rutter, 1963), midway between the trunk and the canopy edge (Carleton and Kavanagh, 1990), or showed no relationship (Helvey and Patric, 1965). These results suggest that the spatial distribution of throughfall is influenced by various canopy structures and meteorological factors. Likewise, the drop size distribution (DSD) of throughfall is also influenced by several meteorological factors. In *'Chapter 4'*, heavy rain and/or strong wind caused throughfall drops to become smaller. Therefore, it is difficult to clarify the spatial distribution of the throughfall amount and drops by only field observations, which can be influenced by various meteorological conditions.

Objectives of this study: To avoid the influence of varying meteorological factors on the spatial distribution of throughfall, we conducted indoor laboratory experiments involving tree stands and water sprinklers. The experiment thus had controlled rainfall intensity and no wind. Our objective was to evaluate the influence of canopy structures on the special distribution of throughfall amount and throughfall drops.

5.2 Materials and Methods

5.2.1 An indoor experiment

Experimental facility

The experiment was conducted at the large-scale rainfall simulator of the National Research Institute for Earth Science and Disaster Prevention (NIED), Tsukuba, Japan, in September and October 2005. The simulator is 49 m wide × 76 m long × 21 m high and has retractable sidewalls on bare-earth floor surface. Artificial rainfall is sprayed from nozzles 16 m high. The spray nozzles are sufficiently high so that raindrops would reach the floor at terminal velocity.

Transplanted trees

Two Japanese cypress (*Chamaecyparis obtusa*) trees of different height were transplanted in the simulator (Fig. 5.1). The taller tree was 21 years old, 9.8 m tall, and 22.6 cm in diameter at breast height (DBH). The other tree was 15 years old, 7.1 m tall, and had a DBH of 12.6 cm. In this study, we describe the results from the taller tree only.

Four kinds of canopy structures were created by staged branch pruning to estimate how canopy structures affect the process of throughfall drop generation in canopies (Fig. 5.2). Each canopy structure had 2, 3, 4, and 5 m of first branch height; these canopy stages are referred to as T1, T2, T3, and T4, respectively. With the branch pruning, the canopy was thinned and the canopy covered area decreased because the tree canopy had a conical shape. The mean radial distance from the trunk to the canopy edge was 250, 225, 200, and 165 cm with T1–T4, respectively.

Data collection

To estimate the spatial distribution of throughfall elements, we set 32 measuring points under the canopy (Fig. 5.3). These points were radially placed in eight directions; four points were placed at 40, 100, 150, and 200 cm from the trunk and are referred to as points [40], [100], [150], and [200], respectively.

Rainfall amount and intensities were measured with 0.2-mm tipping-bucket raingauges (RC-10; Davis Instruments Corp., Hayward, CA, USA); tip time was recorded with 0.5-s accuracy by a data logger (HOBO Event; Onset Computer Corp., Bourne, MA, USA). Throughfall amount and intensities were simultaneously measured at all the measuring points for each canopy structure more than 2 days after the last rainfall event was applied. Likewise, the spatial variability of the applied rainfall was also measured without the tree.

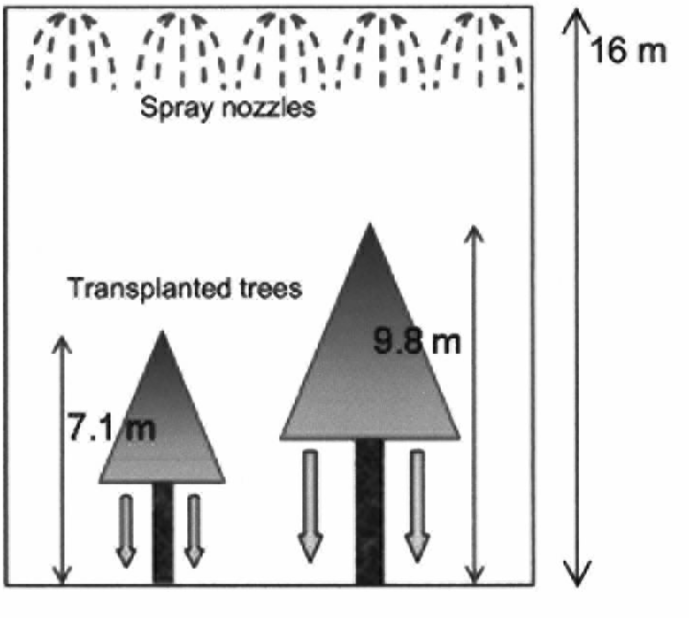

Figure 5.1 Transplanted trees in the rainfall simulator.

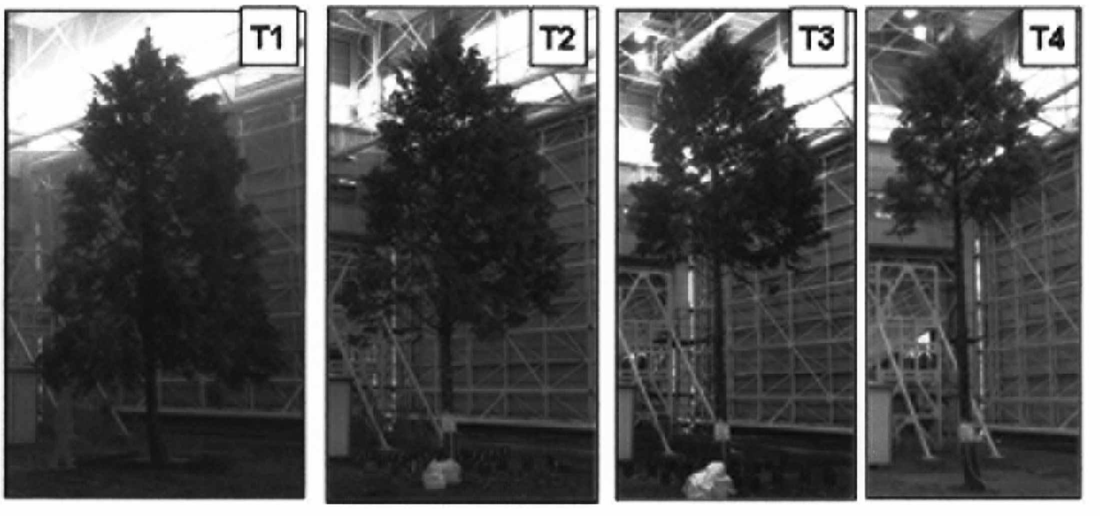

Figure 5.2 Four canopy structures.

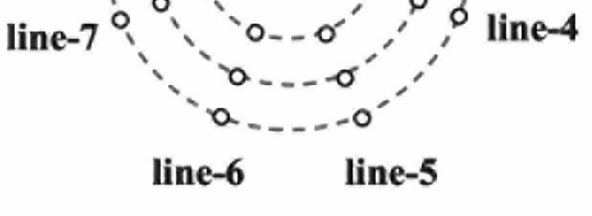

Figure 5.3 32 measuring points under the canopy.

Throughfall drops were measured with four LD gauges of version 2 (Fig. 2.5). The LD gauges were set on the platform 30 cm above the ground surface. A screen net was equipped with the platform 15 cm above the ground surface that was unaffected by rain-splash water drops and splashed soil particles reflected up from the surface. The LD gauges measured the size and velocity of a respective drop.

Throughfall drops were measured at all the points under each canopy structures using relocating LD gauges. Throughfall drops not were measured at [200] for T4, because [200] for T4 was not covered with canopies. We assumed that throughfall in the same rainfall event had the same amount and drops.

Applied rainfall event

The applied rainfall event consisted of continuous two types of rainfall of differing intensity: 31.3 mm h^{-1} for 15 min (lower rainfall intensity: Rain-L) and 67.1 mm h^{-1} for 20 min (higher rainfall intensity: Rain-H). Table 5.1 shows the characteristics of the applied rainfall and Figure 5.4 shows the drop size distribution (DSD) of the applied rainfall. Rain-H had larger rainfall intensity but was consisted of smaller size drops than Rain-L, different from natural rainfall. The applied rainfall had smaller raindrop sizes and kinetic energy than natural rainfall of the same intensity under field conditions. It is considered that the artificial rainfall was applied in calm meteorological condition with little vibration of the canopies; no wind and low raindrop impact to canopy surface.

Several minutes were required to change the rainfall intensity from Rain-L to Rain-H. Thus, data collected for 2 min after the switch from Rain-L were ignored in the analysis.

5.2.2 Method of analysis

Calculation of rainfall kinetic energy

The rainfall intensity measured by the tipping-bucket raingauges and by the LD gauges differed because they had different sampling areas. The raingauges sampled a circle area of 211.2 cm^2 with diameter of 8.2 cm. The LD gauges sampled a rectangular area of 8 cm^2 (described in *'Chapter 2'*). The rainfall volume collected by the LD gauges was calculated by cumulating the total drop volume. Kinetic energy based on the tipping-bucket raingauges (KE: J m^{-2} h^{-1}) was calculated from the following equation:

$$KE = KE_{mm} \cdot I_{TB} = \frac{KE_{LD}}{R_{LD}} \cdot I_{TB}, \qquad \text{(Eq. 5.1)}$$

where KE_{mm} is kinetic energy per unit area per unit rainfall amount (unit kinetic energy: J m^{-2} mm^{-1}), I_{LD} is rainfall intensity measured with the LD gauges (mm h^{-1}), and I_{TB} is rainfall intensity measured with the tipping-bucket raingauges (mm h^{-1}).

Mean value

The mean value was calculated with weighting based on the dominating area. The dominating area

Table 5.1 Characteristics of the applied rainfall.

		Rain-L	Rain-H
Duration	min	15	20
Rainfall intensity	mm h^{-1}	31.3	67.1
D_{MAX}	mm	3.19	2.87
D_{50}	mm	1.13	1.03
Kinetic energy	J m^{-2} h^{-1}	387.3	750.4
Unit kinetic energy	J m^{-2} mm^{-1}	12.4	11.2

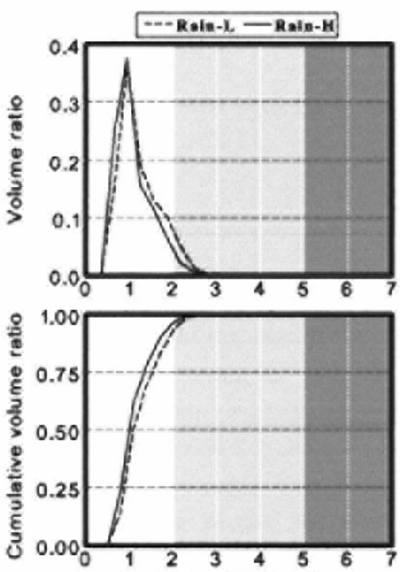

Figure 5.4 DSDs of the applied rainfall of Rain-L and Rain-H.

was defined from the distance between two adjacent measuring points, shown in Figure 5.5. The radial distance ranges from the trunk of the each dominating area were 15–70 cm at [40], 70–125 cm at [100], 125–175 cm at [150], and 175–210 cm at [200]. We considered each measuring point typify the each dominating area. Table 5.2 shows the dominating area and the ratio of each measuring point with the distance from the trunk.

Stable phase in rainfall event

We gained total 120 dataset of throughfall elements measured at different points with each canopy structure; temporal variations of rainfall intensity, drop size, and drop kinetic energy. Figure 5.6 shows an example of the dataset illustrating the applied rainfall and the throughfall measured at [150] on line-4 of T1.

Throughfall intensity was lower than the applied rainfall intensity in the beginning of the event. Once throughfall intensities were stabilized, throughfall fluctuated little in intensity. Stable phases were established in each rainfall event. The stable phase was the duration from 10 to 15 min in Rain-L, and the duration from 5 to 10 min in Rain-H. It was considered that the throughfall elements in the stable phases were generated from the sufficiently saturated canopies.

Spatial variability index

We used the uniformity coefficient (*CU*: %) to create an index of the variability of the spatial distribution, as done by Al-Qinna and Abu-Awwad (1998). *CU* is obtained by

$$CU = 100\left(1 - \frac{Y}{M}\right), \qquad \text{(Eq. 5.2)}$$

where M is the mean and Y is the average deviation from the mean, M: the nearer CU is to 100, the smaller the variability.

5.2.3 Analysis procedure

To estimate the influence of canopy structures for throughfall drop generation, the experimental data were analyzed by two steps. First, the effect of the distance from the trunk for throughfall drop generation was estimated from the comparison among the measuring data of 32 measuring points of T1. Mainly we estimated the integrated data among eight measuring points with same distance from the trunk. The analysis was described in the *'section 5.3: Analysis I'*. Second, the effect of the branch pruning for throughfall drop generation was estimated from the comparison among the measuring data of T1–T4. The analysis was described in the *'section 5.4: Analysis II'*.

In both analysis I and II, the effect estimation was shown for each throughfall element; the rainfall amount, the rainfall intensity, DSD, the drop velocity distribution, and the kinetic energy, in sequence. The drop size distribution was based on the volume ratio normalized by the water volume, with 0.3 mm in diameter class and 0.5 mm in minimum diameter.

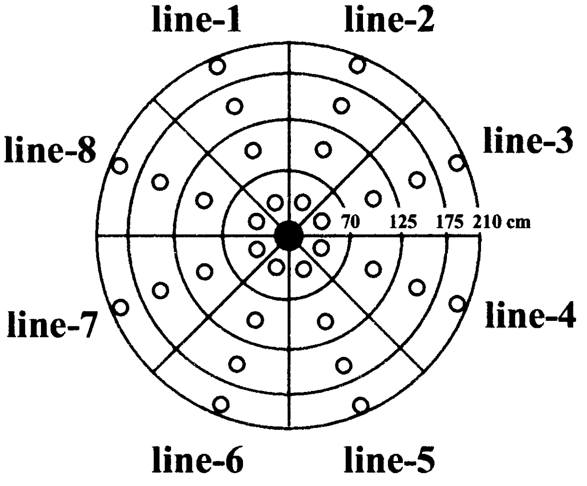

Figure 5.5 Dominating area of each measuring point.

Table 5.2 Dominating ratio of each measuring point with the distance from the trunk.

	[40]	[100]	[150]	[200]	Overall
Dominating area m^2	1.47	3.37	4.71	4.23	13.78
Dominating ratio	0.11	0.24	0.34	0.31	1

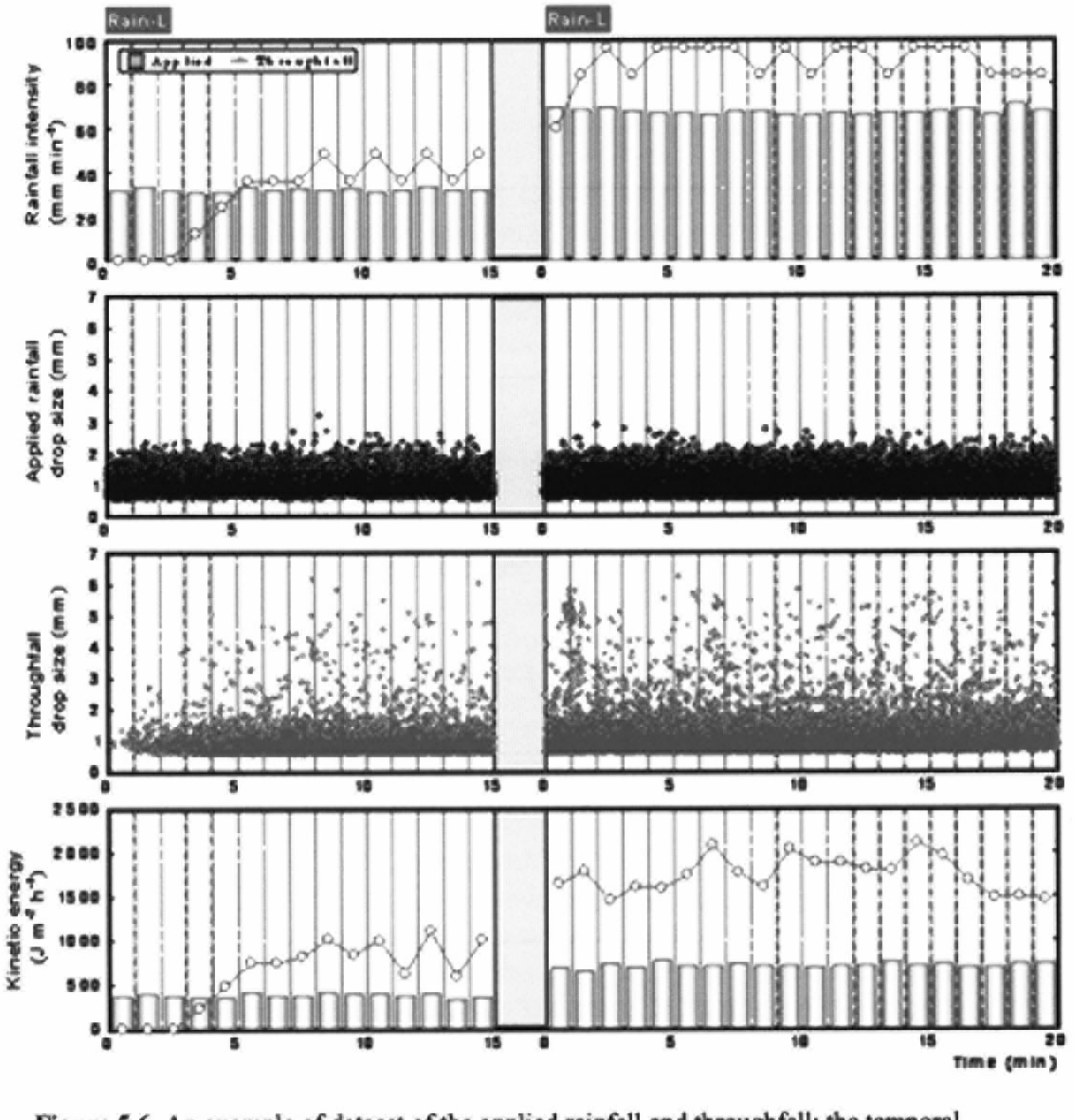

Figure 5.6 An example of dataset of the applied rainfall and throughfall; the temporal variation of rainfall intensity, drop size, and kinetic energy. Throughfall data were measured at [150] on line-4 of T1.

5.3 Analysis I: Effect of the distance from the trunk for throughfall drop generation

5.3.1 Results

Temporal variation of throughfall intensity and throughfall amount

Figure 5.7 shows the temporal variations of throughfall intensity; the mean intensity under the canopy and the mean intensity at each distance from the trunk. For the mean throughfall intensity (the upper of Fig. 5.7), throughfall had lower rainfall intensity than the applied rainfall in the beginning of the event. 6 min was required to stabilize throughfall intensity because rainwater was used to saturate canopies. Once the throughfall intensity was stabilized, throughfall fluctuated little in rainfall intensity. When the applied rainfall intensity increased, throughfall intensity also increased but the increasing timing delayed compared with the applied rainfall. In Rain-H, throughfall intensity was larger than the applied rainfall but gradually reduced and came close to the applied rainfall intensity.

The temporal variation of throughfall intensity varied at each distance from the trunk (the lower in Fig. 5.7). Except for [40], the time lag required to stabilize throughfall intensity became shorter with the distance from the trunk. Moreover, the points farther from the trunk had larger throughfall intensity through the rainfall event. Accordingly the throughfall amount generally increased with the distance from the trunk, shown in Figure 5.8. [200] had larger throughfall intensity than the applied rainfall as well as the mean throughfall intensity.

Throughfall intensity

Throughfall had large spatial variability in rainfall intensity in the stable phases. The throughfall intensity ranged from 19.2 to 67.2 mm h^{-1} in Rain-L (31.3 mm h^{-1} for the applied rainfall), and from 38.4 to 129.6 mm h^{-1} in Rain-H (67.1 mm h^{-1} for the applied rainfall). *CU* was 75 in Rain-L and 72 in Rain-H. *CU* was smaller than the applied rainfall; *CU* of the applied rainfall was 86 in Rain-L and 93 in Rain-H. The mean throughfall intensity was 33.4 mm h^{-1} in Rain-L, and 75.3 mm h^{-1} in Rain-H. Throughfall had larger rainfall intensity than the applied rainfall in the stable phases in the experiment. It is regarded that interception loss during the rainfall event was little.

Figure 5.9 shows throughfall intensity during the stable phases in relation to the distance from the trunk. Throughfall intensity increased with the distance from the trunk in both Rain-L and Rain-H, except for [40]. [100] had lower rainfall intensity, but [200] had higher rainfall intensity than the applied rainfall as well as the mean throughfall intensity.

[40] had larger throughfall intensity than [100], but [40] had large variability among the measuring points. Table 5.3 shows the *CU* of throughfall intensity with the distance from the trunk. Integration measuring points with the distance from the trunk decreased the variability of throughfall intensity, except for [40]. These results suggest that throughfall intensity was dominated by the distance from the trunk except for the points adjacent to the trunk.

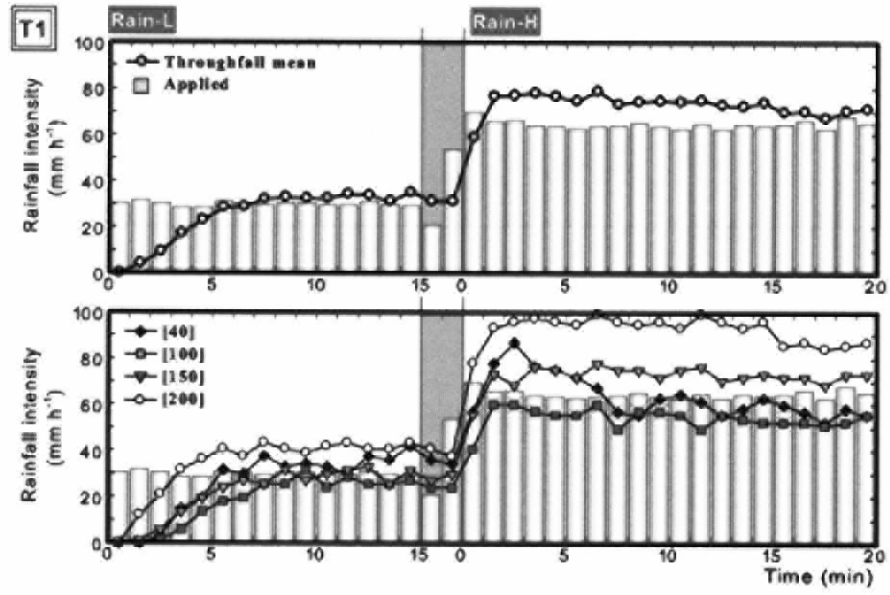

Figure 5.7 Temporal variations of rainfall intensity of throughfall of T1 and the applied rainfall. The *upper* shows the mean throughfall intensity. The *lower* shows the mean value at 8 measuring points with each distance from the trunk.

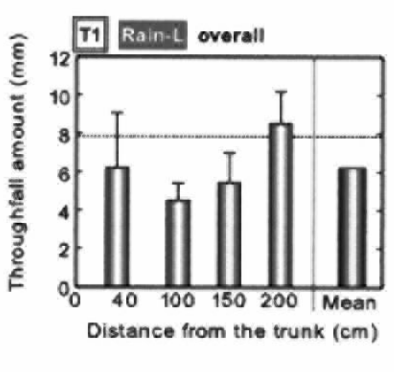

Figure 5.8 Throughfall amount in relation to the distance from the trunk of T1 in Rain-L.

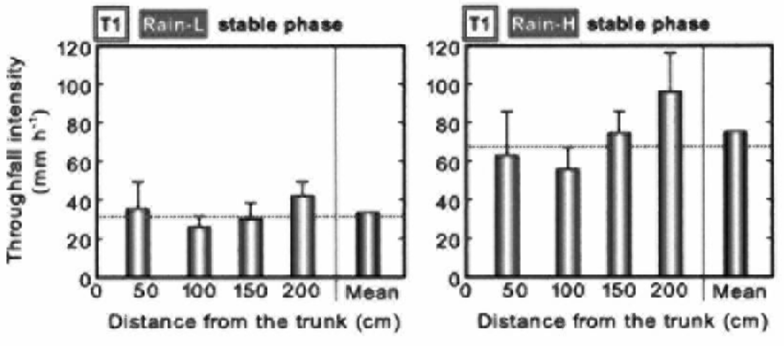

Figure 5.9 Throughfall intensity in relation to the distance from the trunk of T1, during stable phases in Rain-L and Rain-H. *Dotted lines* represents the rainfall intensity of the applied rainfall.

Table 5.3 *CU* of throughfall intensity of T1 during the stable phases in Rain-L and Rain-H.

		Rain-L	Rain-H
Applied		86	93
Throughfall	32-all	75	72
	[40]	68	75
	[100]	85	85
	[150]	77	88
	[200]	83	84

Throughfall drop size distribution

Figure 5.10 shows the examples of throughfall-DSD at each measuring point of T1 during the stable phase in Rain-H. Figure 5.11 shows DSDs of the applied rainfall and throughfall of three measuring points of T1 chosen from Fig. 5.10. Each measuring point, in common, had larger drops than the applied rainfall. D_{MAX} of the applied rainfall was 3.19 mm in Rain-L and 2.85 mm in Rain-H. It is considered that drops with diameters > 3 mm was almost generated as drips from the canopies; raindrops would coalesce in the canopy, forming larger throughfall drops. However, the abundance ratio of large drops was different among measuring points; thus throughfall-DSD varied among measuring points.

The spatial variability of throughfall-DSD was estimated using D_{50}. Throughfall D_{50} ranged from 1.13 to 3.54 mm in Rain-L (1.13 mm for the applied rainfall), and from 1.11 to 4.27 mm in Rain-H (1.03 mm for the applied rainfall). *CU* was 76 in both Rain-L and Rain-H.

Figure 5.12 shows DSDs at each distance from the trunk; each DSD was drawn using all drops of eight measuring points with same distance from the trunk. Throughfall had different DSD with the distance from the trunk. The difference of throughfall-DSD was estimated by D_{50} and the volume ratio of drops with each diameter class. Figure 5.13 shows throughfall D_{50} in relation to the distance from the trunk. Throughfall generally had larger drops with the distance from the trunk. D_{50} increased with the distance, except for [40]. There was little difference in D_{50} between Rain-L and Rain-H.

Figure 5.14 shows the volume ratio of drops with each diameter class in relation to the distance from the trunk during the stable phases in Rain-L and Rain-H. Except for [40], the abundance ratio of large drops increased with the distance from the trunk. The drops with diameters > 3 mm accounted for 33.7%, 31.8%, 35.8%, and 44.2% of throughfall volume in Rain-L, and for 32.1%, 30.5%, 39.5%, and 44.1% of throughfall volume in Rain-H at [40], [100], [150], and [200], respectively. The volume ratio of drops with diameters > 3 mm deferred little between Rain-L and Rain-H. However, the volume ratio of the drops with diameters > 5 mm was higher in Rain-H. The increase of incident rainfall raised the probability of generation of larger drops.

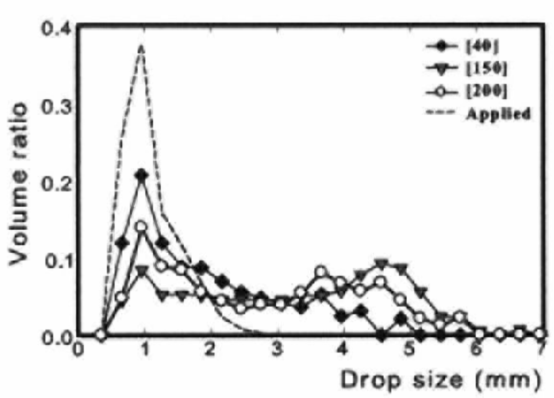

Figure 5.11 DSDs of the applied rainfall and throughfall during the stable phase in Rain-H. Each throughfall-DSD was at [40], [150], [200] on line-4. The canopy stage was T1.

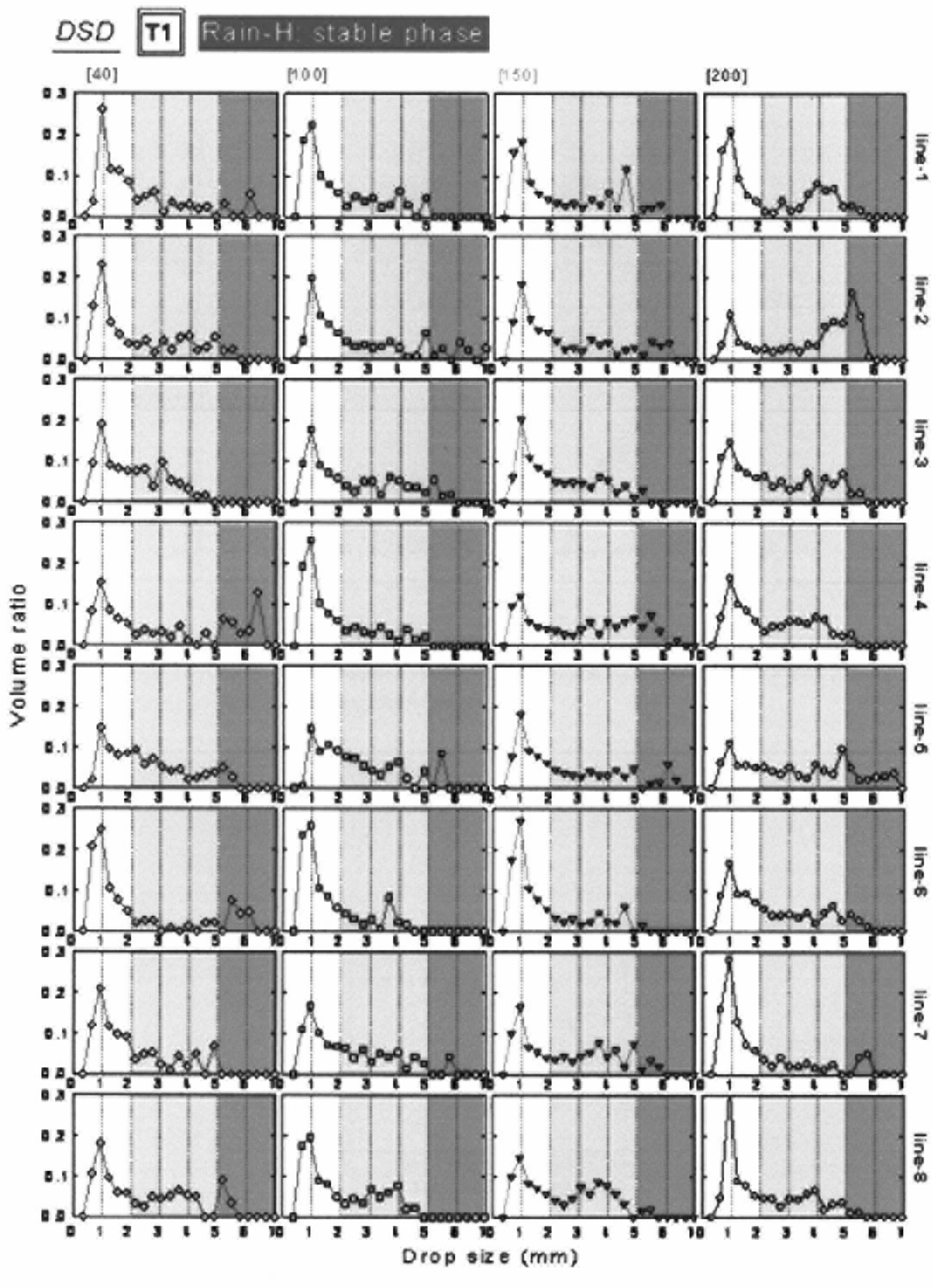

Figure 5.10 Throughfall-DSD at 32 all measuring points during the stable phase in Rain-H. The canopy stage was T1.

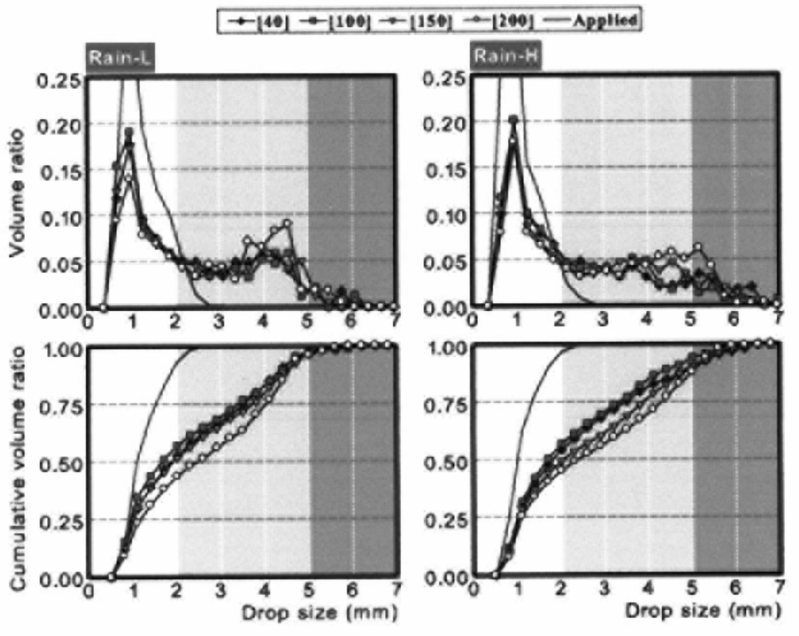

Figure 5.12 DSDs of the applied rainfall and throughfall at each distance from the trunk of T1 during the stable phases in Rain-L and Rain-H. Each throughfall-DSD was drawn using all drops measured at eight measuring points.

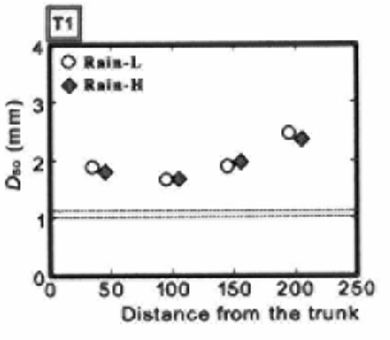

Figure 5.13 Throughfall D_{50} in relation to the distance from the trunk of T1 during the stable phases. *Broken lines* indicate the applied rainfall D_{50} in Rain-L (the *lower*) and the in Rain-H (the *upper*).

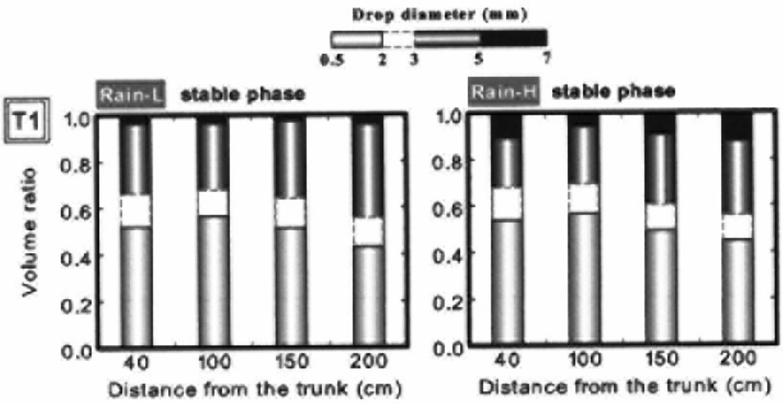

Figure 5.14 Volume ratio of drops with each diameter class in relation to the distance from the trunk, during the stable phases in Rain-L (the *left*) and Rain-H (the *right*).

Throughfall drop velocity distribution

Figure 5.15 shows the relationship between drop diameter and drop velocity of total drops measured at 32 measuring points during the stable phase in Rain-H. The number of drops is shown in a contour plan. Solid line indicates the terminal drop velocity and broken line indicates expected drop velocities when drops fall from a height of 2 m, which was the first branch height of T1, and 5 m, which was the first branch height of T4. Each assumed drop velocity was set out by Zhou et al. (2002).

In total, the number of drops with diameters > 3 mm, considered as drips, was 1778. The drips comprised 1.1% of the total number of throughfall drops, but 41.4% of the total volume. All the drips did not reach terminal velocities. 1576 drops (= 88.6%) had less than 90% of the terminal velocity. The falling height was insufficient for drips to gain terminal velocity. Drops with diameters > 3 mm must fall at least 17 m to accelerate to terminal velocity (Wang and Pruppacher, 1977).

Some drips had higher velocities than that expected velocities of a drop falling from the height of the first branch (the lower broken line in Fig. 5.15). The lowest canopy layer was 2 m high on the first branch height; thus it is expected that drips generated from the lowest canopy layers had velocities < 6.5 m s^{-1} at most. In total, 694 drops (= 39.0%) had more than the velocities of 6.5 m s^{-1}. The results imply drips were generated from the upper canopy layers as well as from the lowest canopy layers.

Figure 5.16 shows the distribution of drop velocities of the drops with diameters > 3 mm. The drop velocity distribution varied among each distance from the trunk. The distribution of [200] was especially skewed and the mode was located in lower velocities. Table 5.4 shows the number and the ratio of drops with velocity < 6.5 m s^{-1}. The ratio was higher at [200]. More than 75 % of drips were generated from the lower canopy layers. In contrast, the drops measured at the other distances accounted for less than half in the drop number. More than half of drops measured on the surface were generated from the upper canopy layers.

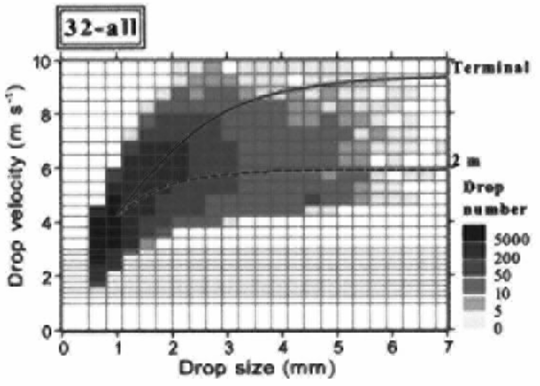

Figure 5.15 Relationship between drop diameter and drop velocity of total drops of T1 measured at 32 measuring points during the stable phase in Rain-H. The *Solid line* indicates the terminal velocity of drops and the *broken line* indicates assumed drop velocity when drops fell from a height of 2 m. Each assumed drop velocity was set out by Zhou et al. (2002).

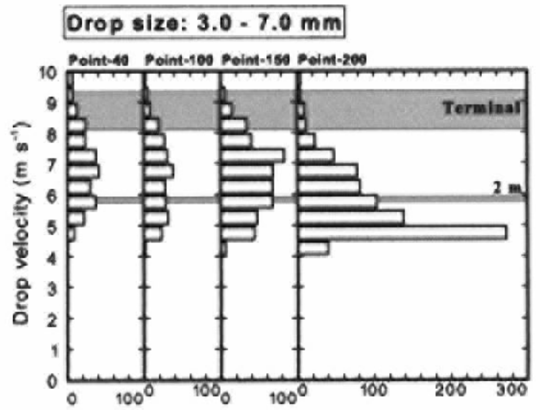

Figure 5.16 The distribution of throughfall drop velocity with diameters > 3 mm of T1. The number of drops was totally counted at 32 all measuring points during the stable phase in Rain-H. *Gray belts* represent terminal velocity and assumed drop velocity when drops fall from 2 m high, both were set out by Zhou et al. (2002).

Table 5.4 The number and the ratio of total drops with velocities < 6.5 m s^{-1} at each distance from the trunk.

	[40]	[100]	[150]	[200]
Total	251	240	479	808
With velocity < 6.5 m s^{-1}	98 (39.0%)	113 (47.1%)	233 (48.6%)	634 (78.5%)

Throughfall kinetic energy

Throughfall also had large spatial variability in kinetic energy. Throughfall kinetic energy in the stable phases ranged from 215.5 to 1055.2 J m^{-2} h^{-1} in Rain-L (387.3 J m^{-2} h^{-1} for the applied rainfall), and from 473.8 to 2415.7 J m^{-2} h^{-1} in Rain-H (750.4 J m^{-2} h^{-1} for the applied rainfall). *CU* was 67 in Rain-L and 75 in Rain-H. The mean throughfall kinetic energy was 524.9 J m^{-2} h^{-1} in Rain-L, and 1156.2 J m^{-2} h^{-1} in Rain-H. Throughfall had larger kinetic energy than the applied rainfall. The mean kinetic energy was 1.4 times larger in Rain-L and 1.5 times larger in Rain-H than the applied rainfall. Most of the measuring points under the canopies had larger kinetic energy than the applied rainfall; 23 points in Rain-L and 27 points in Rain-H.

Figure 5.17 shows throughfall kinetic energy during the stable phases in relation to the distance from the trunk. At [100], throughfall kinetic energy was smallest in both Rain-L and Rain-H. Meanwhile, throughfall intensity at [100] was lower than the applied rainfall (Fig. 5.9), but throughfall kinetic energy was larger than the applied rainfall.

Except for [40], throughfall kinetic energy increased with the distance from the trunk but the increasing trend was not so clear like throughfall intensity (Fig. 5.9). [150] had 72% in Rain-L and 78% in Rain-H of throughfall intensity at [200]. On the other hand, [150] had 87% in Rain-L and 100% in Rain-H of throughfall kinetic energy. It is shown that largest throughfall intensity does not always cause largest throughfall kinetic energy.

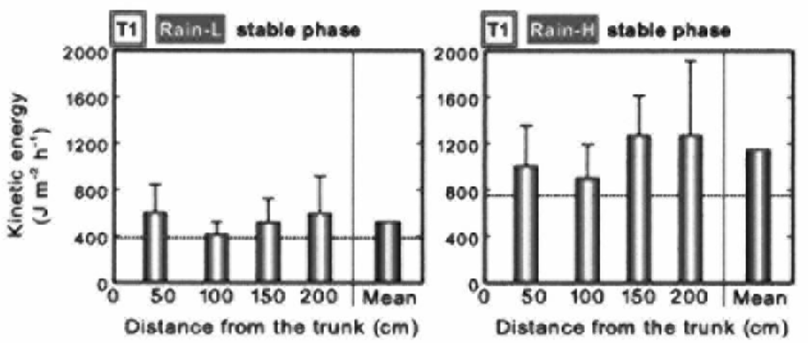

Figure 5.17 Throughfall kinetic energy in relation to the distance from the trunk of T1 during stable phases in Rain-L and Rain-H. *Broken lines* represents the kinetic energy of the applied rainfall.

5.3.2 Discussion

Effect of the distance from the trunk for spatial distribution of throughfall amount and intensity

We discuss why throughfall amount and intensity were dominated by the distance from the trunk. The results showed throughfall amount increased with the distance from the trunk (Fig. 5.8). The canopy thickness adjacent to the canopy edge was thinner than that adjacent to the trunk because the transplanted tree had a conical shape canopy (Fig. 5.1); and hence less rainwater was required to saturate canopies adjacent to the canopy edge. The canopies adjacent to the canopy edge were sufficiently saturated more quickly than the canopies adjacent to the trunk. Accordingly, the time lag required to stabilize throughfall intensity became shorter with the distance from the trunk (Fig.5.7).

Moreover, throughfall intensity increased with the distance from the trunk, as was also found by Johnson (1990) and Hansen (1995). Especially, the canopies adjacent to the canopy edge produced larger rainwater dripping than the applied rainfall (Fig 5.8). If the rainwater passed through canopies only vertically with little interception loss, the spatial distribution of throughfall intensity must be homogeneous toward radial directions. Rainwater applied around the center of the canopy may have spilled over to the edge of the canopy because of the canopy's conical shape. The rainwater runs on the saturated canopies forward the edges of the canopies because the foliages grow down toward the apex. Consequently, a flow of rainwater in the canopies was consisted of three processes; saturating canopies, dripping from canopies and running on canopies. Similar results were showed by Hansen (1995).

At [40], throughfall intensity was larger than [100] (Fig. 5.8) but the variability among eight measuring points was large (Table 5.3). Lower canopy layers are mainly consisted of branches adjacent to the trunk. When the branches grow to the sky, rainwater on the branches runs toward the trunk. The spatial distribution of throughfall adjacent to the trunk would be influenced by the arrangement of branches. Concentrative dripping points of throughfall were readily emerged adjacent to the trunk (Ford and Deans, 1978; Robson et al., 1994). Thus, the spatial variability of throughfall amount and intensity was large adjacent to the trunk.

Effect of the distance from the trunk for spatial distribution of throughfall drop sizes and velocities

We discuss why throughfall-DSD and drop velocity distribution were dominated by the distance from the trunk. For DSD, as the distance from the trunk became farther, throughfall comprised larger drops (Fig. 5.12) and the volume ratio of drops with diameters > 3 mm increased (Fig. 5.14); hence D_{50} became larger (Fig. 5.13).

Throughfall is consisted of three drop components; free throughfall, drips, and splash droplets , shown in *'Chapter 4'*. The splash component is generated from rain-splash on the canopy caused by raindrop impact (Yang and Madden, 1993; Saint-Jean et al., 2004; Murakami, 2006) or spattering water caused by vibration of the canopy by wind. The applied rainfall in the experiment was considered not to generate the splash component because the experiment was conducted under calm meteorological condition.

All the measuring points were absolutely covered with the canopies. Especially [40] and [100] were covered with much foliage and canopy openness was close to zero. It is supposed that the points adjacent to the trunk did not have the free throughfall component. If throughfall was consisted from only the drip component, throughfall-DSD at [40] or [100] was biased toward larger drop sizes exceeding 3 mm in diameter. However, the results showed the points adjacent to the trunk had larger peak around 1 mm in diameter than the points adjacent to the canopy edge (Fig. 5.12). Throughfall would have the splash component even under calm meteorological condition.

Probably the drips generated from the upper canopy layers impacted to the lower canopy layers and were partly splashed into fine droplets. At the points adjacent to the trunk, the canopy is thicker than adjacent to the canopy edge; thus, the drips generated from various canopy layers with different heights. The number and the ratio of drips generated from the lower canopy layers were low (Fig. 5.16 and Table 5.4). The probability is higher to be re-intercepted the drips generated from the upper canopy layers by the lower canopy layers. Meanwhile, the points adjacent to the canopy edges had drops with higher velocities because some drips passed through the canopies without being intercepted by the lower canopy layers.

At the farthest points, [200], drips were mainly generated from the lower canopy layers (Fig. 5.16 and Table 5.4). Canopies adjacent to the canopy edge had thin canopy; thus the number of drips was few with higher velocities. Therefore, the splash component was hardly generated because adjacent to the canopy edge did not have the upper canopy layers.

It is suggested that the canopy thickness affects the throughfall-DSD and throughfall drop velocities.

Effect of the distance from the trunk for spatial distribution of throughfall kinetic energy

We discuss the distribution of the throughfall kinetic energy with the distance from the trunk. Throughfall kinetic energy generally increased with the distance from the trunk (Fig. 5.17), but the increasing trend was not as clear as the throughfall intensity (Fig. 5.9).

A process of generating kinetic energy is associated with rainfall intensity, DSD, and respective

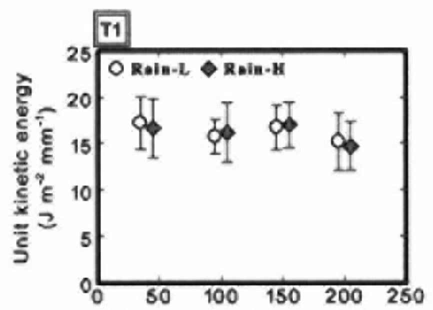

Figure 5.18 Throughfall unit kinetic energy in relation to the distance from the trunk of T1 during stable phases.

drop velocity. The volume ratio of large drops increased with the distance from the trunk (Fig. 5.14), meanwhile, the number and the ratio of drops with higher velocities were much lower at the farthest points from the trunk than other distance from the trunk (Fig. 5.16 and Table 5.4). Figure 5.18 shows the unit kinetic energy in relation to the distance from the trunk during the stable phases in Rain-L and Rain-H. The unit kinetic energy represents the raindrop erosive potential eliminating the influence of rainfall amount and intensity. There were small variation among [40], [100], and [150], but [200] had lower unit kinetic energy than the other points. The points adjacent to the canopy edge had low erosive potential for drop impact.

Therefore, although throughfall intensity generally increased with the distance from the trunk and the furthest points had highest throughfall intensity (Fig. 5.9), the difference of throughfall kinetic energy between [150] and [200] was not clear (Fig. 5.17). The distribution of throughfall kinetic energy was not determined by only that of throughfall intensity.

5.4 Analysis II: Effect of the branch pruning for throughfall drop generation

5.4.1 Results

Temporal variation of throughfall intensity and throughfall amount

Figure 5.19 shows the temporal variations of throughfall intensity of each canopy structure at each distance from the trunk. Throughfall had lower rainfall intensity than the applied rainfall in the beginning of the event. The time lag required to stabilize throughfall intensity became shorter as more branches were pruned at each distance from the trunk at each distance from the trunk. Therefore throughfall amount in Rain-L generally increased with more branch pruning except for [200]. Figure 5.20 shows the throughfall amount in relation to the canopy structures with the distance from the trunk in Rain-L. The mean throughfall amount increased with the branch pruning.

Figure 5.21 shows the throughfall intensity in relation to the canopy structures with each distance from the trunk during the stable phases in Rain-L and Rain-H. With the branch pruning, the mean throughfall intensity fluctuated little but throughfall intensity at each radial distance point from the trunk fluctuated with the branch pruning.

At [200], throughfall intensity decreased with the branches pruning. The decreasing trend was remarkable in Rain-H. For T4, throughfall intensity was approximately same to the applied rainfall because [200] was out of the canopy covers. But, throughfall at [200] for T4 had larger rainfall intensity in first 3 min in Rain-H (Fig. 5.19). The sudden increase of the applied rainfall intensity caused the instantaneous increase of throughfall.

At [150], throughfall intensity increased with the branch pruning. At [100], throughfall intensity fluctuated little with the branch pruning among T1–T3. T4 had slightly larger intensity than T1–T3. [40] had large fluctuation in throughfall intensity with the branch pruning, but clear trend with the branch pruning was not confirmed. The branch pruning changed the rainwater redistribution in the

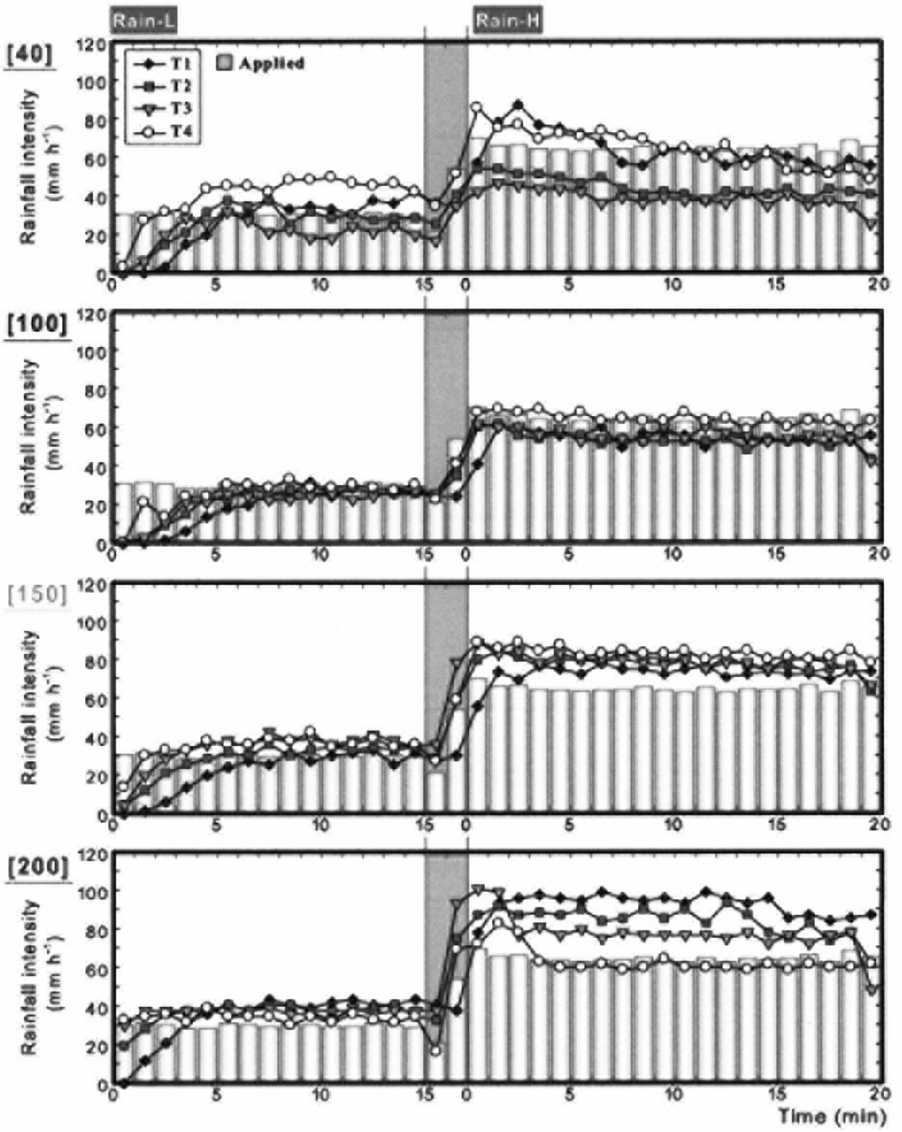

Figure 5.19 Temporal variations of rainfall intensity of throughfall for each canopy structure. Starting from the *top*, the figure shows throughfall intensity at [40], [100], [150], and [200], respectively.

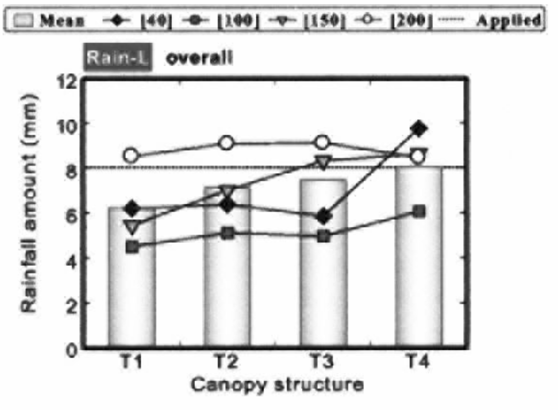

Figure 5.20 Throughfall amount in relation to the canopy structures with the distance from the trunk in Rain-L. The *Broken line* represents the rainfall amount of the applied rainfall.

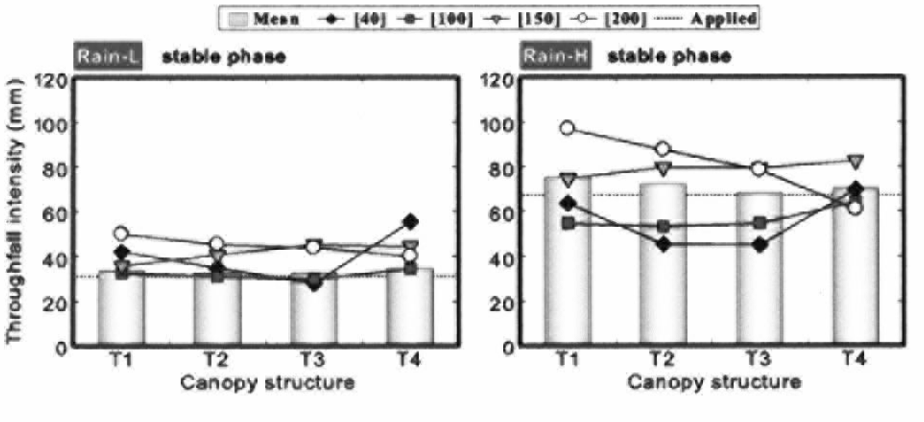

Figure 5.21 Throughfall intensity in relation to the canopy structures with the distance from the trunk during stable phases in Rain-L and Rain-H. The *Broken lines* represent the applied rainfall intensity.

canopies.

Throughfall drop size distribution

The fluctuation of throughfall-DSD among canopy structures was summarized in three figures. Figure 5.22 shows cumulative throughfall-DSD of each canopy structure with each distance from the trunk during the stable phases in Rain-L and Rain-H; each DSD was drawn using all drops of eight measuring points with same distance from the trunk. Figures 5.23 shows the throughfall D_{50} and Figure 5.24 shows the volume ratio of throughfall drops with each diameter class, in relation to the canopy structures with the distance from the trunk during stable phases in Rain-L and Rain-H.

At [200], the drop sizes comprising throughfall became smaller with the branch pruning. Throughfall-DSD shifted to smaller drop size (Fig. 5.22) and throughfall D_{50} decreased with the branch pruning (Fig. 5.23). The abundance ratio of the drops with diameters > 3 mm, which were generated as drips from the canopies, decreased, and correspondingly the abundance ratio of drops with diameters > 2 mm increased with the branch pruning (Figure 5.24). As more branches were pruned, the free throughfall component increased and the drip component decreased.

[40] and [100] were absolutely covered with canopies for each canopy structure. At [40] and [100], the drop sizes comprising throughfall became larger with the branch pruning, in contrast to [200]. Throughfall-DSD shifted to larger drop size (Fig. 5.22) and throughfall D_{50} increased with the branch pruning (Fig. 5.23). The abundance ratio of drops with diameters > 3 mm increased and correspondingly the abundance ratio of drops with diameters < 2 mm decreased with the branch pruning (Fig. 5.24). The thinning of canopy thickness increased the abundance ratio of large drops.

At [150], the increasing trend of the drop size comprising throughfall with the branch pruning was conceded for T1–T3 likewise with [40] and [100], but the decreasing trend of that was conceded between T3 and T4. At the points adjacent with the canopy edge, the abundance ratio of large drops decreased, observed at [200] between T1 and T2.

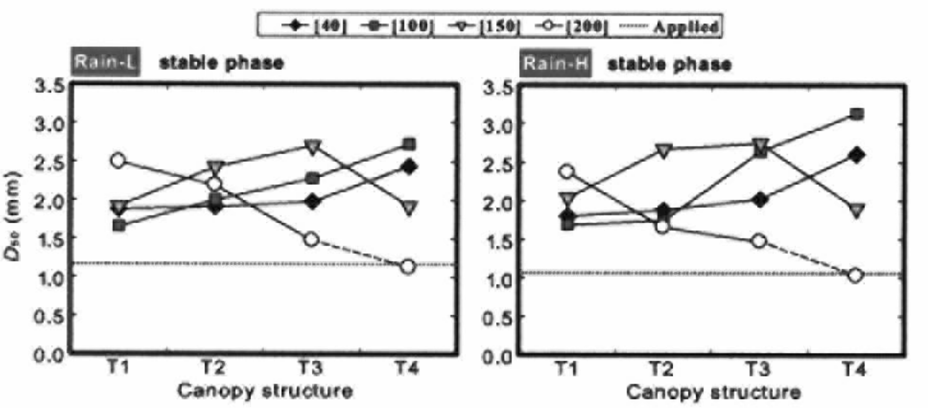

Figure 5.23 Throughfall D_{50} in relation to the canopy structures with the distance from the trunk during stable phases in Rain-L and Rain-H. The *Broken lines* represent D_{50} of the applied rainfall.

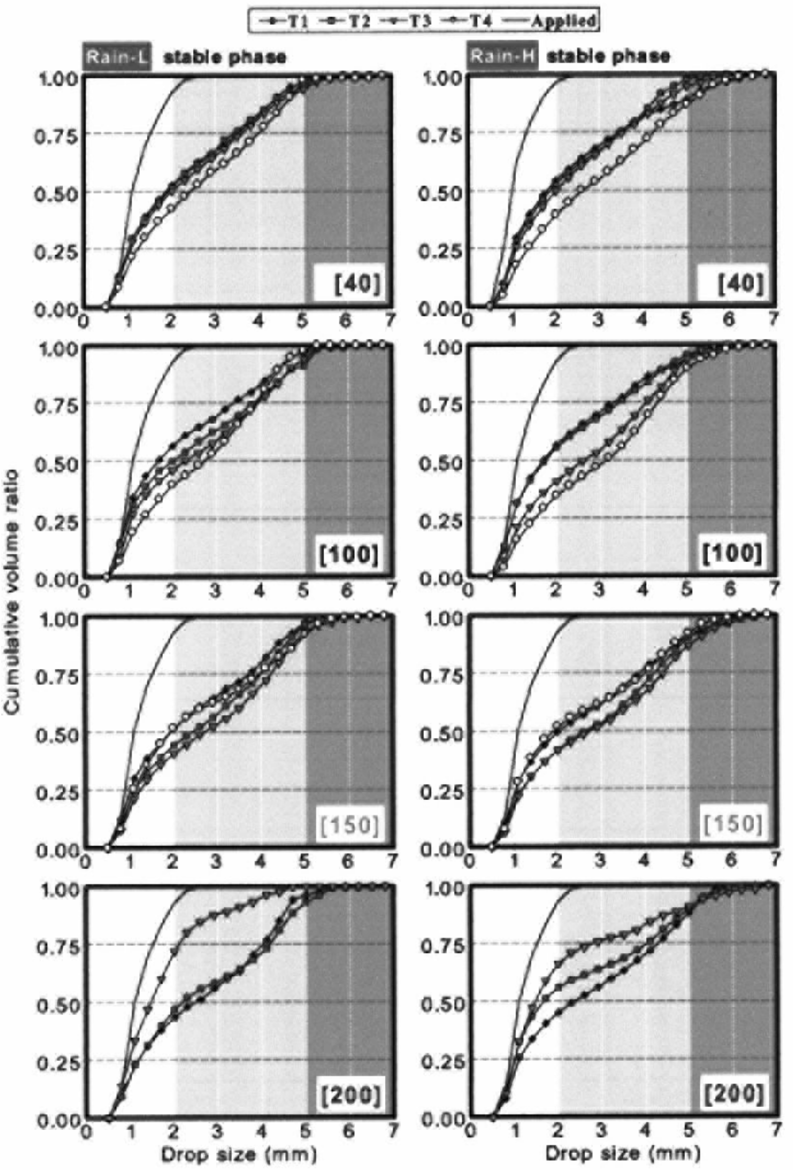

Figure 5.22 Throughfall-DSD of each canopy structure during stable phases in Rain-L and Rain-H. Starting from the *top*, the figure shows throughfall intensity at [40], [100], [150], and [200], respectively.

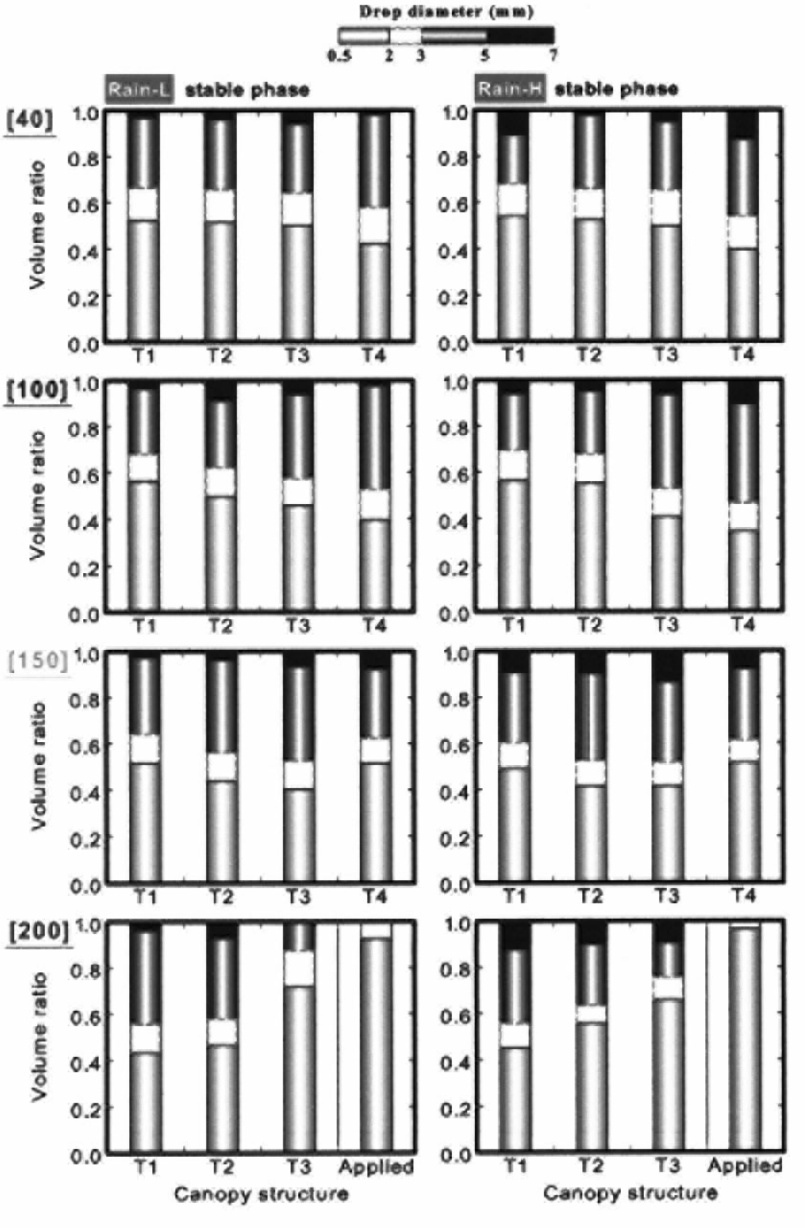

Figure 5.24 Volume ratio of drops with each diameter class in relation to the canopy structures during the stable phases in Rain-L and Rain-H. Starting from the *top*, the figure shows throughfall intensity at [40], [100], [150], and [200], respectively.

Throughfall drop velocity distribution

Figure 5.25 shows the distribution of throughfall drop velocity with diameters > 3 mm with each canopy structure at all measuring points during the stable phase in Rain-H. As more branches were pruned, the first branch height rose and falling distance increased for the drips generated from the lowest canopy layers. With the branch pruning, the number and the ratio of drops with higher velocity increased and, correspondingly, the number and the ratio of drops with lower velocities decreased. The mode of the velocities of drips increased with the branch pruning.

Figure 5.26 shows the distribution of throughfall drop velocity divided into each distance from the trunk from Fig. 5.25. The number and the ratio of drops with higher velocity increased with the branch pruning at each distance. Table 5.5 shows the number and the ratio of drops with velocities > 7.5 m s^{-1} with each canopy structure at each distance from the trunk. The drops with velocities > 7.5 m s^{-1} were regarded to be generated from the upper canopy layers more than 5 m high, the first branch height of T4, judged from Fig. 5.26.

At [200], the number of drops with diameters > 3.0 mm decreased with the branch pruning (Fig. 5.26). The distribution width was narrow compared with the other points under any canopy structure. More than 77% of drips were generated from the lower canopy layers.

At [40], [100], and [150], the number of drops with diameters > 3.0 mm increased with the branch pruning (Fig. 5.26). Furthermore, As more branches were pruned, the number and ratio of drips generated from the upper canopy layers increased (Table 5.5).

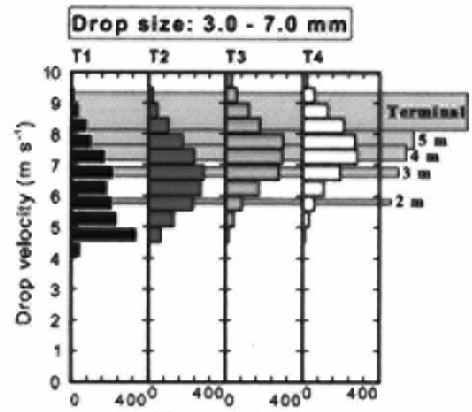

Figure 5.25 The distribution of throughfall drop velocity with diameters > 3 mm with each canopy structure. The number of drops was totally counted at 32 all measuring points during the stable phase in Rain-H. *Horizontal belts* represent the expected drop velocity when drops fell from 2–5 m high, respectively, and terminal velocity, set out by Zhou et al. (2002).

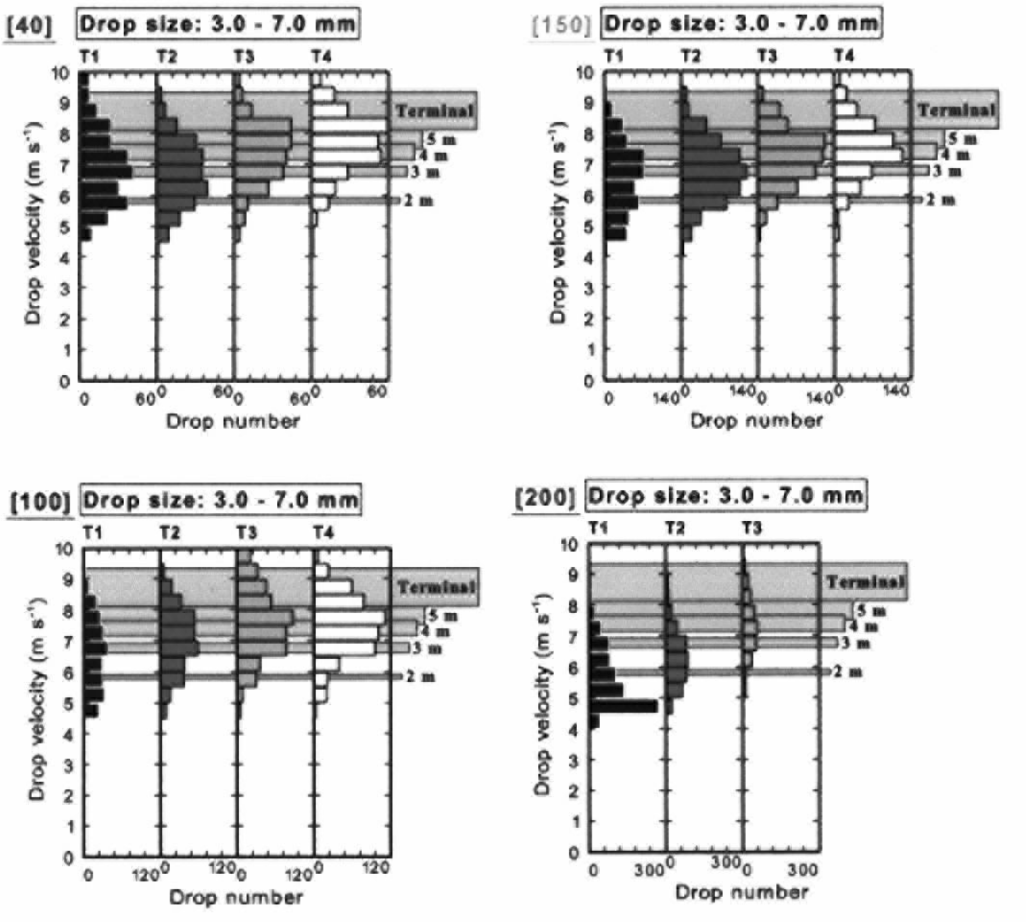

Figure 5.26 The distribution of throughfall drop velocity with diameters > 3 mm with the distance from the trunk. The figures were separately drawn using Fig. 5.25

Table 5.5 The number and the ratio of total drops with velocities > 7.5 m s^{-1} with each canopy structure at each distance from the trunk.

	[40]				[100]			
	T1	T2	T3	T4	T1	T2	T3	T4
Total	251	219	238	284	240	316	472	559
With velocities	75	54	111	164	59	107	240	278
> 7.5 m s^{-1}	(29.9%)	(24.7%)	(46.6%)	(57.7%)	(24.6%)	(33.9%)	(50.8%)	(49.7%)

	[150]				[200]		
	T1	T2	T3	T4	T1	T2	T3
Total	451	612	578	543	808	422	289
With velocities	94	140	227	258	49	41	112
> 7.5 m s^{-1}	(20.8%)	(22.9%)	(39.3%)	(47.5%)	(6.1%)	(9.7%)	(38.8%)

Throughfall kinetic energy

Figure 5.27 shows the throughfall kinetic energy in relation to the canopy structures with the distance from the trunk during the stable phases in Rain-L and Rain-H. Each distance from the trunk of each canopy structure measured larger kinetic energy than the applied rainfall, except for at [40] of T2 in Rain-H. The mean kinetic energy at all measuring points increased with the branch pruning. As more branches were pruned, the drips had higher velocities depends on the increase of the first branch height (Fig. 5.25), in common at each measuring point.

At [100] absolutely covered with the canopies, throughfall kinetic energy increased with the branch pruning. At [40], throughfall kinetic energy had peculiar fluctuation with the branch pruning.

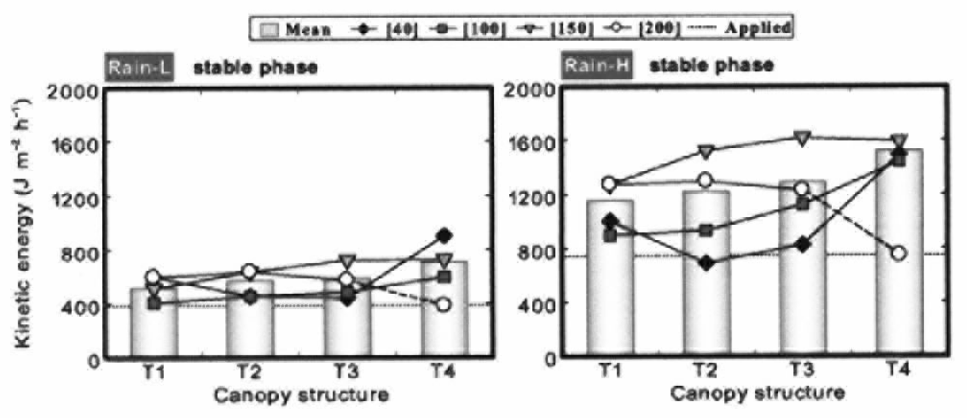

Figure 5.27 Throughfall kinetic energy in relation to the canopy structures with the distance from the trunk, during stable phases in Rain-L and Rain-H. *Broken lines* represent the kinetic energy of the applied rainfall.

On the other hand, at [200], throughfall kinetic energy had little fluctuation with the branch pruning. T3 had smaller kinetic energy than T2 and T1.

At [150], throughfall kinetic energy increased with the branch pruning under T1–T3, likewise with [100], but had little fluctuation between T3 and T4. [150] was absolutely covered with canopies under T1–T3, but was partially exposed or adjacent to the canopy edges under T4. The variation of throughfall kinetic energy between T3 and T4 was similar to [200].

5.4.2 Discussion

Influence of the branch pruning on canopy structures

Four canopy structures were given (Fig. 5.2) in the present experiment by the staged branch pruning. The branch pruning caused not only the increase of the first branch height but also the decrease of canopy thickness and the reduction of canopy cover area. The distance from the trunk to the canopy edge was reduced with the branch pruning. Therefore the influence of canopy structures was estimated from three standpoints; the first branch height, the canopy thickness, and the canopy edge effect.

The first branch height affected the drop velocities of drips generated from the canopies. The branch pruning increased the velocities of drips (Fig. 5.25). Therefore the branch pruning caused positive change for the throughfall kinetic energy from the standpoint of the first branch height. This increase trend was confirmed at any distance from the trunk (Fig. 5.26).

The influence of canopy thickness was estimated from the comparison of throughfall elements at [100] among T1–T4 because the points at [100] were absolutely covered with the canopies under any canopy structures. On the other hand, the influence of canopy edges was estimated from the comparison of throughfall element at [200] among T1–T3.

Influence of canopy thickness on throughfall generation process

The influence of canopy thickness on throughfall generation process was estimated with the comparison of the data at [100] among T1–T4. The throughfall elements fluctuated with thinning the canopy thickness. First, the canopy thickness affects the canopy water storage. Thinner canopy has less foliage so that the canopy water storage is smaller. The time lag required to stabilize throughfall intensity became shorter with the branch pruning (Fig. 5.19).

Second, the canopy thickness affected little in the throughfall intensity. Throughfall intensity during the stable phases fluctuated little among T1–T3 (Fig. 5.21).

Third, the canopy thickness affects the throughfall-DSD. The abundance ratio of drips, which were the drops with diameters > 3 mm, increased with the branch pruning (Fig. 5.24). Furthermore, the number of drops with diameters > 3 mm increased with the branch pruning; 240, 316, 472, and 559 under T1–T4, respectively (from Fig. 5.26). The result suggested that thinner canopy readily generate large drips than thicker canopy.

Forth, the canopy thickness affects the number and the ratio of drips generated from the upper canopy layers. The drips generated from the upper layers had higher velocities than the expected velocities from the first branch height. The drips generated from the upper layers increased with the branch pruning (Table 5.5). The result suggested that the drips generated from the upper canopy layers were re-intercepted by the lower canopy layers. When the canopy was thin, the possibility to be re-intercepted by the lower canopy layers decreased for the drips generated from the upper canopy layers. Thinner canopy readily had higher number and abundance ratio of large drops. In contrast, when the canopy was thick, the possibility rose and the drips were splashed into fine droplets by the impact onto the foliage in lower canopy layers. Thicker canopy readily had lower number and ratio of large drops. Consequently, it is suspected that thinner canopy had two positive influences for throughfall kinetic energy; the increase of the number and the ratio of large drops depend on the decrease of splash droplets, and the increase of the number and the ratio of drips with higher velocities generated from the upper canopy layers.

The influence of the canopy thickness to throughfall kinetic energy was discussed from the above four results. A process of generating kinetic energy is associated with rainfall intensity, DSD, and respective drop velocity. Throughfall intensity fluctuated little with the canopy thickness. On the other hand, with thinning the canopy thickness, the abundance ratio of large drops increased and the number and the ratio of drips with higher velocities increased. Figure 5.28 shows the unit kinetic energy in relation to the canopy structures with the distance from the trunk during the stable phases in Rain-L and Rain-H. The unit kinetic energy increased with the branch pruning at [100]. Consequently the branch pruning caused positive change for the throughfall kinetic energy from the standpoint of the canopy thickness. At the points absolutely covered with the canopies, throughfall kinetic energy increased with the branch pruning (Fig. 5.27).

Influence of canopy edges on throughfall generation process

The influence of canopy edges on throughfall generation process was estimated with the comparison

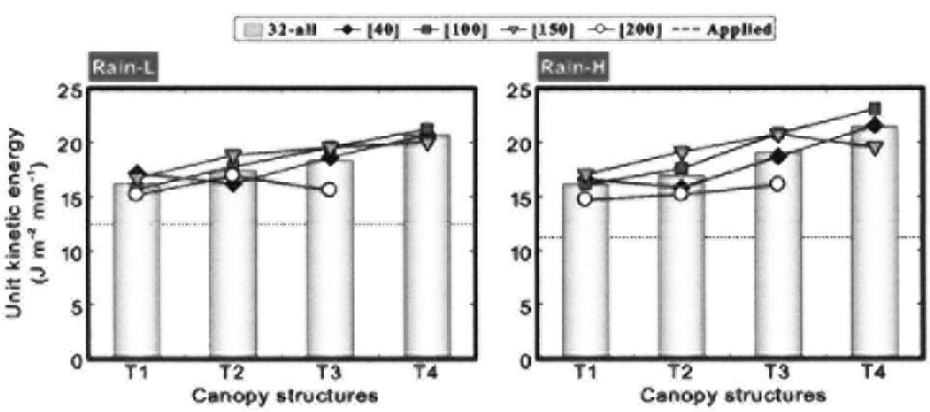

Figure 5.28 Throughfall unit kinetic energy in relation to the canopy structures with the distance from the trunk during stable phases in Rain-L and Rain-H. *Broken lines* represent the unit kinetic energy of the applied rainfall.

of the data at [200] among T1–T3. With the branch pruning, the points of [200] became outside of the canopy covers. The time lag required to stabilize throughfall intensity became shorter (Fig. 5.19) because the foliage amount decreased. Throughfall intensity decreased with the branch pruning (Fig. 5.21). The rainwater runs on the saturated canopies forward the edges of the canopies because the foliages grow down toward the apex (described in *'section 5.3.2'*). With the branch pruning, the points of [200] became out of the canopy covers, and decrease the receiving amount of the spilled water.

Under T4, throughfall intensity at [200] was almost same with the applied rainfall intensity because the points were absolutely out of the canopy covers, but had much larger throughfall intensity than the applied rainfall for four minutes after the change of rainfall intensity of the applied rainfall (Fig. 5.19). The sudden increase of rainfall intensity may increase the running components and the running water may arrive far from the canopy edges.

Second, the abundance ratio of drips decreased with the branch pruning (Fig. 5.24). Additionally, the number of drops with diameters > 3 mm decreased with the branch pruning; 808, 422, and 289 under T1–T3, respectively (Table 5.5). Consequently the DSD shifted to smaller sizes (Fig. 5.22) and the throughfall D_{50} became smaller in size (Fig. 5.23) with the branch pruning. The decrease of canopy cover caused the decrease of drips from the canopies and correspondingly the increase of the abundance ratio of the free throughfall component.

The influence of the canopy edges on throughfall kinetic energy was discussed from the results. With the decrease of the canopy covers, throughfall intensity decreased and the abundance ratio and the number of large drops decreased. The drop velocities increased with the branch pruning depend on the increase of first branch height, but most of drips were generated from the lower canopy layers adjacent to the canopy edge because of the thin canopy thickness. Therefore, the unit kinetic energy at [200] was lower than the other points with the distance from the trunk. Between T1 and T2, the unit kinetic energy increased; the effect of increase of drop velocity was higher than that of DSD. Throughfall kinetic energy fluctuated little under T1–T3 at [200]. The influence of the increase of drop velocities and the decrease of throughfall intensity and the abundance ratio of large drops offset each other. Throughfall may have a certain peak of kinetic energy with the distance from the trunk depend on the first branch height.

At [150], throughfall kinetic energy increased with the branch pruning under T1–T3., but there was little fluctuation between T3 and T4 (Fig. 5.27). The unit kinetic energy decreased from T3 to T4 (Fig. 5.28). Additionally, from T3 to T4, the abundance ratio of drops with diameters > 3 mm decreased (Fig.5.24). [150] was absolutely covered with canopies under T1–T3, but the canopy edge became closely to [150]. The average distance from the trunk to the canopy edges was 165 cm under T4. Approaching to the canopy edges caused the increase of throughfall intensity because of the running component on canopies. The peak of throughfall intensity with the distance from the trunk appeared adjacent to the canopy edges but the peak of throughfall kinetic energy appeared more inner side of the canopy edges compared with the throughfall intensity.

5.5 Conclusion

To estimate the influence of canopy structures for throughfall drop generation, the indoor laboratory experiment was conducted involving a transplanted Japanese cypress tree and water sprinklers. Throughfall amount and raindrops were measured at 32 points under four kinds of canopy structures created by the staged branch pruning. By the two steps of analyses of the experimental data, the followings were clarified.

First, the distance from the trunk affected the distribution of throughfall amount and intensity. The spatial variability of throughfall intensity was dominated by the distance from the trunk and generally increased as the radial distance from the trunk became further. The running component would exist in the process of rainwater flow in canopies. Rainwater applied around the center of the canopy may have spilled over to the edge of the canopy because of the canopy's conical shape.

Second, the canopy thickness affected the throughfall drop generation. The canopy thickness would determine the canopy storage and the probability to be re-intercepted drips generated from the upper canopy layers. The time lag required to stabilize throughfall intensity became shorter with the distance from the trunk and with the branch pruning. When the measuring points were covered with canopy foliage, the abundance ratio of large drops with diameters > 3 mm increased with the distance from the trunk and with the branch pruning. Furthermore, the number and the ratio of drips with higher velocities increased with the branch pruning. Consequently, throughfall kinetic energy increased with the distance from the trunk and with the branch pruning.

Third, the first branch height affected the drop velocities of drips generated from the canopies. The branch pruning increased the velocities of drips.

Forth, the process of throughfall drop generation adjacent canopy edge was shown. Adjacent to the canopy edge, throughfall comprised larger drops because of thin canopy thickness, but the drips had lower velocities because they were almost generated from the lower layers. Consequently, throughfall kinetic energy generally increased with the distance from the trunk but the increasing trend was less clear than the throughfall intensity. The peak of throughfall intensity with the distance from the trunk appeared adjacent to the canopy edges but the peak of throughfall kinetic energy appeared more inner side of the canopy edges compared with the throughfall intensity.