Title

Effect of canopy thickness and canopy saturation on the amount and kinetic energy of throughfall: an experimental approach

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Abstract

To investigate how canopy thickness and canopy saturation affect the amount and kinetic energy of throughfall, we conducted indoor experiments using a 9.8-m-tall transplanted Japanese cypress (*Chamaecyparis obtusa*) and a large-scale rainfall simulator with spray nozzles at a height of 16 m. The amount of throughfall and raindrop sizes and velocities were measured at twenty-four points under four canopy structures generated by staged branch pruning. Decreasing the canopy thickness resulted in increases of the initial throughfall amount, volume proportion of large throughfall drops, the number of drops with high velocities, and throughfall kinetic energy. Compared to a saturated canopy, a canopy undergoing wetting had lower throughfall amounts and volume proportion of large drops, but higher mean drop velocity. Canopy thickness affected throughfall generation by affecting the processes of canopy saturation and drop generation within the canopy.

1. Introduction

The impact of a raindrop is an important first step toward soil loss and subsequent sediment transport [e.g., *Ellison*, 1944]. Many studies have proposed the use of the kinetic energy of rainfall as an indicator of rainfall erosivity [e.g., *Mihara*, 1951; *Brandt*, 1990; *Morgan et al.*, 1998; *Kinnel*, 2005]. The forest canopy can modify the amount of rainfall and kinetic energy that reaches the ground surface by altering two main factors [*Wainwright et al.*, 1999]: raindrop characteristics and interception. Throughfall consists of three drop components: free throughfall, drips, and splash water droplets [*Nanko et al.*, 2006]. Compared to open rainfall, throughfall drops are larger in size because of the dripping effect [*Chapman*, 1948; *Nanko et al.*, 2004] and generally have lower velocity because they have a shorter fall height [*Laws*, 1941; *Wang and Pruppacher*, 1977; *Zhou et al.*, 2002]. However, in mature forests, throughfall drips may have sufficient fall heights to reach terminal velocity and greater kinetic energy compared to open rainfall [*Chapman*, 1948; *Mosley*, 1982; *Zhou et al.*, 2002; *Nanko et al.*, 2004]. The Brandt model [1990] is widely used to calculate throughfall kinetic energy, but *Nanko et al.* [2008] demonstrated that the Brandt model may overestimate kinetic energy because it does not incorporate the water splash component of throughfall. The water splash component is generated by rain-splash on the canopy, and thus various canopy structures should have different effects on the water splash component.

Furthermore, the canopy dissipates the amount of rainfall, resulting in substantial temporal and spatial variability of interception [*Keim et al.*, 2005; *Staelens et al.*, 2006]. Levia and Frost [2006] reviewed the findings of 163 studies and concluded that the temporal and spatial variability of throughfall was affected by both meteorological factors (e.g., event magnitude and wind speed) and canopy factors (e.g., interception storage and the leaf area index [LAI]). Studies of rainfall magnitude have indicated that the temporal stability of spatial throughfall patterns differs between small and large rainfall events [*Staelens et al.*, 2006] and that throughfall variability decreases with increases in the rainfall amount [*Bouten et al.*, 1992]. Therefore, the process of throughfall generation may vary by the degree of canopy saturation. The effects of canopy factors on the amount of throughfall and characteristics of raindrops can only be estimated by excluding the effects of varying meteorological factors.

In this study, we conducted indoor experiments using a 9.8-m-tall stand of transplanted Japanese cypress (*Chamaecyparis obtusa*) and a large-scale rainfall simulator with spray nozzles at a height of 16 m. Soil erosion in unmanaged Japanese cypress plantations poses a serious problem [e.g., *Akenaga and Shibamoto*, 1933; *Miura et al.*, 2002; *Fukuyama et al.*, accepted, 2007; *Gomi et al*, submitted, 2007; *Mizugaki et al.*, submitted, 2007], and solutions will require estimations of the amount and kinetic energy of throughfall. Our goal was to evaluate how canopy thickness (an easy-to-measure canopy factor) affects the amount and kinetic energy of throughfall under varied canopy saturation by measuring the amount, drop size, and drop velocity of throughfall.

2. Experimental Setup and Procedure

2.1. Experimental Facility

All experiments were conducted from September to October 2005 in the large-scale rainfall simulator at the National Research Institute for Earth Science and Disaster Prevention (NIED), Japan. This simulator is 49 m wide, 76 m long, and 21 m high; it sits on a bare-earth floor surface and has retractable sidewalls. Artificial rainfall is sprayed from 544 nozzles at a height of 16 m, which is sufficient for raindrops to reach the floor at terminal velocity. Four different types of wide-cone nozzles (D1/8G-4.3W, D1/8G-8W, D1/4G-14W, and D3/8G-20W, Spraying Systems Co., Wheaton, IL, USA) are capable of producing rainfall rates of 15 to 200 mm h^{-1} with pressures of 0.069 to 0.490 MPa [*Maki et al.*, 2005]. The total area can be divided into four quarters that can be sprinkled separately.

2.2. Applied Rainfall Event

Rainfall was applied with a rate of 39.8 mm h^{-1} for 15 min using the D1/4G-14W. This rainfall had smaller drop sizes and kinetic energy than natural rainfall of the same rate under field conditions. In the applied rainfall, the median volume diameter, D_{50}, and the maximum drop size were 1.10 and 2.66 mm, respectively. The applied rainfall took place in the simulator with the doors and windows closed under constant meteorological conditions of no wind, little canopy vibration, low raindrop impact to canopy surface, and little evaporation.

2.3. Transplanted Tree

One Japanese cypress (*Chamaecyparis obtusa*) was transplanted in the simulator. This tree was 21 years old, 9.8 m tall, and 22.6 cm in diameter at breast height (DBH). Four types of canopy structure were created using staged branch pruning to estimate the effect of canopy thickness. Each canopy had a first branch height of 2, 3, 4, and 5 m, canopy thickness of 7.8, 6.8, 5.8, and 4.8 m and LAI of 11.1, 10.1, 8.0, and 6.3; these respective canopies are referred to as T1, T2, T3, and T4 (Figure 1).

2.4. Data Collection

Thirty-two measuring points were established under the canopy, positioned radially in eight directions (Figure 1). We placed four points 40, 100, 150, and 200 cm from the trunk in each direction (Point-40, Point-100, Point-150, and Point-200, respectively). The amount of rainfall was measured using 32 tipping-bucket rain gauges (tipping at 0.254 mm; RC-10; Davis Instruments Corp., Hayward, CA, USA) set on a platform located 50 cm above the ground surface to prevent the backsplash of drops from the surface; the tip time was recorded with 0.5-s accuracy using a data logger (HOBO Event; Onset Computer Corp., Bourne, MA, USA). The throughfall rate was simultaneously measured at all the measuring points for each canopy structure; rainfall for each event was applied more than 2 days after the previous application.

Drop sizes and velocities were measured using four laser drop-sizing (LD) gauges consisting of a paired laser transmitter and receiver, as described by *Nanko et al.* [2006]. When a raindrop passes through the laser sheet, the output voltage from the receiver is reduced in proportion to the intercepted area. Detailed explanations of the measurement principle, the calculation procedure, and the reliability estimation have been provided by *Nanko et al.* [2008]. A screen net was affixed to the platform 15 cm above the ground surface to prevent backsplash of drops from the surface. The LD gauges were placed on a platform located 30 cm above the ground surface, lower than the rain gauges. The measurements of throughfall drops at all 32 points under T1, T2, and T3, respectively, and 24 points except for Point-200 under T4 were achieved by relocating the LD gauges. Even if the process of throughfall drop generation changed over time and among rainfall events, a given rainfall event would result in the same effects on the amount of throughfall and throughfall drops because of the constant meteorological conditions in the indoor simulator.

In this study, we did not use the data collected at Point-200. We mainly use mean value among 24 points under each canopy structure. Individual measured data at each point were shown as online auxiliary materials (Dataset 1 – 6).

3. Results and Discussion

3.1. Temporal Variation in Throughfall Rates

The throughfall amount and rate differed with canopy thickness (Figure 2, Dataset 1 and 2). At the beginning of an event, the throughfall rate was lower than the applied rainfall rate because water was used to saturate the canopy. The time lag required to stabilize the throughfall rate shortened and mean throughfall amount increased as canopy thickness decreased: 8, 5, 4, and 4 min, and 6.9, 7.9, 8.1 and 10.5 mm for T1, T2, T3, and T4, respectively. T4 resulted larger mean throughfall amount than the applied rainfall (=10.0 mm) because two measuring points near the trunk (Point-40-7 and Point-40-8) yielded more than twice the amount of applied rainfall, 24.1 and 23.1 mm, respectively. Previous studies found that concentrated throughfall was often observed close to a tree trunk [*Ford and Deans*, 1978; *Robson et al.*, 1994]. The mean throughfall amount without the two points under T4 was 9.3 mm.

To estimate the effect of canopy saturation on throughfall generation, two phases were defined: the initial phase (0–5 min), when the canopy was moving toward saturation, and the stable phase (10–15 min), when the canopy was saturated.

3.2. Drop Size of Throughfall

Throughfall drops were larger in size than the applied raindrops. Drops with diameters > 3 mm were considered to be generated by dripping because the applied rainfall consisted of the drops with diameters of less than 2.66 mm.

The mean volume of throughfall drops, which is the volume of all drops with diameter > 3 mm divided by the total throughfall drops, differed with canopy thickness and canopy saturation (Figure 3). Drops had a lower volume proportion during the initial phase than during the stable phase for all canopy structures; for example, the mean proportion for T1 was 24% during the initial phase and 33% during the stable phase. This indicates that throughfall generated from a saturated canopy was composed of larger drops than throughfall generated from a canopy that was not yet saturated. In addition, differences in drop volume proportions between the phases decreased as the canopy thickness decreased. As canopy thickness decreased, drop volume proportions increased during both phases: from T1 to T4, volume proportions increased from 24 to 36% during the initial phase and from 33 to 40% during the stable phase, respectively.

The volume proportion varied spatially among the measuring points, particularly during the initial phase. The coefficients of variation (CVs) were 57, 53, 35, and 44% during the initial phase and 33, 37, 29, and 32% during the stable phase for T1, T2, T3, and T4, respectively. While undergoing wetting, large spatial variability was found on the ease of large drop generation.

3.3. Drop Velocity of Throughfall

Few drops came close to reaching terminal velocity (Figure 4). During the stable phase under all canopy structures, > 90% of the drops had < 95% terminal velocity. The fall height was insufficient for drops to gain terminal velocity. Raindrops with diameters > 3 mm must fall at least 12 m to reach terminal velocity [*Wang and Pruppacher*, 1977].

The drop velocity distribution differed with canopy thickness. During the stable phase, the mean drop velocity increased as canopy thickness decreased (Figure 4), with values of 6.7, 7.0, 7.3, and 7.6 m s^{-1} for T1, T2, T3, and T4, respectively. The number of drops with lower velocities decreased, whereas the number of drops with higher velocities increased. Slow drops (velocity < 6 m s^{-1}), which are expected to be generated by a canopy height of < 2 m, represented 32, 20, 8, and 4% of the total drops under T1, T2, T3, and T4, respectively. The falling height of drops generated from the lowest canopy layers increased as the first branch height increased. In contrast, fast drops (velocity > 7.5 m s^{-1}), which are expected to be generated by a canopy height of > 5 m, represented 27, 32, 41, and 53% of the total drops under T1, T2, T3, and T4, respectively. The estimated mean drop fall height was close to the height of the first branch, following the assumption set out by Brandt [1990], at 3.8, 4.5, 5.1, and 5.4 m for T1, T2, T3, and T4, respectively.

The distribution of drop velocity differed with canopy saturation, particularly under thicker canopy structures. For all canopy structures, the initial phase yielded fewer drops than the stable phase, but throughfall in the initial phase was consisted of faster drops than the stable phase. The differences of the number proportion of the fast drops between the initial phase and the stable phase were 15, 10, 7, and 5% under T1, T2, T3, and T4, respectively. During the initial phase, the lower canopy layers were not saturated and thus the upper canopy layers allowed more drops to be generated compared to the lower canopy layers.

3.4. Drop Generation and Kinetic Energy of Throughfall

Canopy thickness affected the amount and drop generation of throughfall because the canopy water storage and re-interception possibilities of the drops changed. A thinner canopy like T4 requires less water to saturate the canopy and allows for a higher volume proportion of large drops. In contrast, a thicker canopy like T1 requires more water for canopy saturation, allowing a lower volume proportion of large drops. As the canopy thickness increased, the possibility for re-interception by the lower canopy layers increased, and the drops were splashed into fine droplets via impact with the foliage of the lower canopy layers. Consequently, the drop volume proportion decreased as the canopy thickness increased (Figure 3).

The experiments revealed that the kinetic energy of throughfall was greater than that of the applied rainfall. Furthermore, thinner canopies generated greater kinetic energy than thicker canopies and sufficiently saturated canopies generated greater kinetic energy than canopies undergoing wetting. The applied rainfall yielded a unit kinetic energy (i.e., the kinetic energy per unit area and unit volume of precipitation) of 12.7 J m^{-2} mm^{-1}. The throughfall yielded mean unit kinetic energies of 15.9, 16.5, 17.7, and 19.6 J m^{-2} mm^{-1} during the initial phases and of 16.6, 17.6, 19.2, and 20.7 J m^{-2} mm^{-1} during the stable phases of T1, T2, T3, and T4, respectively. The initial phases yielded lower unit kinetic energy than the stable phases.

4. Conclusion

This experimental study revealed the effect of canopy thickness and canopy saturation on the amount and kinetic energy of throughfall. Decreasing the canopy thickness resulted in increases in the initial throughfall amount, volume proportion of large drops, the number of drops with higher velocities, and kinetic energy. Compared to saturated canopies, canopies undergoing wetting had lower throughfall amounts and volume proportions of large drops, but higher mean drop velocities. Canopy thickness affected the amount, drop generation, and kinetic energy of throughfall due to the change in canopy water storage and re-interception possibilities of drops within the canopy.

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Figure Captions:

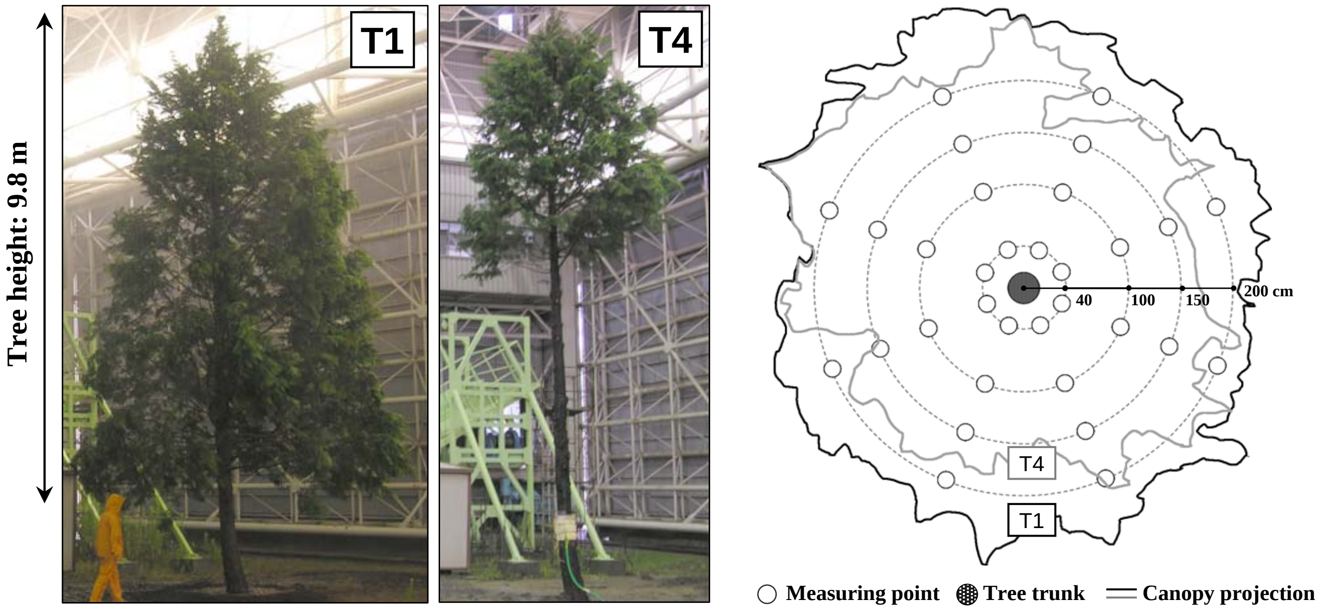
Figure 1. The experimental canopy structures (T1 and T4) and 32 measuring points under the canopy.

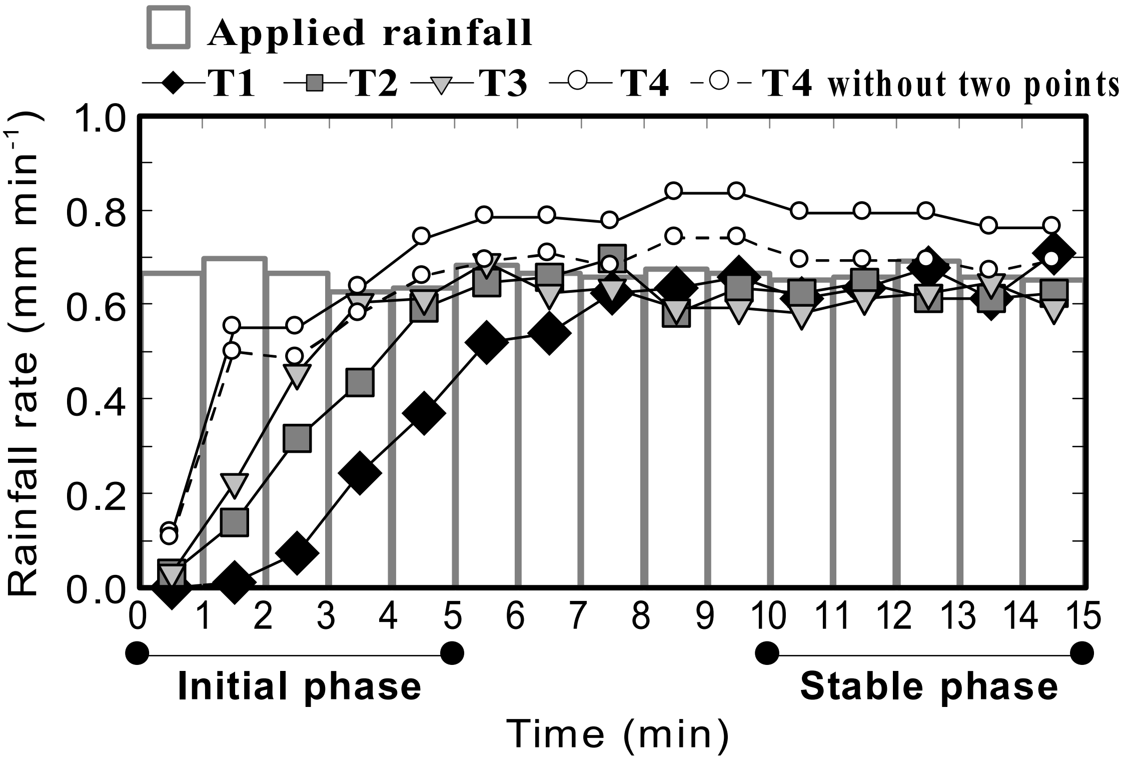
Figure 2. Temporal variation in the mean rainfall rate for the applied rainfall and throughfall under four canopy structures. A broken line of T4 is the mean

throughfall rate without two measuring points (Point-40-7 and Point-40-8), yielded more than twice larger throughfall amount than the applied rainfall.

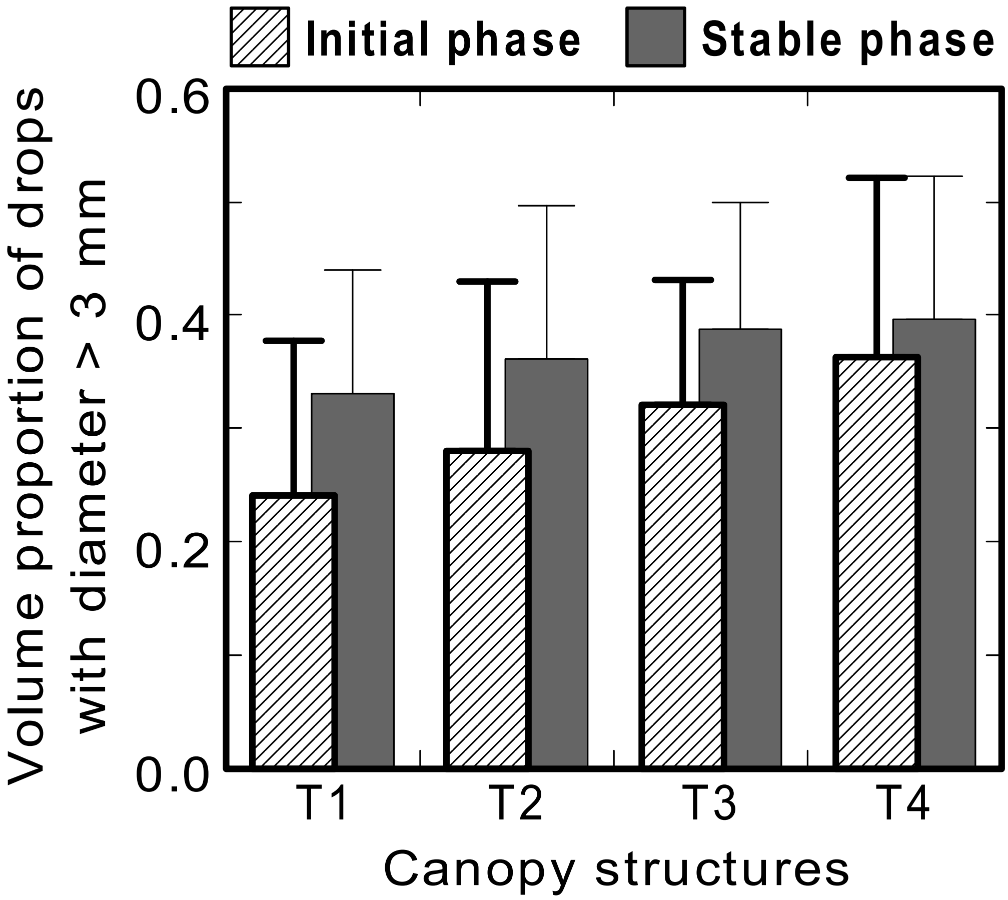
Figure 3. Mean volume proportion of drops with diameters > 3 mm under four canopy structures during the initial and stable phases.

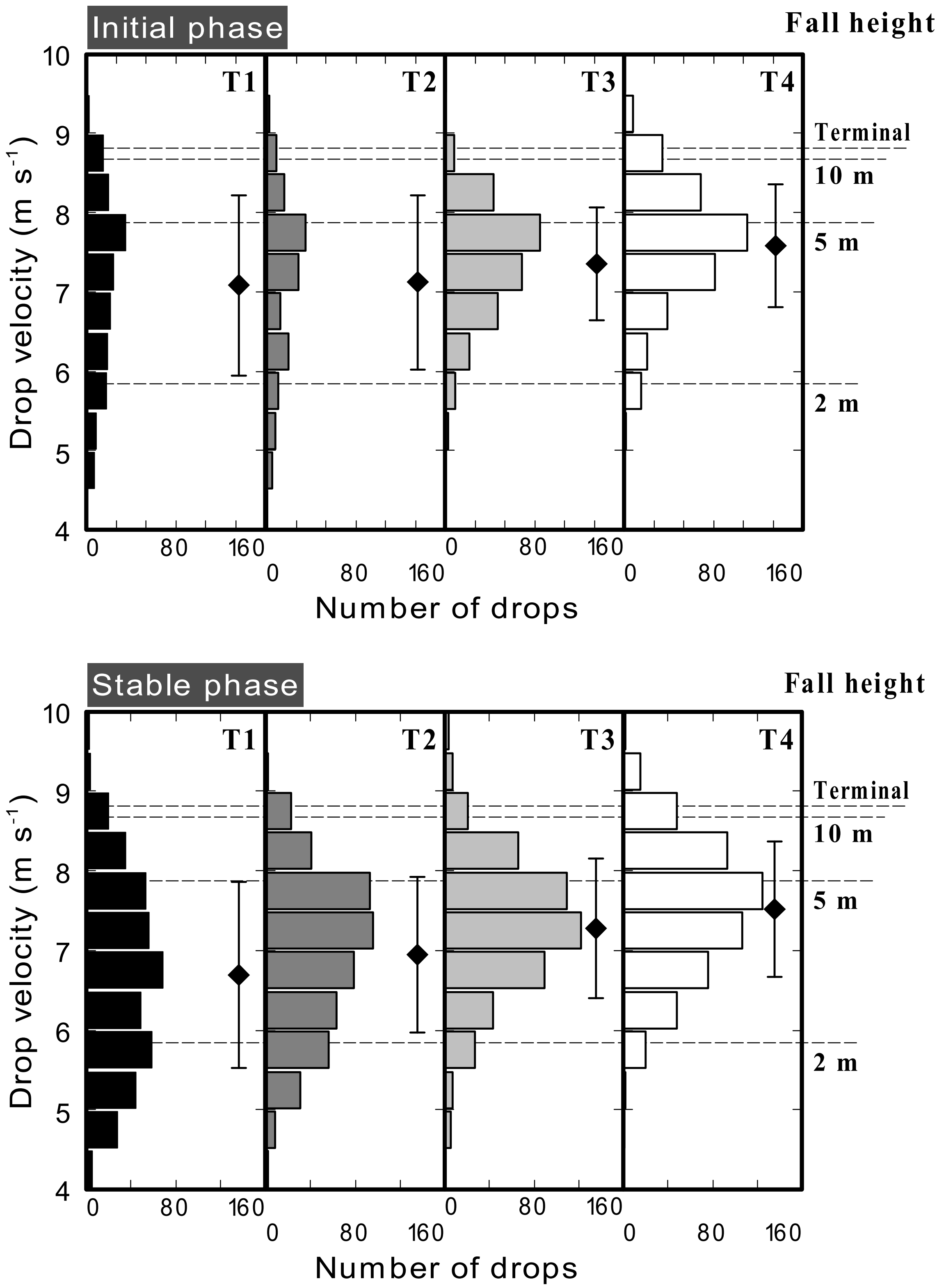
Figure 4. Distribution of drop velocity under four canopy structures during the initial (upper) and stable (lower) phases. Plots represent mean velocity. Broken lines indicate the expected velocity of drops with a diameter of 4 mm falling from heights of 2, 5, and 10 m, and the terminal velocity, respectively, as set out by *Zhou et al.* [2002].


Tree height: 9.8 m
T1
T4
40
100
150
200 cm
T4
T1
Measuring point
Tree trunk
Canopy projection



Applied rainfall
T1
T2
T3
T4
T4 without two points
Rainfall rate (mm min-1)
1.0
0.8
0.6
0.4
0.2
0.0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
Initial phase
Stable phase
Time (min)


Initial phase
Stable phase
Volume proportion of drops with diameter > 3 mm
0.6
0.4
0.2
0.0
T1
T2
T3
T4
Canopy structures


Initial phase
Fall height
T1
T2
T3
T4
Terminal
10 m
5 m
2 m
Drop velocity (m s-1)
Number of drops
Stable phase
Fall height
T1
T2
T3
T4
Terminal
10 m
5 m
2 m
Drop velocity (m s-1)
Number of drops