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A New Approach in Measuring Rainfall Interception by Urban Trees in Coastal British Columbia

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Interception loss plays an important role in controlling the water balance of a watershed, especially where urban development has taken place. The aim of this study was to illustrate the importance of urban trees as a form of 'green infrastructure' where they reduce stormwater runoff and rainwater intensity. In addition, trees cause a delay in precipitation reaching the ground. Interception loss was studied in the North Shore of British Columbia. We applied a unique methodology for measuring throughfall under six different urban trees using a system of long polyvinyl chloride pipes hung beneath the canopy capturing the throughfall and draining it to a rain gauge attached to a data logger. Different tree species (Douglas-fir [*Pseudotsuga menziesii*] and western red cedar [*Thuja plicata*]) in variable landscape sites (streets, parks, and natural forested areas) and elevations were selected to ensure that the system adequately captured the throughfall variability. Interception and throughfall were monitored over a one year cycle for which the results of seven discrete storm events for coniferous trees from the District of North Vancouver during 2007 to 2008 are presented. Cumulative gross precipitation for seven selected events was 377 mm. Average canopy interception during these events for Douglas-fir and western red cedar were 49.1 and 60.9%, where it corresponded to average net loss of 20.4 and 32.3 mm, respectively. The interception loss varied depending on canopy structure, climatic conditions, and rainfall characteristics.

Key words: **urban environment, throughfall, interception loss, stormwater runoff**

Introduction

Urbanization has resulted in profound changes to natural watershed conditions by altering terrain, vegetation, soil characteristics, and surface conditions. Urban development impacts climatic conditions and alters the hydrological processes leading to more flashy runoff and increased pollution in urban watersheds (Sanders 1986; McPherson et al. 1997). The losses in vegetation cover and increases in impervious surfaces, such as paved roads, sidewalks, and concrete buildings, increase the total amount of runoff, the flashiness of runoff events, flooding, erosion, and the cost of stormwater management. Villarreal and Bengtsson (2004) noted that stormwater runoff prior to development was regulated by trees, vegetation, and natural soils. Trees and soil function together to reduce stormwater runoff. Trees reduce stormwater runoff by intercepting rainwater on leaves, branches, and trunks. Some of the intercepted water evaporates into the atmosphere and some infiltrates into the ground, decreasing peak flows and the total amount of urban runoff. Trees also slow storm flow events by reducing the volume of water that must be managed at one time and the rainfall intensity. Trees are generally overlooked in urban planning, but they are an integral component of the urban infrastructure, capable of controlling the hydrological processes, regulating air and water quality, reducing Urban Heat Islands (UHI) and absorbing CO_2 (Sanders 1986; Taha 1997).

Stormwater managers have started to use trees as a tool to help reduce stormwater generation and, in this way, reduce the cost of constructing traditional stormwater control infrastructure. The value of the tree for stormwater management has been calculated based on the avoided costs of handling stormwater runoff (McPherson et al. 1997; Zipperer et al. 1997; Villarreal and Bengtsson 2004). McPherson et al. (2005) reported that in some cities in the U.S.A., the urban tree investment can be between $13 to $65 per tree annually in planting and maintenance cost. In return, gains in stormwater services are between $1.37 to $3.09 per dollar that would have otherwise been invested in traditional stormwater management. Another study has estimated the worth of the U.S.A.'s urban forests as $400 billion in terms of stormwater management mitigation alone (American Forests 1996). These studies demonstrate the importance of trees as source controls capable of treating stormwater at the site level by reducing the runoff component within the hydrological cycle.

Urban vegetative cover is arranged as individual or stands of trees that contribute to the sustainability of the environment. From an urban hydrological point of view, the most noticeable effect of vegetation is rainfall interception by the canopy (Xiao and McPherson 2002; Guevara-Escobar et al. 2007; McJannet et al. 2007a, 2007b). Canopy interception losses frequently modify the intensity and distribution of precipitation reaching

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the ground. Trees retain water on site temporarily or permanently, slowing the flow to waterways. Horton (1919) and Rutter et al. (1975) classified canopy interception (I_{net}) into various components: a fraction of gross precipitation (P_G) that falls as throughfall (p), the proportion that is diverted to stemflow (p_t), and the proportion that is stored and evaporated. Canopy interception represents the difference between gross precipitation (above canopy) and net precipitation (below canopy) (Jetten 1996; Aboal et al. 1999; Xiao et al. 2000a, 2000b).

Previous studies on rainfall interception, primarily carried out in naturally forested areas, report a wide range of values for interception losses, throughfall, and stemflow. Interception loss is commonly 20 to 40% in coniferous, and between 10 to 20% in deciduous forests (Crockford and Richardson 1990; Llorens et al. 1997; Link et al. 2004; Llorens and Domingo 2007). The amount of interception loss is highly dependent on forest structure (e.g., species, dimension, density), canopy structure (e.g., foliation period, leaf and stem surface areas, gap fraction, surface detention storage capacity) and meteorological factors (e.g., rainfall amount, duration, intensity, frequency, temperature, wind, humidity) (Crockford and Richardson 2000; Xiao and McPherson 2002; Nadkarni and Sumera 2004).

While considerable research concerning the impact of tree interception loss on hydrological processes has been conducted in forested areas, the effects of urban trees on rainfall interception and runoff have not been well quantified. The characteristics of trees in forested areas are different from those in urban settings in terms of available growing space, canopy cover, age, diversity, and microclimate (Zipperer et al. 1997; Xiao and McPherson 2002; Wang et al. 2008). The measurement and monitoring methods involved in closed forested areas ranged from troughs and rain gauges to plastic sheets; however, it has been suggested that most of these common sampling techniques cause large errors in the estimated interception (Horton 1919; Xiao et al. 2000b; Link et al. 2004). It is important to note that sampling design that captures the throughfall variability is key in determining the accuracy and time resolution of obtained data (Lundberg et al. 1997; Keim et al. 2005). These studies illustrate that rainfall interception by forests is extremely variable and difficult to measure.

In urban settings, field observations and experimental measurements of rainfall interception processes are sorely needed in order to better understand these processes. Urban tree interception processes are somewhat different from those reported for natural forests as a result of various factors such as edge effect, isolation (greater distances between individuals), open canopies, higher temperatures, and wind penetration and associated rainfall (Zipperer et al. 1997; Guevara-Escobar et al. 2007). These characteristics define the storage capacity for each stand or individual tree, and control the evapotranspiration rate.

The objective of this paper was to gain a better understanding of the rainfall interception processes for a large number of urban trees, and to quantify the throughfall and estimate the interception losses using an innovative monitoring approach.

Methods and Materials

To address the objectives of this research with regard to rainfall interception, throughfall for six coniferous trees was measured along the North Shore (North Vancouver) in British Columbia during 2007 to 2008. The selected trees were located on private and public properties along streets, parks, and in forested areas.

Study Site and Climate

North and West Vancouver are highly urbanized cities with increasing urban development that resulted in the creation of larger proportion of impervious surfaces. The dominant land use in these municipalities is residential, followed by industrial and commercial areas. The major rivers and creeks pertaining to these areas are: Capilano, MacKay, Mosquito, Lynn, and Seymour. The major concern regarding these waterways is the direct drainage of stormwater runoff into the rivers leading to flooding and nonpoint sources of pollution (Environment Canada 2007).

The regional climate is characterized by cool, wet winters and warm, moderate summers. In Vancouver it is common to have more than 166 days per year with measurable precipitation on average. These coastal rainfall events are described as long durations with low intensities. The average annual precipitation near sea level ranges from 1,200 to 3,000 mm at higher elevations, with most of the rainfall occurring in the winter. The amount of precipitation varies with elevation, increasing by about 100 mm for every 100 m rise in altitude. Consequently, the North Shore receives more rain and snowfall at higher elevations during the winter. The average annual temperature is 10°C at sea level (Environment Canada 2007).

Experimental Design and Instrumentation

Tree selection. The experimental setup focused on the direct measurement of throughfall for coniferous trees. The main coniferous species selected were Douglas-fir (*Pseudotsuga menziesii*) and western red cedar (*Thuja plicata*). The trees were classified into different types: dominant, codominant, single, and forested area (control). Dominant species were the main overstory trees in a plant community, which contributed the most cover or basal area to the community. Trees with crowns receiving full light from above, but comparatively little from the sides, were defined as codominant species. Single standing trees were exposed to light and wind from all sides. Forested areas were used as control sites, where trees were embedded within large groups of trees independent from any edge effect; these areas have little or no development (Oke et al. 1989; Zipperer et al. 1997; Brooks et al. 2003).

Tree health condition was also assessed because it reflects the structural integrity. This assessment helped indicate patterns of throughfall for individual trees. The rating of tree condition involved analysis of the tree crown and the density of foliage. Two different classes were assessed based on density of the canopies for coniferous trees as good and poor. Tree health conditions in control sites were not evaluated as they were considered to be away from urban areas. These controls were assumed to be representative of health conditions in forested settings, which are naturally variable.

Throughfall measurement. The experimental unit built under each tree consisted of four components: a wooden frame, PVC (polyvinyl chloride) pipes, a rain gauge, and a data logger. The wooden structure included a platform on which the rain gauge was placed. Four metal rods supported a wooden roof and held the platform together. This frame was mounted directly to the trunk of the tree. Two PVC pipes were used per experimental unit. They were hung at an angle from branches using ropes and bolts. The two pipes were positioned underneath the canopy of each tree based on the shape and structure of the tree in a way that the entire diameter of the canopy was covered. The length of each pipe was approximately 3-m long, where three 0.85-m by 0.028-m slits were cut on top along the length of each pipe providing the total surface area of 0.1428 m^2. The throughfall was captured by these openings and drained into a tipping bucket rain gauge (RAINEW, RainWise Inc., Bar Harbor, Maine). Data loggers (HOBO, Onset Computer Corporation, Pocasset, Mass.) attached to the rain gauges recorded both the air temperature and rainfall events of the canopy. The temperatures recorded by the data loggers accounted for within-canopy temperature variation, which is suggested to change along the vertical gradient and have a minor impact on canopy interception responses (Jetten 1996; Brooks et al. 2003). Overall, this flexible system allowed independent movement of the different components of each experimental unit without causing any serious damage to the entire structure (Fig. 1).

Meteorological station. Gross precipitation was measured using control units of the same design (Fig. 2). These units were positioned on the rooftops of buildings away from any structures that may block rainfall. Figure 3 illustrates the proximity of the six study sites in the District of North Vancouver to the rain gauge on the rooftop. Additional climate stations were set up in each municipality to capture the meteorological variability along the elevation gradient. These climate stations were within a 5-km radius of the study sites. Each station was equipped to measure barometric pressure, temperature, humidity, rainfall, wind speed, and direction. These supplemental records were utilized to validate the tipping rain gauge data, thus ensuring correct identification of rainfall events.

Fig. 1. The rainfall interception measuring system.

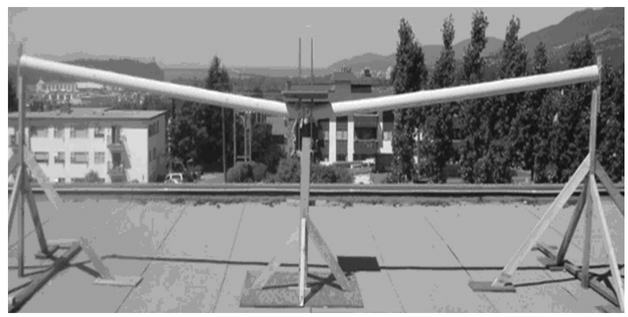

Fig. 2. Reference experimental system installed on the rooftop of North Vancouver's City Hall to measure gross precipitation (above canopy rainfall).

Data collection and calibration. The data loggers were programmed to record the number of tippings where these numbers were converted into total amount of gross precipitation/throughfall and intensity readings. The climate stations and rain gauges were calibrated after the installation in the field.

Methods for calculation. Table 1 shows the location and assessed attributes for the selected trees. Rainfall events were defined as storms with cumulative gross precipitation exceeding 1 mm, with a minimum of four hours without precipitation between events. Numerous events were eliminated due to clogging of rain gauges by leaves in late autumn and ice during the winter season when temperature fell below 0°C.

In this study, stemflow was not measured since it is considered to be a minor component of the water balance for mature canopies especially conifers, where the branches slope downward from the stem. This structural characteristic minimizes the probability for intercepted water to be routed to the stem, even if a small amount of precipitation intercepted in the upper canopy

Fig. 3. Locations of study sites and the rooftop rain gauge in the District of North Vancouver (orthophotos provided by District of North Vancouver's GIS Department).

TABLE 1. Characteristics of the selected experimental trees including their location and tag numbers

Tag #	*Tree species*	*Longitude*	*Latitude*	*Tree type*	*Condition*	*Height (m)*	*Diameter at breast height (cm)*
586	Douglas-fir	-123.078936	49.336042	Dominant	Poor	32	66
585	Douglas-fir	-123.078469	49.335931	Single	Good	35	78
590	Douglas-fir	-123.079685	49.336425	Single	Poor	39	68
587	Cedar	-123.078917	49.336200	Codominant	Good	29	70
588	Cedar	-123.078894	49.336311	Codominant	Poor	29	43
591	Cedar	-123.078558	49.338600	Single	Good	32	95

TABLE 2. Rainfall depth from two other nearby stations [a]

Event	**Duration of Measurement**	*Rain gauge on [b] therooftop of District of North Vancouver*	*Standard climate [b] station in the District of North Vancouver*	*Rain gauge on [c] rooftop of City of North Vancouver*
		P_G (mm)	***P_G (mm)***	***P_G (mm)***
1	October 15–23, 2007	209.6	205	205.9
2	November 3–4, 2007	26.6	31.2	28.6
3	December 18–19, 2007	39.7	39.6	37.8
4	January 2–3, 2008	28.2	31.8	29.9
5	March 16–17, 2008	22.6	25.2	20.6
6	May 13–14, 2008	26.3	24	— [d]
7	June 9, 2008	23.8	24.2	—

[a] P_G = gross precipitation.
[b] Elevation = 130 m.
[c] Elevation = 110 m.
[d] Missing data for two events.

still contributes to stemflow. In addition, the bark is ridged and ruffled where it absorbs greater amounts of water. The absorption of water by epiphytes and various moss species on branches and tree trunks also play a role in controlling the stemflow. As a result we assumed the stemflow to be insignificant, based on the results of previous research studies (Crockford and Richardson 1990; Brooks et al. 2003; Link et al. 2004; Llorens and Domingo 2007).

For this investigation we computed the total volume of throughfall captured underneath each tree for individual events by using the total number of tippings and the obtained volume from calibration. To note, the difference between the surface areas of the PVC pipes and the rain gauge (which is 4.2) was taken into account. Canopy interception was derived from the difference between the P_G and p for individual events. The data for P_G was obtained from the reference climate station on the rooftop of the District of North Vancouver; however, for comparison, Table 2 includes P_G from a standard climate station in the District of North Vancouver, and a nonstandard rain gauge on the rooftop of North Vancouver's City Hall.

Results

The high spatial and temporal resolution of the throughfall data enabled us to determine canopy interception losses for a wide range of trees (Xiao et al. 2000b; Link et al. 2004). The selected trees were differentiated by species, type, and health condition.

Seven discrete storm events were chosen between October 2007 and June 2008. Table 3 highlights the event characteristics. Selected events generated 377 mm of gross precipitation with a maximum hourly rainfall intensity of 13.3 mm/hr. This intensity corresponds to a two-year event in this area (Denault et al. 2006). These obtained results reflect on the rainfall characteristics in the North Shore, where the frontal system during October through April produces long durations and relative low rainfall intensities.

Climate and Precipitation Variability During an Event

Precipitation and above- and within-canopy climate data for Douglas-fir and western red cedar for event 3 are shown in Fig. 4 and 5. These figures show the effect of the urban tree canopies on throughfall intensity, and demonstrate the range of conditions controlling interception loss during the rainfall event.

Event 3 began at 0500 hours on December 18 and lasted 39 hours. During this period, 39.7 mm of precipitation was recorded by the reference rain gauge on the rooftop of North Vancouver's District Hall. Precipitation intensity, humidity, wind speed, and temperature were typified as moderately low. Figures 4a and 5a illustrate that there was not much variation between the measured temperatures above and below the canopy for both species. Wind speed was recorded below 0.1 $m \cdot s^{-1}$, indicating absence of wind during the event. Average humidity was above 95%. The amount of throughfall captured underneath each canopy averaged 50.1 and 46.2% (19.9 mm and 18.3 mm) for Douglas-fir and western red cedar, respectively.

Figures 4b and 5b show that throughfall levels for both species are not constant, but they are dynamic. The difference in gross precipitation and net precipitation magnitude is shown in Fig. 4c and 5c. Table 4 presents the delay in throughfall reaching the ground for all study sites. The delay ranged from 6 to 7.5 hours for event 3. This delay did not affect the peak in net precipitation; however, as shown by Xiao and McPherson (2002), this delayed the peak runoff for a storm. Throughfall ceased roughly 3.8 hours after the rainfall stopped.

The average rainfall intensity for event 3 was determined by dividing the gross precipitation by the rainfall duration. Figures 4c and 5c illustrate the impact of canopy on throughfall intensity, and exemplify how the climatic conditions control evaporation during the rainfall event. Both temperature and wind are suggested to play an important role in driving the evaporation rate, however, wind was omitted due to low velocities, which were less than 0.1 $m \cdot s^{-1}$ (Brooks et al. 2003; Link et al. 2004).

TABLE 3. Event characteristics

Event	*Duration of Measurement*	*Duration (h)*	*P_G (mm)*	*Average rainfall intensity (mm/h)*	*Maximum Rainfall intensity (mm/h)*	*Average temperature (°C)*	*Wind speed (ms^{-1})*
1	October 15–23, 2007	179	209.6	1.1	13.3	9.6	0.006
2	November 3–4, 2007	31.2	26.6	0.8	7.3	8.6	0.03
3	December 18–19, 2007	39	39.7	1.0	6.9	4.8	0.03
4	January 2–3, 2008	24	28.2	1.2	8.7	6.1	0.03
5	March 16–17, 2008	20	22.6	1.1	3.3	3.5	0.006
6	May 13–14, 2008	25	26.3	0.9	3.0	9.7	0.006
7	June 9, 2008	15	23.8	1.6	8.4	8.6	0.006

[a] P_G = gross precipitation.

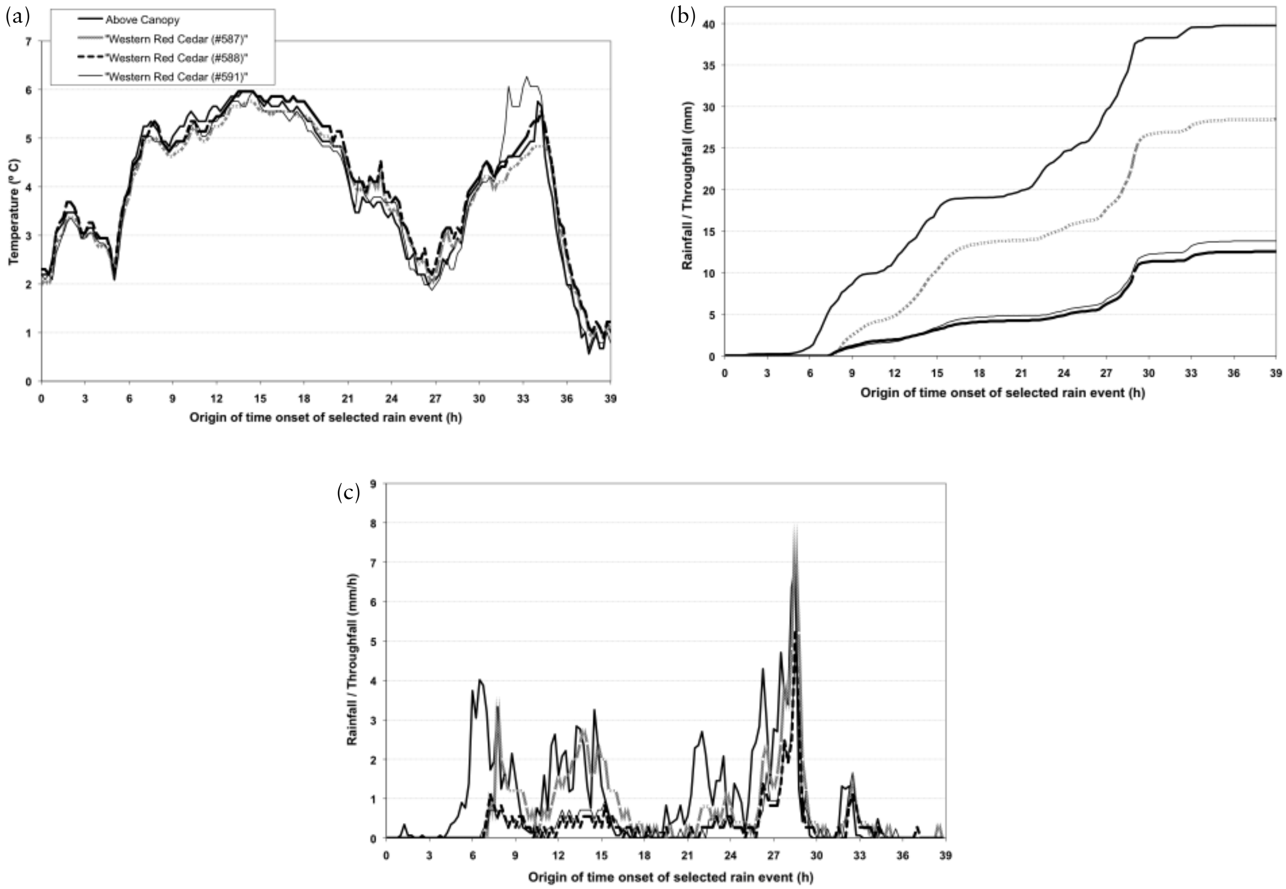

Fig. 4. Meteorological and throughfall data for rainfall event three (western red cedar).

TABLE 4. Delay in throughfall with respect to gross precipitation

Tag #	*Event 1 Start time (h)*	*Event 2 Start time (h)*	*Event 3 Start time (h)*	*Event 4 Start time (h)*	*Event 5 Start time (h)*	*Event 6 Start time (h)*	*Event 7 Start time (h)*
586	28	0.2	9.5	2.5	0.2	11.0	4.2
585	—	—	7.5	2.5	0.2	8.7	4.7
590	8.5	0.2	6.5	2.2	0.2	0.2	1.0
587	27.7	0.2	7.5	2.7	0.5	6.7	4.0
588	28	0.2	7.2	3.0	0.5	10.5	2.0
591	45.5	1.0	6.5	2.7	0.2	6.5	5.2

TABLE 5. Precipitation and interception summary[a]

Tag #	*Event 1* I_{net} *(%)*	*Event 2* I_{net} *(%)*	*Event 3* I_{net} *(%)*	*Event 4* I_{net} *(%)*	*Event 5* I_{net} *(%)*	*Event 6* I_{net} *(%)*	*Event 7* I_{net} *(%)*
586	44.4	24.0	49.5	9.0	70.5	98.3	78.3
585	—	—	52.6	25.1	76.9	88.5	77.3
590	10.9	15.4	48.10	17.4	57.9	80.5	60.3
587	40.3	31.3	28.3	5.4	53.1	70.8	60.1
588	68.6	67.5	68.4	49.2	76.0	95.3	72.8
591	73.7	56.6	65.20	51.2	70.6	94.0	80.3

[a] I_{net} = canopy interception.

Throughfall and interception loss. Interception loss was defined as the difference between the total gross and total net precipitation. Table 5 summarizes throughfall and interception losses for the selected trees and events. For events 1 and 2 there are no data available for one of the Douglas-fir trees (# 585) due to rain gauge failure (clogging).

When evaluating the average interception losses, it is evident that two of the cedar trees (# 588 and 591) showed the highest interception losses compared with the other selected trees during the events in the fall and winter. Both western red cedar trees were codominant; however, one was of good health condition and the other, poor. Events 5, 6, and 7 occurred during the spring and summer, where both Douglas-fir and western red cedar had high interception losses. The highest interception loss calculated was in event 6 by a dominant Douglas-fir of a poor condition. Based on the results, compared with western red cedar, the Douglas-fir trees showed a wider range of interception losses during the seasons.

Event 5 was the smallest precipitation event with relatively moderate levels of interception loss for all selected trees. Event 7 had the shortest duration in comparison with the other selected events. The highest interception loss was seen for event 6 with 26.3 mm of gross precipitation over 25 hours. The average temperature was recorded as 9.7ºC with a maximum rainfall intensity of 3.0 mm/hr. In general, rainfall type plays a role in determining interception loss. For instance, a low intensity, long-duration frontal rainfall generates a different interception loss than a high intensity short duration convectional storm (Xiao et al. 2000a, 2000b; Pypker et al. 2005; Deguchi et al. 2006).

Discussion

The measurement of throughfall using gauges under individual tree canopies has been successfully conducted to estimate interception loss. The methodology applied in this research is innovative and has not been applied in any other research within urban environments. The measuring system was easy to build and install, and the design minimized evaporation and splashing. These experimental units had the ability to collect spatially variable throughfall underneath the canopy.

Net interception loss is determined as the difference between gross precipitation and the sum of throughfall and stemflow. In this study, we did not include the stemflow since it was assumed to be negligible. Based on the obtained throughfall data, the average percent I_{net} for

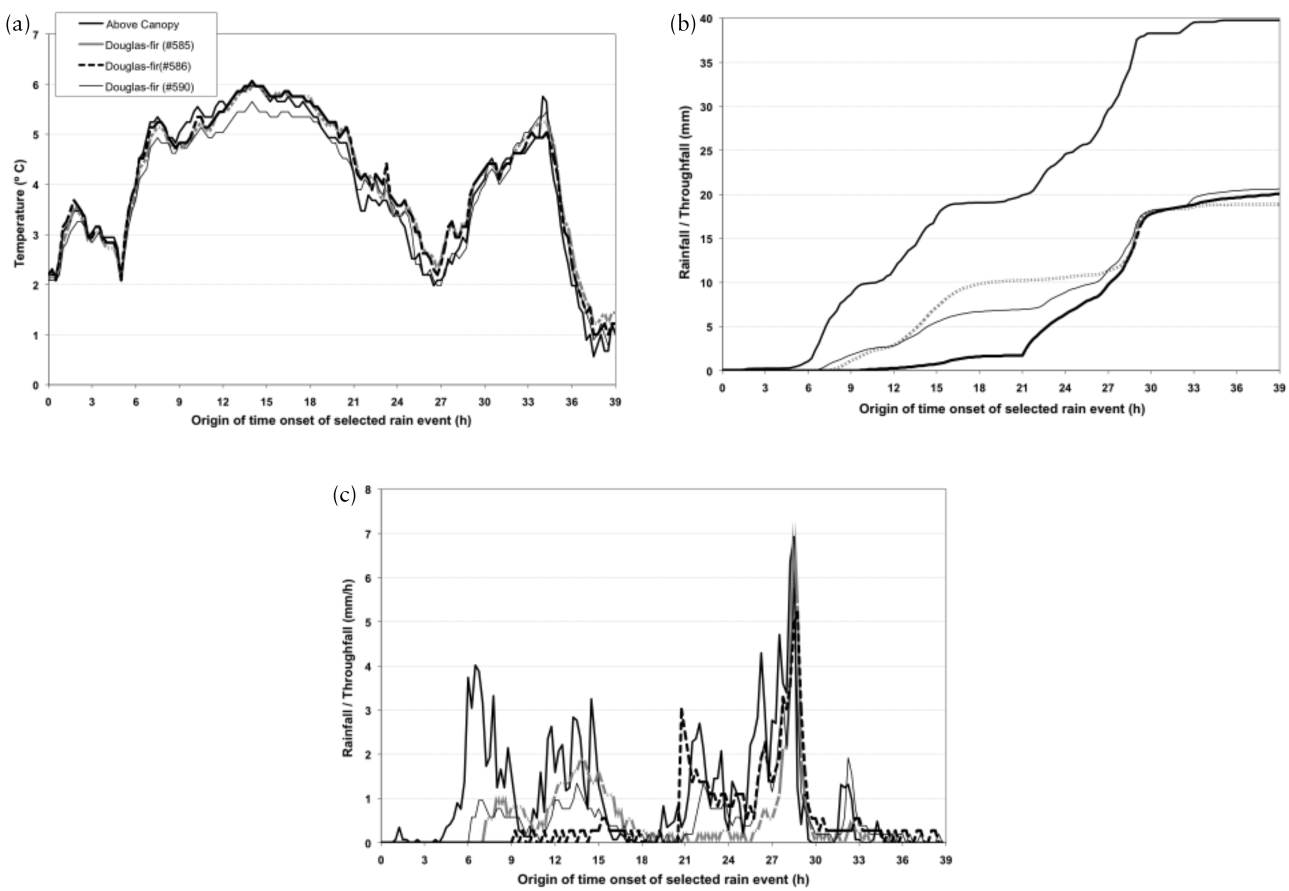

Fig. 5. Meteorological and throughfall data for rainfall event three (Douglas-fir).

the seven events ranged between 17 and 89%, which were 4.8 and 22.0 mm of gross precipitation respectively. The lowest interception losses occurred during event 1 and 4. Based on the variability in rainfall amount, intensity, and duration the interception losses for coniferous trees in this study ranged from 5 to 98% (1.5 to 24.3 mm with reference to the amount of gross precipitation).

Our results suggest that interception losses for coniferous trees are significantly higher within urban environments compared with forested areas. Link et al. (2004) suggested that in temperate forests, annual interception losses for coniferous canopies ranged from 9 to 48%, while Bryant et al. (2005) reported 22.3% interception loss in a pine forest. The interception values obtained in our study suggest that the interception losses for trees in urban environments are twice as much as trees in natural forested areas. Possible factors contributing to these differences are UHIs (urban areas which have significantly higher temperatures than the surroundings), greater distances between trees (edge effect), and open grown canopies.

UHIs cause local-scale variation in temperature differences between urban and natural forested areas. Taha (1997) stated that the temperatures within urban areas tend to be higher due to replacement of natural vegetation by man made structures, consequently resulting in less evapotranspiration. In addition, urban trees are isolated with greater distances between them, making them more exposed during severe weather events, unlike trees within forested areas where they are surrounded by other trees (Aboal et al. 1999; Nadkarni and Sumera 2004). High wind during a rainfall event can mechanically shake precipitation from the canopy and thus reduce interception loss. Winds during evaporation can either shake precipitation loose, or increase the rate of evaporation and decrease the time until maximum interception capacity is attained. Urban tree canopies are classified as open grown trees as a result of no intertree competition; consequently, they have larger structural dimensions (e.g., larger storage capacity) than trees in forests (Horton 1919; Zipperer et al. 1997; Brooks et al. 2003). In our study, UHIs, isolation, and open canopies attributed higher interception losses by urban trees.

Tree health condition and type were also found to affect interception rate. Single standing trees in good health were expected to have a higher interception rate. This was demonstrated in some, but not in all the events. A codominant western red cedar of poor health intercepted at higher rates compared with other trees of better health conditions and types. Also, a dominant Douglas-fir with poor canopy condition showed the highest interception rate for event 6. Western red cedar trees generally had higher interception losses compared with Douglas-firs. This is due to the differences in canopy structure between the two tree species. For the events between March and June, the interception losses were relatively high for both species. The high rates can be explained by small rainfall events, where most of the water from the event is used to wet the crown surfaces.

The time delay in throughfall penetrating through canopy was greatest for event 1 (8.5 to 45.5 h) in comparison with events 2, 4, and 5 where there were no significant delays. Events 3, 6, and 7 had moderately higher time delays, however, lower than event 1. Tree type and health condition played an important role in controlling the time delay. For the seven events it was noticed that the dominant and codominant trees with good health conditions showed a longer time delay in throughfall. Also, when comparing the time delays between the two species, western red cedar showed later delays than Douglas-fir trees.

Trees generally dampen rainfall intensity; however, there were instances where the throughfall intensity was equivalent or higher than the actual rainfall intensity. The highest throughfall intensity was seen in event 3 at 28.7 h. The throughfall intensity exceeded the actual rainfall intensity by single standing Douglas-fir and a codominant western red cedar. The calculated rainfall intensity was 6.0 mm/h while the througfall intensities for Douglas-fir and western red cedar were recorded at 7.3 and 8.0 mm/h. This variation can be explained by rainfall characteristics, meteorological factors, and structure of the canopy. It is evident in Fig. 4c and 5c that high throughfall intensity is delayed in time for lower rainfall intensities. Crown density wetness is another factor to consider. As the crown dampens, the drip becomes larger, consequently resulting in higher throughfall intensities. Another reason can be suggested to reflect on crown wetness. As the crown dampens the drip becomes larger, consequently resulting in higher throughfall intensities (Crockford and Richardson 2000; Brooks et al. 2003).

The observed reduction in throughfall intensity by tree canopies serves two purposes. First, it delays water reaching the ground by temporary storage of the water on the tree. This storage both reduces and delays the peak in the stormwater runoff. Second, it protects the mineral soil surface from the energy of raindrops reaching the ground at maximum velocity. Reduction of raindrop energy by interception minimizes soil detachment and subsequent erosion, which in turn protects soil structure and infiltration capacity leading to less stormwater runoff (Xiao and McPherson 2002; Pypker et al. 2005). All the selected events demonstrated reduction in raindrop energy by having lower intensities captured underneath the canopy. The differences in the magnitudes of rainfall intensity for the events were dependent on climatic conditions. A tree's health condition, type, and species can be suggested to contribute to the differences in throughfall intensities.

Our results confirm that canopy interception loss is greater in urban areas due to isolation, open canopies, and higher temperatures. These higher interception losses play an important role in controlling stormwater runoff. This novel perspective of the interception processes in nonforested settings may prove to be useful for modelling future impacts of large-scale urban tree plantings on interception and runoff.

Conclusion

This study evaluated the interception losses for coniferous species in North Vancouver. Interception losses calculated for urban trees were approximately twice as great as those calculated for trees within natural forest stands. The identified controls on interception loss were meteorological factors, tree type, and health. The results were variable depending on location, tree health, and canopy structure. The interspecies variation on interception was evident as western red cedar trees showed higher interception losses, longer time delays, and lower throughfall intensities compared with Douglas-firs.

The goal of this project was to shed some light on rainfall interception by single and stands of trees in urban environments in order to provide data, models, and additional information for planners, developers, and municipal engineers to utilize in the planning of future urban development. Using natural vegetation as a low impact development and best management practice is an effective technique as it controls stormwater runoff on site, mitigating the impacts of urbanization on urban hydrology at a local scale (Graham et al. 2004).

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