RAINFALL INTERCEPTION IN AN URBAN ENVIRONMENT

by

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B.Sc., The University of British Columbia, 2007

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA
(Vancouver)

April 2010

Abstract

Vegetation 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 is to document the importance of urban trees as a form of 'green infrastructure' to reduce stormwater runoff and rainwater intensity, and cause a delay in precipitation reaching the ground. A 21 months study was carried out in the North/West Vancouver in British Columbia to determine how effective urban trees are to intercept and detain rainwater. We applied a unique methodology for measuring rain/throughfall under 54 different urban trees using a system of PVC pipes hung beneath the canopy to capture the throughfall where it drained into a rain gauge attached to a data logger. To ensure that the study adequately captured the range of throughfall variability, trees were selected to sample different landscape sites (streets, parks, and natural forested areas), elevations, tree type, health condition and species, including Douglas-fir (*Pseudotsuga menziesii*), Western red cedar (*Thuja plicata*), Bigleaf maple (*Acer macrophyllum*), Oak (*Quercus sp.*), Copper beech (*Fagus sylvatica*), Horse chestnut (*Aesculus hippocastanum*), Cherry (*Prunus sp.*), and Poplar (*Populus sp.*). Interception loss and throughfall were monitored from February 2007 until November 2008. Rainfall interception varied seasonally for all species. Interception losses accounted for on average 76.5% and 56.4% of gross precipitation for coniferous and deciduous trees, respectively. The interception loss varied depending on canopy structure, climatic conditions, and rainfall characteristics. The results showed that urban trees intercept and evapotranspire more rain than trees in forested environments. Together with the delay in runoff trees can act as an effective stormwater management tool on individual properties.

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Acknowledgements

I would like to express my gratitude to my supervisors Dr. Dan Moore and Dr. Markus Weiler for all their support throughout this project, for keeping me focused, for listening to my concerns, and for providing me with advice that enabled the production of this thesis. Sincere appreciation is extended to Dr. Hans Schreier for his encouragement and useful suggestions throughout this research work.

I am heartily thankful to Martin Tromp, Gerald Lohmann, Sophie Bachmair, Nils Ilchmann, Selina Agbayani, Maheen Javed and Eoin O'Neill for their assistant in the field and invaluable advice on fieldwork and data analysis. I also offer my enduring gratitude to Richard Boase and Kim Stephens for their unconditional support, enthusiasm and inspiration whenever I needed the most.

I would also like to thank all those responsible for providing financial support. Thank you to District of North Vancouver, City of North Vancouver, District of West Vancouver, Greater Vancouver Regional District, Province of British Columbia, Real State Foundation of British Columbia, Inter-Governmental Water Balance Model Partnership, and Canadian Water Network. I also like to express my appreciation to the North Shore Mentally Handicapped Association for their assistance in assembling the structures for the throughfall gauges.

I am as ever, especially indebted to my mom (Soheila), grand parents (Jafar and Pooran), Yalda and Mohammad for their love and support throughout my life. This milestone could not have been possible without the support and sense of humor of my friends.

Chapter 1
Introduction

Water quality concerns have intensified and stormwater management practices have come under scrutiny as development occurs on an increasing percentage of the available land area. 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 in urban watersheds (McPherson et al. 1997; Sanders 1986). The losses in vegetation cover and increase in impervious surfaces, such as paved roads, sidewalks, and concrete buildings, increases the total amount of runoff, the flashiness of runoff event, 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 where they function together to reduce stormwater runoff. Trees reduce stormwater runoff by canopy interception loss, which is the proportion of incident precipitation that is intercepted, stored and subsequently evaporated from the leaves, branches and stems of vegetation. Interception provides two major roles in a watershed. First, interception is an important part of the water balance, serving as either a loss or gain of water to the watershed. Second, interception plays an important role in protecting the mineral soil surface from the energy of rainfall. Reduction of raindrop energy by interception minimizes soil detachment and reduces subsequent erosion as well as protection of soil structure and infiltration capacity. Interception can be impacted by management which affects the amount, type, and distribution of vegetation in a watershed. Another portion of the same rainfall event infiltrates into the ground, decreasing peak flows and the total amount of runoff. Trees also slow storm flow event by reducing the volume of water that must be managed at any one time and also reduce the rainfall intensity. Trees are generally overlooked in urban planning, but they are an essential 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 trees for stormwater management has been calculated based on the avoided costs of handling stormwater runoff (McPherson et al. 1997; Villarreal et al. 2004; Zipperer et al. 1997). McPherson et al. (2005) reported that in some cities in the USA the urban tree investment can be between \$13 – \$65 per tree annually in planting and maintenance cost. In return, gains in stormwater services are between \$1.37 – \$3.09 per dollar invested that would have been spent otherwise toward traditional stormwater management. Another study has estimated the worth of the USA'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.

Relatively few investigations have focused on the effects of urban forests on rainfall interception and runoff reduction. Some studies have focused on conceptualizing the influence of urban forests on hydrology by using satellite remote sensing to estimate vegetation coverage. However, the resolutions were too low to distinguish between conifers and deciduous trees (American Forests 1996). Previous studies primarily were conducted in naturally forested areas (Carlyle-Moses 2004; Crockford 1990; Domingo et al. 1998; Link et al. 2004; Llorens et al. 2007; Llorens et al. 1997; Nadkarni et al. 2004). Intuitively, the next step is to conduct a study that provides a fundamental understanding of spatial and temporal throughfall at the single tree level in an effort to improve understanding of rainfall interception in urban settings. This thesis is an attempt to achieve this link by presenting results of an investigation of temporal and spatial changes in throughfall and rainfall interception using an innovative study design for urban trees on the North Shore (North and West Vancouver) in British Columbia. The target users who will benefit from the study of these processes are academics, city/municipal engineers, planners, decision makers, and developers involved in urban planning and management of stormwater.

Sections 1.1 and 1.2 provide a focused literature review and identify knowledge gaps that this thesis will aim to fill through the objectives stated in Section 1.3. Section 1.1 focuses on the processes of canopy interception. Section 1.2 concentrates on the methods to measure rain interception evaporation process. It also deliberates on how interception loss by forest canopies can be estimated by analytical models.

1.1 Interception Process

1.1.1 The Terminology of Canopy Interception

Tree canopy interception accounts for storing precipitation temporary in the canopy and releasing it slowly to the ground and back into the atmosphere. Interception by the forest canopy is defined as:

$$I_c = P_g - T_F - S_F \qquad \text{Equation 1.1}$$

where I_c is the canopy interception loss (mm); P_g is the gross precipitation, measured above canopy or in an open area (mm); T_F is the throughfall, precipitation that passes through the canopy or as drip from vegetation (mm); and S_F is the stemflow, water that flows down the stems to the ground surface. Net precipitation (P_n) is also commonly referred to as the quantity of rain water that actually reaches the ground. It is the sum of throughfall and stemflow. The division of a given quantity of rainfall into the above pathways is highly dependent on forest structure, canopy structure and meteorological factors (Crockford et al. 2000; Nadkarni et al. 2004; Xiao et al. 2002).

A number of interception studies have been conducted in tropical (Jetten 1996), temperate broadleaf, and temperate conifer forest (Link et al. 2004; Rutter et al. 1975; Toba et al. 2005) to evaluate the net interception loss over a period of time, estimate the components of interception, and assess/improve interception models. Interception loss is commonly 29-40% of gross precipitation in coniferous forests and between 10-20% in deciduous forests (Carlyle-Moses 2004; Crockford 1990; Link et al. 2004; Llorens et al. 2007; Llorens et al. 1997).

1.1.2 Controls on Interception Loss

The rainfall interception capacity of the natural/urban forest is strongly influenced by forest structure, which includes species, dimensions, and understory (Keim et al. 2005; Xiao et al. 2002; Xiao et al. 2000b). The size and shape of the canopy, which can be described as tree architecture (e.g., foliation period, leaf and stem surface areas, gap fractions, and surface detention storage capacity), affect the amount, intensity, and spatial distribution of throughfall. Variation in these characteristics creates variation in interception. The structure of the overstory, mainly the branch and leaf angles, concentrates throughfall in drip points, which can result in greater amounts and intensities of rainfall at these particular places (Brooks et al. 2003; Bryant et al. 2005; Keim et al. 2005; Masukata et al. 1990; Xiao et al. 2002; Xiao et al. 2000b). Many other locations in a dense forest canopy may receive no throughfall at all. Relationships have been verified for the amount of throughfall captured and forest types in many parts of the world. Moreover, species variation has been distinguished to play an important role in influencing the result of interception loss. It has been suggested that conifers tend to have greater interception capacity than broadleaf species. It is noted that during a rainfall event, raindrops can run together on deciduous leaves, forming large raindrops which can fall as throughfall; however, the needles of conifers do not allow for this to take place (Ford et al. 1978; Iroumé et al. 2002; Keim et al. 2006; Lee et al. 2005; Lundberg et al. 1997; Toba et al. 2005).

Observations of interception loss indicate that the precipitation and associated meteorological characteristics as well as vegetation characteristics influence the interception process. In general, the precipitation and storm factors which affect interception loss are precipitation amount, intensity, duration, frequency of events, and antecedent rainfall conditions (Asdak et al. 1998; Brooks et al. 2003; Horton 1919). For instance, low intensity long duration frontal storms may generate different interception losses than high intensity, short duration convectional storms. Furthermore, the intercepted water is lost to evaporation during periods of rain, as well as during breaks within it, and the amount lost depends on meteorological conditions including temperature, humidity, and wind speed (Dunkerley 2000).

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, growing spaces (isolation: greater distances between individuals), open canopies, age, canopy structure, diversity, and microclimate (higher temperatures and wind penetration and associated rainfall) (Xiao et al. 2002). These characteristics define the storage capacity for each stand or individual tree, and control the evapotranspiration rate (Guevara-Escobar et al. 2007; McJannet et al. 2007a; McJannet et al. 2007b; Sanders 1986; Wang et al. 2008; Xiao et al. 2002; Zipperer et al. 1997).

1.2 Methods for Measuring Rainfall Interception

The net precipitation method has been used in most interception studies to quantify interception loss, based on gross precipitation, throughfall, and stem flow (Calder 1996; Gash 1979; Horton 1919; Rutter et al. 1975). There is a wide variety of measurement techniques with associated accuracies conducted in both the field and laboratories. The two commonly used methods in the field are: point and area measurements (Aston A. R. 1979; Li et al. 1997; Lloyd et al. 1988). Point measurements involve collecting throughfall directly beneath the canopy at randomly or systematically selected points, while area measurements involve determination of the amount of throughfall for a defined area underneath the canopy. Throughfall has been measured with stationary precipitation funnels (Carlyle-Moses 2004; Crockford 1990; Horton 1919), with plastic sheet (Calder et al. 1976), with roving precipitation funnels (Lloyd et al. 1988), and with troughs (Kelliher et al. 1992). It has been indicated that most of these common sampling techniques entail large errors in the estimated interception. Time resolution of gross or net precipitation is highly dependent on the type of data collection. For instance, if gauges are manually emptied, the time resolution is per day or per storm event. There is a higher temporal resolution if tipping bucket rain gauges are used. Marsalek (1981) suggested that tipping bucket rain gauges are not suited for long term monitoring, due to both catching and counting inaccuracies, related to the positioning and mechanics/electronics of the instrument employed. Mechanical errors as a result of inherent characteristics of the counting device have a strong influence on the measurement of rainfall intensity, with increasing impact as the rate increases (Brooks et al. 2003; Lundberg et al. 1997; Marsalek 1981). Consequently, tipping bucket rain gauges under-catch during high rainfall rates. Weighing devices are not widely used. A few studies that have applied this technique have reported good time resolution. Lundberg (1997) noted that a major cause of error with collecting gross precipitation is associated with under-catch, which is due to the wind around the precipitation gauges. Gross precipitation is measured above the canopy or in an open area away from any obstructions. Wind loss problems tend to be higher above the canopy due to higher wind speeds.

Plastic sheets can obtain spatially correct averages; however, losses through adhesion, blockage, holes in the sheets, and evaporation can cause errors. This method is not favored for prolonged periods, as the areas underneath the sheets are deprived from receiving water (Calder 1996). Comparing funnels to troughs, it can be concluded that troughs provide a better representation of average areas (Crockford 1990). A disadvantage of using these methods is wetting losses through adhesion of water to the collectors/containers. Moreover, other losses such as splashing, combined with blockage of collection gutter during large rainfall events, may produce large measurement errors (Horton 1919; Link et al. 2004; Lundberg et al. 1997; Xiao et al. 2000).

In this study, we developed and applied a rainfall interception measuring system that evaluates the net precipitation directly underneath individual trees (representative canopy area averages). This method is applicable in both urban settings and mixed forest stands. It has the ability to function during the quickly changing climatic conditions. It provides a high temporal resolution, with indication of the time and date for each tipping.

1.2.1 Rainfall Interception Models

Models developed to estimate the interception loss from forests vary from simple empirical relationships to physically based conceptual models. They provide estimation of interception loss from climate data. The most commonly applied models were found to be the original and sparse Rutter and Gash models. Link et al. (2004) suggests that empirical models are developed for a given set of conditions in specific vegetation covers, consequently there is limited utility outside the conditions for which they were developed. These models have been successfully used in a wide range of canopy conditions, from closed forests to isolated trees. In closed and sparse forests the models are generally applied at the stand level whereas in isolated or widely separated (savanna-type) trees a tree-based approach has been preferred (Aboal et al. 1999; Carlyle-Moses et al. 1999; Deguchi et al. 2006; Dykes 1997; Lloyd et al. 1988; Muzylo et al. 2009; Návar et al. 1999).

Rutter et al. (1971) were the first to present a conceptual, physically based model. The original Rutter model characterizes a running water balance of rainfall input storage and output in the form of drainage and evaporation. Drainage and evaporation rates/amount are dependent on the amount of water stored in the canopy during each event. This model was revised by adding a stemflow component, where a portion of the rainfall input is directly diverted to stems and trunks (Rutter et al. 1975).

Gash's analytical model (1979) is a simpler storm-based model that incorporates some of the features of linear regression models in the physical background of the Rutter model. This model segregates rainfall input as a series of discrete storms that are divided into intervals sufficiently long enough for canopy to dry out completely. This assumption is valid as it can occur in forest canopies and urban trees. Subsequently, each event is separated into three phases: canopy wetting up, saturation and drying. The separation stresses the significance of the meteorological factors in combination with vegetation characteristics. The Gash model (1995) was revised to incorporate the canopy cover fraction parameter in order to take into account the evaporation per unit area of the canopy rather than unit area of the ground. Canopy cover or closure is a measure of the fraction of the landscape covered by vegetation. Canopy cover, such as LAI (leaf area index), measures the amount of leaf material in an ecosystem, which imposes important controls on photosynthesis, respiration, rain interception, and other processes that link vegetation to climate. LAI estimation is calculated based on the light penetration through vegetation, where the difference between the sky and the canopy is recorded. Using this method of calculation provides permanent temporal and spatial data of the canopy (Deguchi et al. 2006; Martens et al. 1993). The separate components of Rutter and Gash models are shown in Table 1.1.

Table 1.1: The original and revised Rutter & Gash model

Source	Interception Model	Components of Interception	Property	Output Variable
Rutter (1971)	$D_r = Ke^{(C/b)}$	D_r – Canopy drainage C – Canopy storage K & b – Constants characteristics of the canopy	Empirical	I_c – Interception loss
Revised Rutter (1975)	$\frac{dC}{dt} = (1-p)R - E - K(e^{bC} - 1)$	C – Canopy storage p – Free throughfall coefficient R – Precipitation rate E – Evaporation rate K & b – Constants characteristics of the canopy	Empirical	I_c – Interception loss
Gash (1979)	$P'G = \frac{\overline{R}S}{\overline{E}W} \ln\left[1 - \frac{\overline{E}W}{\overline{R}}(1 - p - p_t)^{-1}\right]$	$\overline{R}$ – Mean rainfall rate $\overline{E}_w$ – Mean evaporation rate S – Canopy storage capacity p – Free throughfall coefficient p_t – Stemflow portioning coefficient	Empirical	I_c – Interception loss T_F – Throughfall S_F – Stemflow
Revised Gash (1995)	$P'G = -\frac{\overline{R}S_c}{\overline{E}_c} \ln[1 - (\frac{\overline{E}_c}{\overline{R}})]$	$\overline{R}$ – Mean rainfall rate c – canopy cover $\overline{E}_c$ – Mean evaporation rate/unit cover S_c – canopy capacity/unit are of cover	Empirical	I_c – Interception loss T_F – Throughfall S_F – Stemflow

1.3 Objectives

Following from the knowledge gaps identified in the preceding literature review, the objectives of this thesis are: (1) to quantify rainfall interception by urban trees, using the innovative throughfall gauges; (2) to determine the dominant variables (vegetation or meteorological characteristics) influencing the interception process; (3) to derive seasonal storage capacity (S) for different tree species; and (4) to test the effectiveness of spatial representation of results produced by throughfall gauges.

1.4 Thesis Outline

Chapter 2 provides information about the study area and methods used. In Chapter 3 the results of the investigation are presented. Firstly, an overview of the climate conditions for the period of 2007 and 2008 are shown. The seasonal linear regression of the divided incident rainfall events versus the throughfall depth is illustrated. Seasonal throughfall patterns and temperature for both coniferous and deciduous trees are evaluated. Event based temperature, throughfall amount and intensities are shown for four selected events. The linear regressions of rainfall versus throughfall depth are examined for different species, tree type and condition. Furthermore, these regressions are used to determine the key canopy parameters, and evaluate how these parameters change seasonally. The effectiveness of the throughfall gauges is compared to the bottles installed underneath five selected trees. Chapter 4 discusses the pattern of throughfall in urban trees, and the most effective variables influencing the results. Chapter 5 summarizes the key findings of the thesis and makes suggestions for future research.

Chapter 2
Study Area and Methods

2.1 Site Description

This study was conducted in the District of West Vancouver, and the District and City of North Vancouver in British Columbia. Together these three municipalities are commonly referred to as the North Shore. North and West Vancouver communities are highly urbanized cities with increasing urban development that has resulted in the creation of larger proportions of impervious surfaces. The dominant land use in these municipalities is residential, followed by industrial and commercial.

The North Shore sprawls in an east-west direction across the Coast Mountain slopes, and can be characterized by rugged and steep terrain. The three municipalities are described individually for a better understanding of their location/characteristics.

The city of North Vancouver with an elevation range of 0–80 m for urban areas falls in the Regional District of Greater Vancouver. It is surrounded on three sides by the District of North Vancouver and bounded by Burrard Inlet to the south. The District of North Vancouver with urban areas' elevation range of 0–200 m is in the Regional District of Metro Vancouver. This District is surrounded by the Coast Mountains to the North, Burrard Inlet to the south, Capilano River to the west, and Indian Arm to the east. The District of West Vancouver is also in the Regional District of Metro Vancouver. This district municipality with an elevation range of 0–

300 m for urban areas is located northwest of the city of Vancouver on Burrard Inlet and Howe Sound, and is adjoined by the District of North Vancouver to its east (Environment Canada 2007).

Major rivers and creeks flow through these areas, including Capilano River, MacKay Creek, Mosquito Creek, Lynn Creek, and Seymour River. The major concern regarding these waterways is the direct drainage of stormwater runoff into the rivers leading to flooding and non-point sources of pollution (Environment Canada 2007).

The regional climate is characterized by cool, wet winters and warm, moderate summers. In Vancouver 166 days per year have measurable precipitation, on average. These coastal rainfall events are described as having long durations and low intensities. The average annual precipitation near sea level is about 1200 mm but reaches up to 3000 mm at higher elevations, with most of the rainfall occurring in November to February period. 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 10º C at sea level.

2.2 Throughfall Measurements

2.2.1 Tree Selection

The study design focuses on the direct measurement of throughfall for 54 urban trees located on private and public properties along streets, parks, and forested areas. Different species including coniferous, deciduous, and some ornamental trees were randomly selected. The main coniferous trees assessed were Douglas-fir (*Pseudotsuga menziesii*) and Western red cedar (*Thuja plicata*). Bigleaf maple (*Acer macrophyllum*) was the deciduous tree examined. The evaluated ornamental trees included: Cherry (*Prunus sp*.), Copper beech (*Fagus sylvatica*), Horse chestnut (*Aesculus hippocastanum*), Oak (*Quercus sp.*), and Poplar (*Populus sp*.). The locations of the study sites on the North Shore are shown in Figure 2.1 to 2.4.

Figure 2.1: Study Sites in Northlands Golf course and Roche Point Park in City of North Vancouver with latitude and longitude equal to 49º 19' 02" N and 122º 58' 01" W respectively (Ortho-photos provided by District of North Vancouver's GIS Department).

Figure 2.2: Study Sites in Mahon Park, Mosquito Park, and the District Hall Area, in District of North Vancouver with latitude and longitude equal to 49º 20' 00" N and 123º 04' 00" W respectively (Ortho-photos provided by District of North Vancouver's GIS Department).

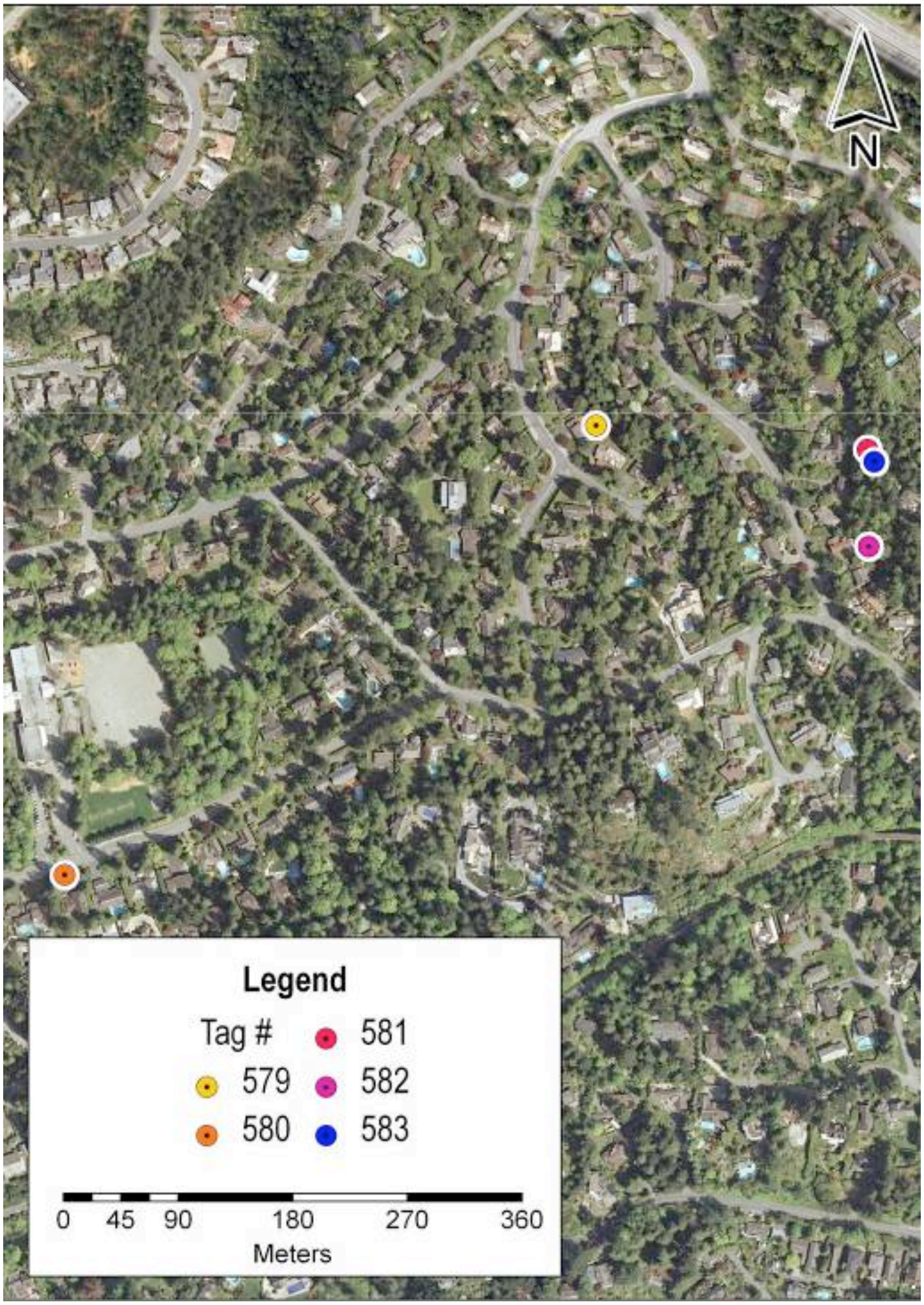

Figure 2.3: Study Sites at Caulfield Area in District of West Vancouver with latitude and longitude equal to 49º 21' 00" N and 123º 15' 02" W respectively (Ortho-photos provided by District of West Vancouver's GIS Department).

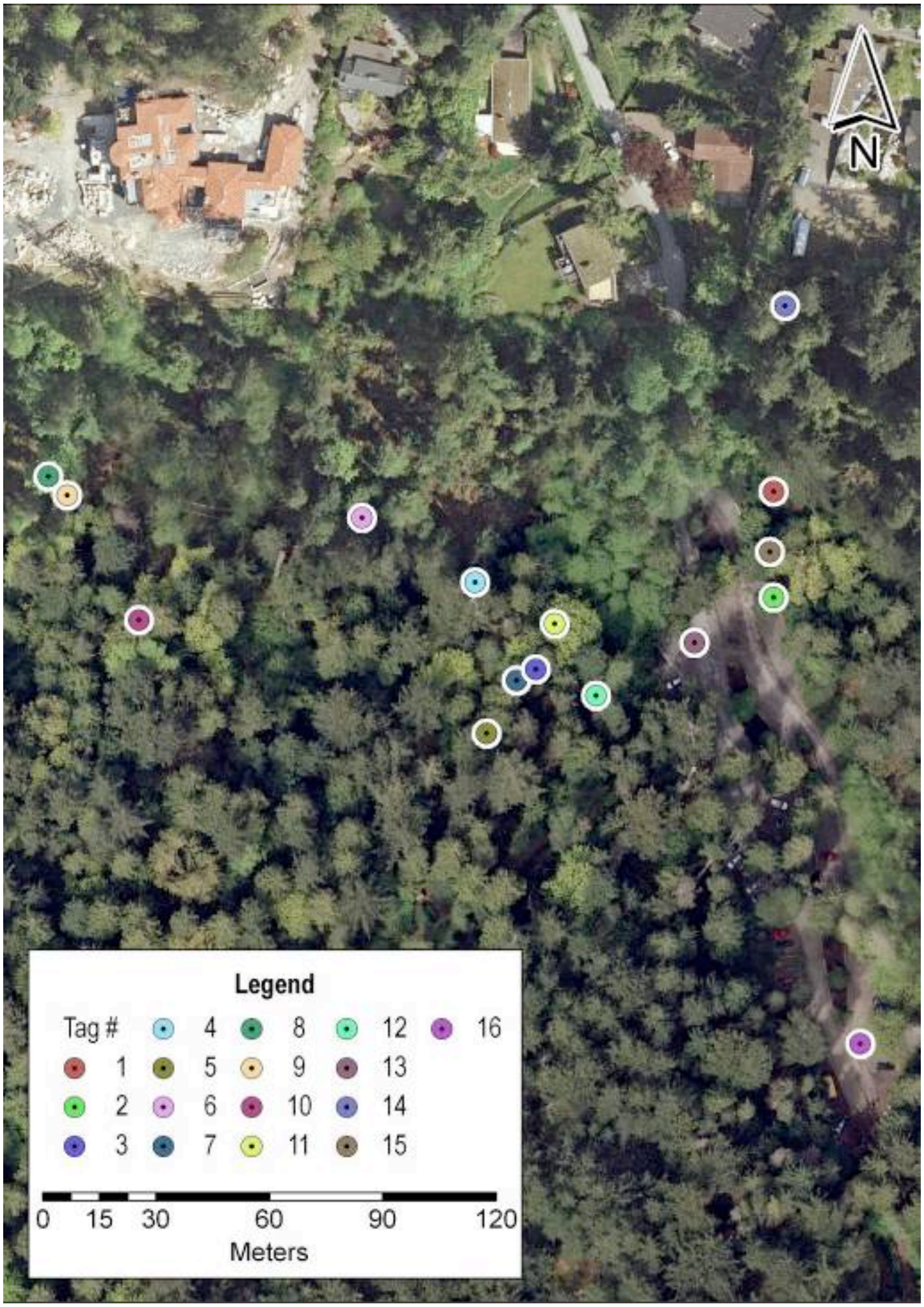

Figure 2.4: Study Sites in Lighthouse Park in District of West Vancouver with latitude and longitude equal to 49º 20' 02" N and 123º 16' 00" W respectively (Ortho-photos provided by District of North Vancouver's GIS Department).

2.2.2 Tree Classification

The trees were classified into different types: dominant, co-dominant, single, and within-forest (control). Dominant trees were described as the trees with crowns receiving full light from above and partly from the side. They were typically larger than the average trees in the stand with crowns that extended above the general level of the canopy. Crowns were also well developed. Trees with crowns receiving full light from above, but comparatively little from the sides, were defined as co-dominant trees. Co-dominant crowns formed the general level of the main canopy in even-aged groups of trees. 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 (Brooks et al. 2003; Oke et al. 1989; Zipperer et al. 1997).

Tree health condition was also assessed as it reflected 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. Four different classes were assessed based on density of the canopies: good and poor were used to describe coniferous trees, while good/broad and poor/less broad were used to describe deciduous trees. 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. Table 2.1 shows the location and assessed attributes for the selected trees.

Hemispherical photography was used to estimate the Leaf Area Index (LAI) for all selected tree canopies. A Nikon digital camera with a Nikon fisheye converter (FC-E8) was used to take a series of upward photographs from the ground to produce circular images that record the size, shape, and location of gaps in tree canopies. For evaluation we divided the longest diameter of the tree into three sections: the edges and the center, where hemispherical photographs were taken 1 m above the ground (Figure 2.5). Hemiview software was applied to obtain the LAI and Gap Fractions. Moreover, an average of the results obtained from the three images was taken to assess the horizontal/vertical heterogeneity in canopies. This assessment provided us with an estimate of canopy coverage (c – canopy cover).

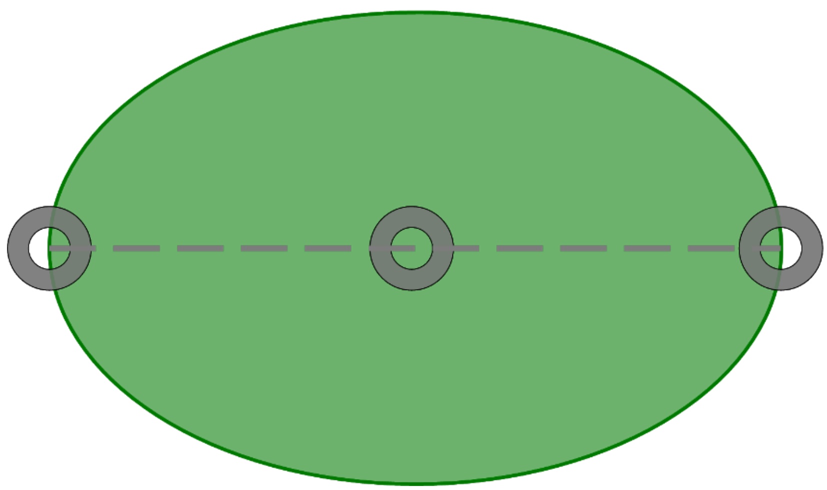

Figure 2.5: Locations along the longest diameter where hemispherical photographs were taken

Table 2.1: Characteristics of the selected trees including their location and tag numbers

Tag #	Tree species	Longitude	Latitude	Tree type	Condition	Height (m)	DBH[a] (cm)	Crown Spread (m)
1	Douglas-fir	49.33842249	-123.263099	Single	Poor	30	70	10
2	Bigleaf maple	49.33817063	-123.2630977	Single	Poor	23	48	25
3	Bigleaf maple	49.33799775	-123.263964	Single	Good	30	120	25
4	Douglas-fir	49.33820413	-123.2641853	Co-dominant	Good	26	45	12
5	Western red cedar	49.33784443	-123.2641421	Control (Forest)		24	45	18
6	Douglas-fir	49.3383561	-123.2645991	Co-dominant	Poor	25	40	9
7	Bigleaf maple	49.33797061	-123.2640327	Control (Forest)		27	65	15
8	Bigleaf maple	49.33845242	-123.2657421	Dominant	Good	24	65	14
9	Bigleaf maple	49.33840761	-123.2656731	Dominant	Poor	28	55	23
10	Bigleaf maple	49.33811137	-123.2654099	Co-dominant	Poor	29	60	12
11	Douglas-fir	49.33810585	-123.2638957	Dominant	Good	33	120	11
12	Douglas-fir	49.33793529	-123.2637434	Control (Forest)		32	45	11
13	Douglas-fir	49.33806203	-123.2633862	Single	Good	27	50	18
14	Western red cedar	49.33886334	-123.2630601	Single	Poor	30	125	10
15	Western red cedar	49.33827854	-123.263112	Single	Good	19	40	12
16	Douglas-fir	49.33710994	-123.2627754	Dominant	Poor	35	150	13
579	Western red cedar	49.346794	-123.245806	Co-dominant	Good	35	24	10
580	Western red cedar	49.343614	-123.251533	Dominant	Poor	30	29	12
581	Bigleaf maple	49.346631	-123.242867	Co-dominant	Good	32	18	24
582	Western red cedar	49.345947	-123.242853	Dominant	Good	30	24	10
583	Western red cedar	49.346544	-123.242794	Co-dominant	Poor	30	18	8
17	Copper beech	49.323514	-123.083294	Single	Good/Broad	25	120	25
18	Copper beech	49.323481	-123.083311	Single	Good/Broad	25	100	24
19	Oak	49.323789	-123.083492	Single	Good/Broad	15	60	14
20	Copper beech	49.323475	-123.081867	Single	Poor/Less Broad	23	100	12
21	Copper beech	49.323506	-123.081839	Single	Poor/Less Broad	24	100	16
22	Horse chestnut	49.32399445	-123.094307	Single	Good/Broad	13	75	15
23	Horse chestnut	49.3237155	-123.0944303	Single	Poor/Less Broad	13	60	12
24	Cherry	49.32412075	-123.0938531	Single	Good/Broad	14	55	12
25	Cherry	49.324328	-123.093592	Single	Poor/Less Broad	18	40	13
26	Oak	49.32508438	-123.0924237	Single	Poor/Less Broad	19	40	11
27	Poplar	49.32359091	-123.0927787	Single	Good/Broad	22	55	12
28	Poplar	49.32374374	-123.0928891	Single	Poor/Less Broad	23	45	10
585	Douglas-fir	49.335931	-123.078469	Single	Good	35	78	14
586	Douglas-fir	49.336042	-123.078936	Dominant	Poor	32	66	10
587	Western red cedar	49.3362	-123.078917	Co-dominant	Good	29	70	13
588	Western red cedar	49.336311	-123.078894	Co-dominant	Poor	29	43	9
590	Douglas-fir	49.336425	-123.079685	Single	Poor	39	68	10
591	Western red cedar	49.3386	-123.078558	Single	Good	32	95	15
200	Western red cedar	49.3186613	-122.9811076	Dominant	Poor	25	90	10
598	Douglas-fir	49.31679946	-122.9820302	Dominant	Good	35	43	9
599	Western red cedar	49.31692549	-122.9826631	Single	Poor	38	68	10
1408	Bigleaf maple	49.32380575	-122.976936	Co-dominant	Good/Broad	27	69	10
1409	Douglas-fir	49.3224305	-122.9826474	Co-dominant	Good	25	37	8
1411	Western red cedar	49.32359887	-122.9769773	Dominant	Good	31	83	8
4607	Bigleaf maple	49.31963279	-122.981176	Dominant	Poor/Less Broad	33	61	14
100	Western red cedar	49.30903392	-122.9690737	Control (Forest)		24	35	10
592	Bigleaf maple	49.3106711	-122.9693066	Dominant	Good/Broad	38	110	26
593	Bigleaf maple	49.3087099	-122.968331	Co-dominant	Poor/Less Broad	36	78	10
594	Bigleaf maple	49.30905167	-122.9681795	Control (Forest)		34	45	14
595	Douglas-fir	49.30899795	-122.9690875	Control (Forest)		37	35	11
596	Douglas-fir	49.30926791	-122.9694863	Co-dominant	Poor	39	45	12

Tag #	Tree species	Longitude	Latitude	Tree type	Condition	Height (m)	DBH[a] (cm)	Crown Spread (m)
597	Bigleaf maple	49.30906995	-122.9692525	Single	Good/Broad	29	50	19
1033	Bigleaf maple	49.30918659	-122.9681519	Single	Poor/Less Broad	27	68	22

[a] DBH = diameter at breast height

2.2.3 Field Instrumentation

The throughfall gauge under each tree consisted of four components: the wooden frame, the PVC (Polyvinyl chloride) pipes, the tipping bucket rain gauge and the data logger. The wooden structure included a platform where 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 throughfall unit. These pipes were hung from branches using ropes and bolts, at an angle. The two pipes were positioned underneath the canopy based on the shape and structure of individual tree in a way that the entire diameter of the canopy was covered. Each pipe was approximately 3 m long, with three 0.85 m by 0.028 m slits cut on top along the length of each pipe providing a total orifice area of 0.1428 m^2. The throughfall was captured by these openings and drained into a tipping bucket rain gauge with a total surface area of 0.034 m^2 (RAINEW, RainWise Inc., Bar Harbor, ME). Data loggers (HOBO, Onset Computer Corporation, Pocasset, MA) attached to the rain gauges recorded both canopy's air temperature and rainfall events. The temperatures recorded by the data loggers accounted for within-canopy temperature variation. Trees modify canopy microclimate along a vertical gradient, which is suggested to have a minor impact on canopy interception responses (Brooks et al. 2003; Jetten 1996). Overall, this flexible system allowed independent movement of the different components of each throughfall gauge without causing any serious damage to the entire structure (Figure 2.6).

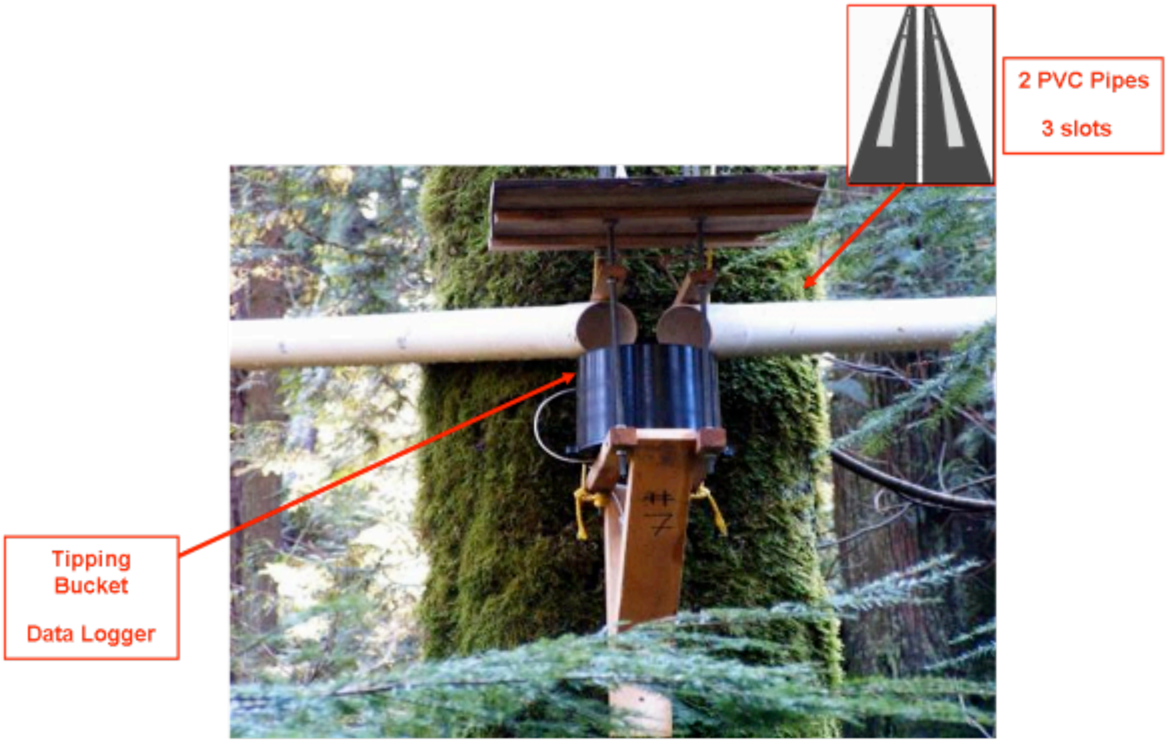

Figure 2.6: The throughfall gauges measuring system

2.2.4 Meteorological Station

Gross precipitation was measured using control units of the same design (Figure 2.7). These units were positioned on the rooftops of buildings away from any structures that may block rainfall. 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.

Figure 2.7: Example of reference rainfall gauge installed on the rooftop of North Vancouver's City Hall to measure gross precipitation (above canopy rainfall).

2.2.5 Data Collection and Calibration

The throughfall gauges were operated from February 15, 2007, to November 28, 2008. The data loggers were programmed to record the number of tips and the air temperature every 15 minutes. The number of tips was related to the depth of rainfall/throughfall. The climate stations and rain gauges were twice calibrated after the installation in the field during the study period. The throughfall gauges required regular maintenance to clear obstructions including: dirt, debris leaves and insects. The tipping bucket rain gauges were frequently wiped clean to remove mud and dirt.

2.2.6 Testing the Efficiency of the Throughfall Gauges

Additional point collectors were installed from September 16 to November 30, 2008, to ensure that the throughfall gauges were capturing the variability in throughfall. Five trees (coniferous and deciduous) situated in the District of West Vancouver (Lighthouse Park and privately owned lands) were used for this assessment. The chosen trees with tag numbers 580, 579, 11, 6, and 2 were located far from trails and human sight to minimize vandalism.

Throughfall collectors were built using 0.15 m length of PVC pipes fitted within the mouth of Nalgene wide mouth bottles (capacity 2.5 L) using couplers. Application of the silicon sealant both inside and outside of the bottles prevented leakage. Wooden stakes were driven into the ground and Dutch taped to individual bottles following each rotation. Staking helped in upholding the vertical position and minimizing the movement of the bottles. This type of set up had three main advantages: (1) greater receiving surface area (81.1 cm^2); (2) less throughfall loss due to splashing; and (3) less evaporation (due to the light color of the bottles). The throughfall collectors were manually emptied every 10 to 14 days.

Ten throughfall collectors were placed randomly under the selected trees as shown in Figure 2.8. The point throughfall collectors were moved after each rainfall event. Lloyd and Marques (1988) suggested that for a certain number of gauges, roving provides more accurate estimates of cumulative throughfall rather than using fixed collectors. This roving method is not accurate if used for season long or annual time periods. Also, it does not increase the accuracy for a single event estimates when assessing temporal or spatial variability (Loustau et al. 1992).

Figure 2.8: Random distribution of point throughfall collectors under a Douglas-fir (Tag# 6) in Lighthouse Park

2.3 Methods for Calculation of Interception Loss

Rainfall events were defined as storms with cumulative gross precipitation exceeding 1 mm, with a minimum of 6 hours without precipitation between events (Harr 1977; Pierson 1980). Cumulative precipitation records for each rain gauge and event were manually evaluated to identify gauges that had clogged or failed during individual events. Events were categorized into two seasons. Seasons were classified as summer (April – October) and winter (November – March). This division was particularly applied due to deciduous trees not retaining their leaves all year around.

In this study, stemflow was not measured since it was 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 still contributes to stemflow. In addition, the bark is ridged and ruffled, which enhances absorption of water. The absorption of water by epiphytes and various moss species on branches and tree trunks also plays a role in controlling the stemflow. Consequently, we assumed stemflow to be insignificant, based on the results of previous research studies (Brooks et al. 2003; Crockford 1990; Link et al. 2004; Llorens et al. 2007).

We computed the total volume of throughfall captured underneath each tree for individual events by using the total number of tips and the obtained average volume from the calibrations. The difference between the surface areas of the PVC pipes and the rain gauge (ratio: 4.2) was taken into account. For each event, canopy interception was computed as the difference between P_g and T_F ($T_F = P_n$). The data for P_g were obtained from the reference gauges on the rooftops and standard climate stations in the municipalities. The rainfall and throughfall intensities for each event were determined as the ratio of the total depth of storm precipitation to its duration.

2.3.1 Canopy Parameters

Canopy interception parameters are commonly derived from the relationship between cumulative P_g and P_n volumes on a weekly or event basis (Gash 1979; Leyton et al. 1967; Link et al. 2004). We used the method (mean method) applied by Klassen et al. (1998), where it takes a linear regression between interception (I) and P_g for rain events sufficiently large to saturate the canopy has the form

$$I = (\frac{E}{R})P_g + S \quad \text{Equation 2.1}$$

where E is the mean wet canopy evaporation rate and R is the mean rainfall rate. Consequently we plotted the sum of throughfall (T_F) against the P_g with the expression as follows:

$$T_F = (1 - \frac{E}{R})P_g - S$$ Equation 2.2

A regression of T_F against P_g therefore had a slope of (1- E/R) and the negative intercept was S.

2.4 Statistical Analysis

Statistical analyses were completed using R Version 2.8.1 and S-PLUS Version 8.0.4. Linear regressions were performed on untransformed data of rainfall versus throughfall, since exploratory analyses showed residuals to be normally distributed with no heteroscedasticity in the data. All the results for this study were chosen based on goodness of fit and residual analysis.

Chapter 3

Results

3.1 Overview of Study Period

Vancouver's climate for the year 2007 and 2008 is shown in Figure 3.1. These data were obtained from the District of North Vancouver's climate station, British Columbia. It is observed that during the month of November until March the highest amount of precipitation is received particularly during the year 2007. The highest mean temperatures were observed in the month of July and August.

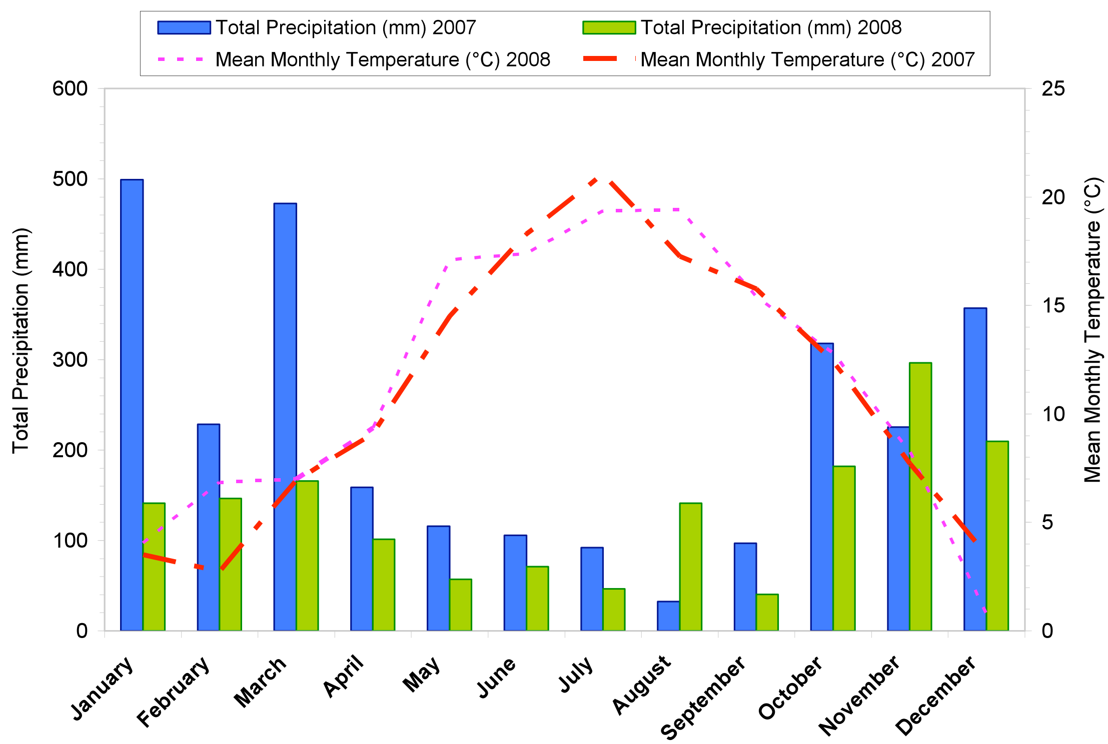

Figure 3.1: Vancouver's Climate Data for 2007 and 2008 (Location of rain gauge: Latitude 49.33618º N and Longitude 123.07814 º W)

3.1.1 Rainfall Event Summary

The total number of events assessed from the climate stations on the North Shore equaled 318. Rainfall events for the study period were classified based on the total amount of precipitation and average rainfall intensity as shown in Table 3.1.

Table 3.1: Rainfall events classification summary

Gross Precipitation (mm)	***Average Rainfall Intensity (mmh^{-1})***			
	<1	1-2	2-3	>3
<10	Medium			
10-30	Low	Medium		
30-50	-	Low		
50-70	-			
>70	-			
	-			

Figure 3.2 illustrates the amount, average intensity, and duration frequency of classified rainfall events. It is evident that events with gross precipitation less than 10 mm were the most frequent followed by the 10 – 30 mm category. The highest frequency was seen for average rainfall intensities of 2 – 3 mmh^{-1} followed by 1 – 2 mmh^{-1}. Events with duration between 12 – 24 h were the most frequent, followed by 6 –12 h, and less than 6 h. Overall, it can be noted that the frequencies decreased as the amount and duration of events increased. The total number of 172 events was utilized. The selected events represented the overall variability of all rainfall events during the study period. It is important to note that many events were eliminated due to the

problems associated with throughfall gauges. Figures 3.3 and 3.4 illustrate the seasonal histograms for the selected events. The most common event duration for summer was approximately 8 h, while for winter it was 12 h. The highest frequency of average rainfall intensity was observed to be 1.18 m mh^{-1} and 1.20 mmh^{-1} for summer and winter respectively. The highest frequencies recorded for the selected events during summer and winter were 4.31 mmh^{-1} and 5.14 mmh^{-1}.

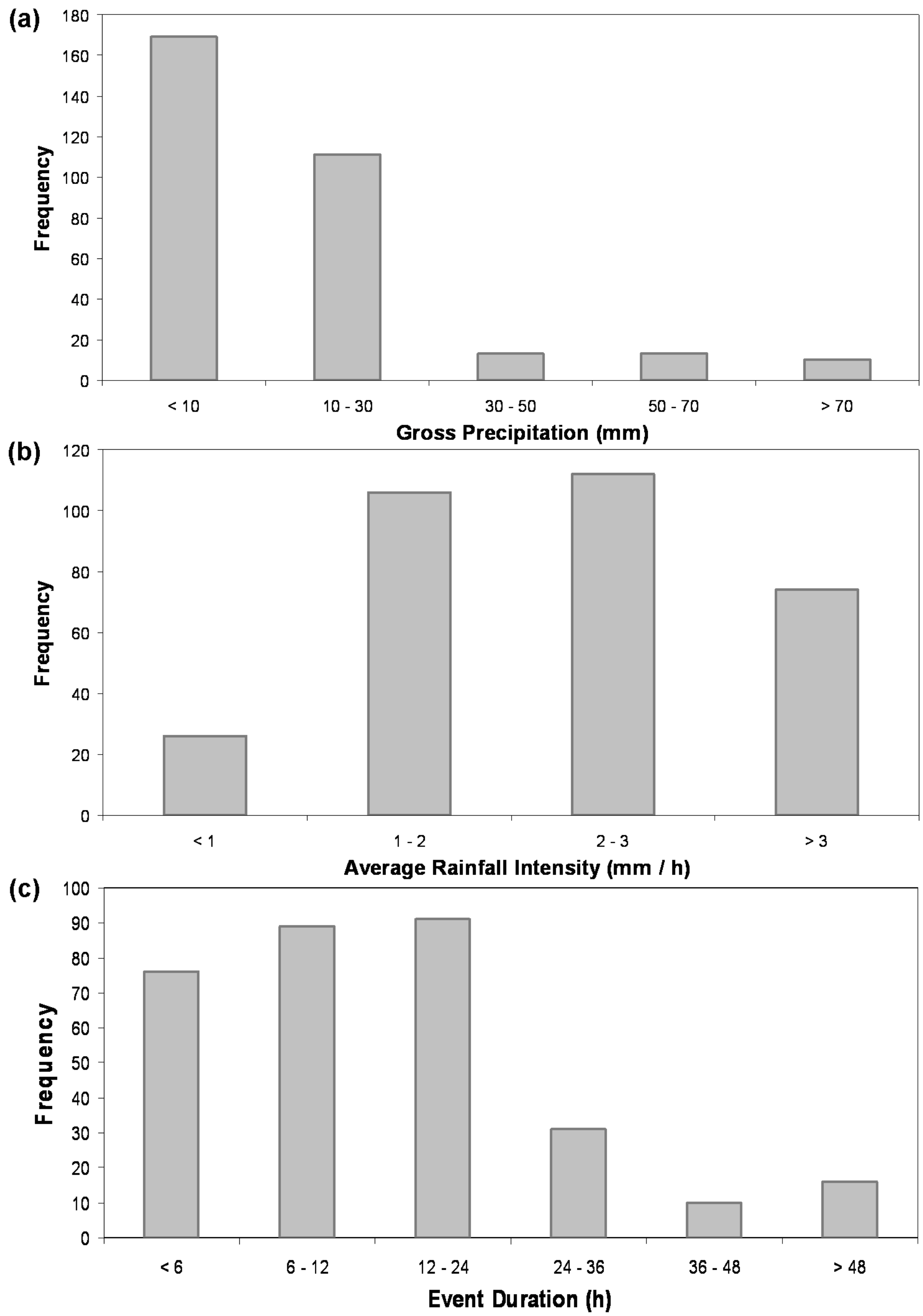

Figure 3.2: Rainfall event histograms of (a) gross precipitation; (b) average rainfall intensity; (c) event duration

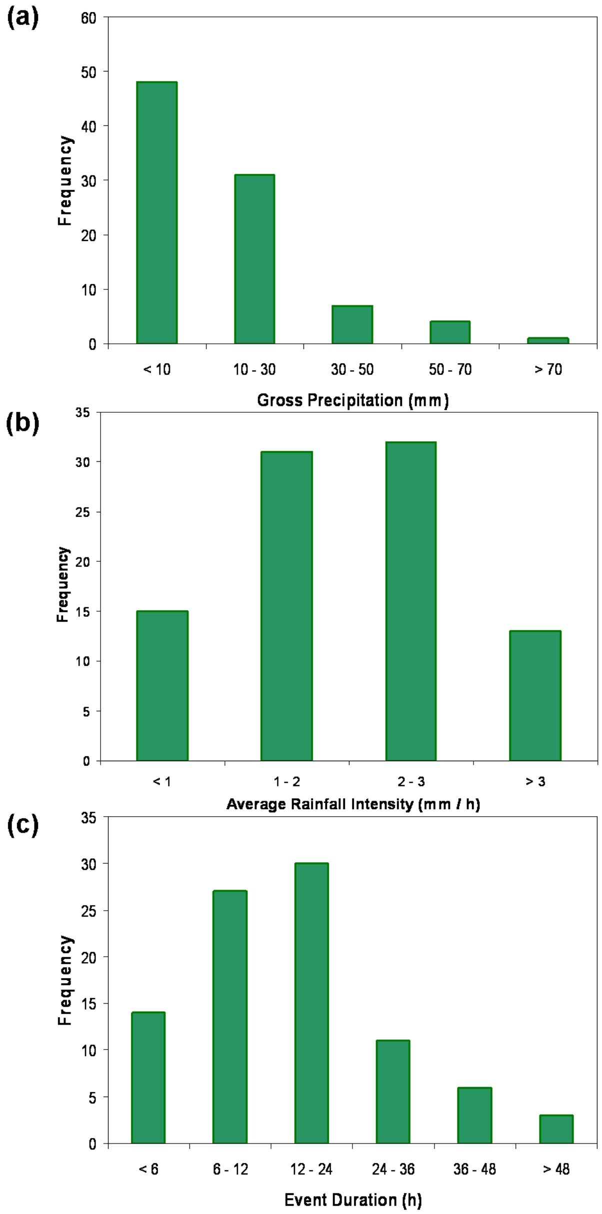

Figure 3.3: Summer season histograms of events used in the study:(a) gross precipitation; (b) average rainfall intensity; (c) event duration

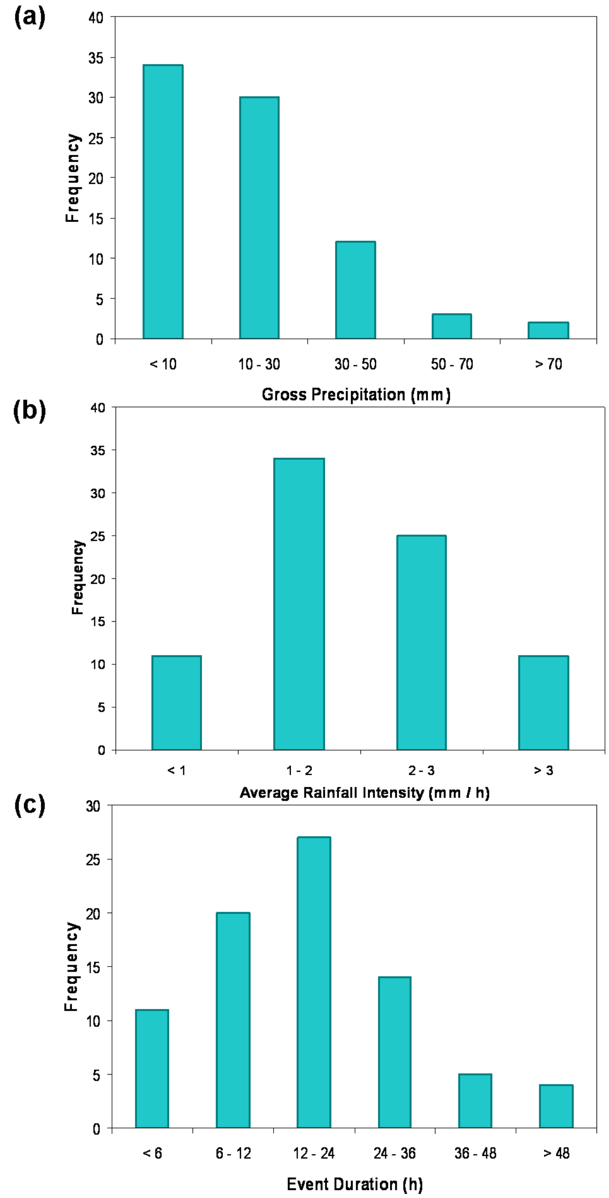

Figure 3.4: Winter season histograms of events used in the study: (a) gross precipitation; (b) average rainfall intensity; (c) event duration

3.2 Relation between Event Throughfall and Gross Precipitation

For the 54 selected trees during 2007 and 2008, 7042 events were recorded in total. 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 0º C. Also, many rain gauges/data loggers were vandalized or stolen; thus, there are missing data for some of the selected trees. Seasonal throughfall depth as a function of gross precipitation for both coniferous and deciduous trees is shown in Figures 3.5 and 3.6. The highest R^2 for throughfall and gross precipitation can be seen in deciduous trees during winter (Figure 3.6b), while the lowest R^2 is seen for coniferous trees during the summer (Figure 3.5a).

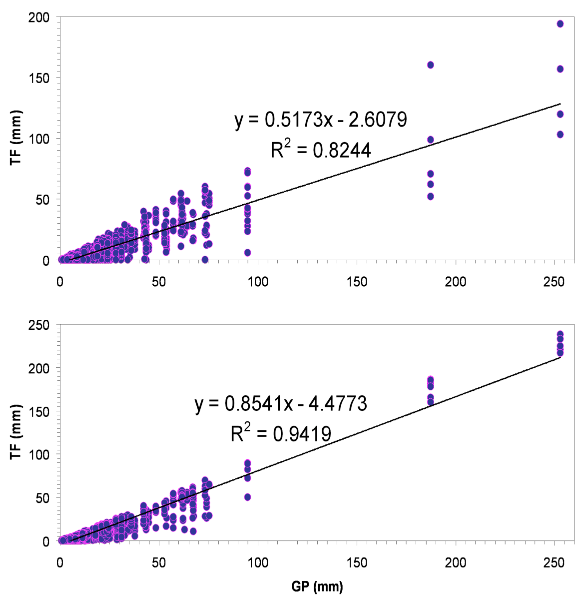

Figure 3.5: Throughfall as a function of gross precipitation (season: summer) for (a) coniferous and (b) deciduous trees.

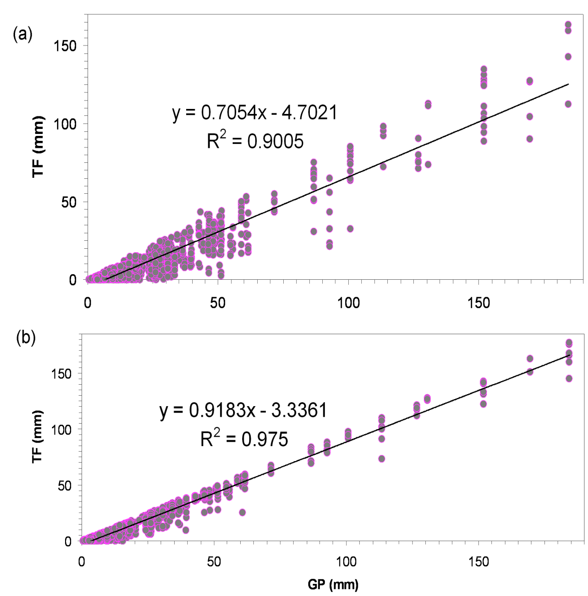

Figure 3.6: Throughfall as a function of gross precipitation (season: winter) for (a) coniferous and (b) deciduous trees.

3.2.1 Event Throughfall Patterns

Figures 3.7 and 3.8 provide an overview of the average temperature and throughfall depth for individual events in each season for coniferous and deciduous trees. The seasonal throughfall pattern is similar for both coniferous and deciduous trees; however, the only difference can be noted to be the magnitude. The highest amount of throughfall is seen during the summer season, particularly in the month of October (Figure 3.7a).

Event throughfall as a percentage of gross precipitation for coniferous trees averaged 35.5% and 46.6% for summer and winter respectively. While the event throughfall as a percentage of gross precipitation for deciduous trees averaged 57.6% and 74.9% for summer and winter respectively. It is evident that there is a higher throughfall percentage in deciduous trees particularly when they lose their leaves between mid October through April, while the highest throughfall amount was recorded to be 237.9 mm. Within-canopy seasonal mean temperatures were similar for both coniferous and deciduous trees. Figures 3.7 a and b show that the highest mean temperature was seen during the month of April and May (18.8 ºC). However the mean temperatures remained relatively high throughout June to September. The lowest mean temperature was -0.5 ºC during the month of January (Figures 3.8 a and b).

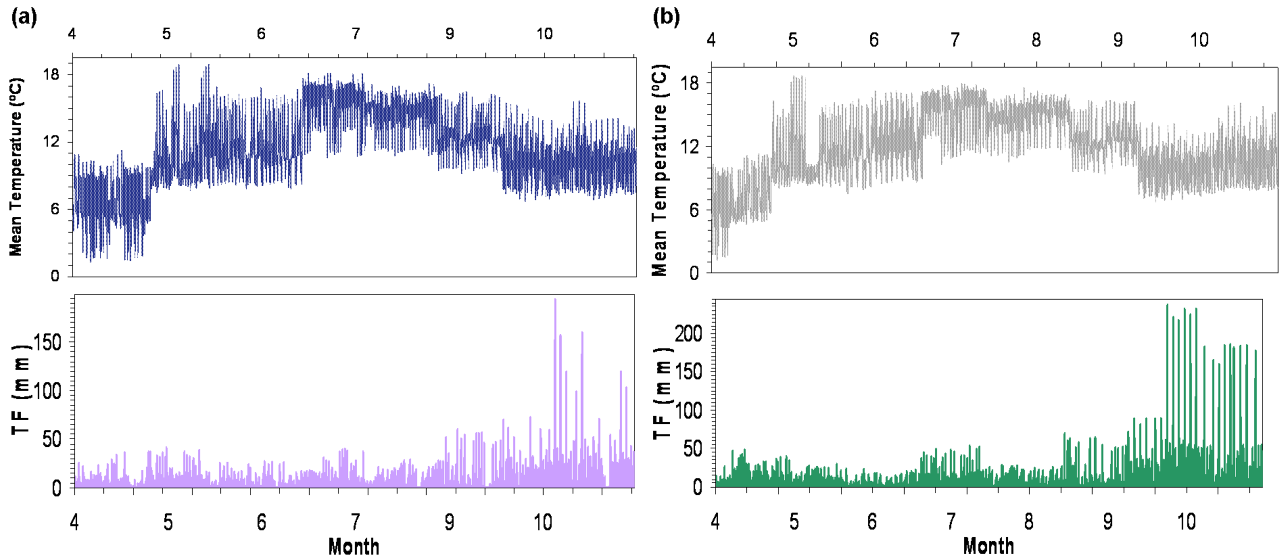

Figure 3.7: Summer event throughfall and average event temperature (a) coniferous; and (b) deciduous trees

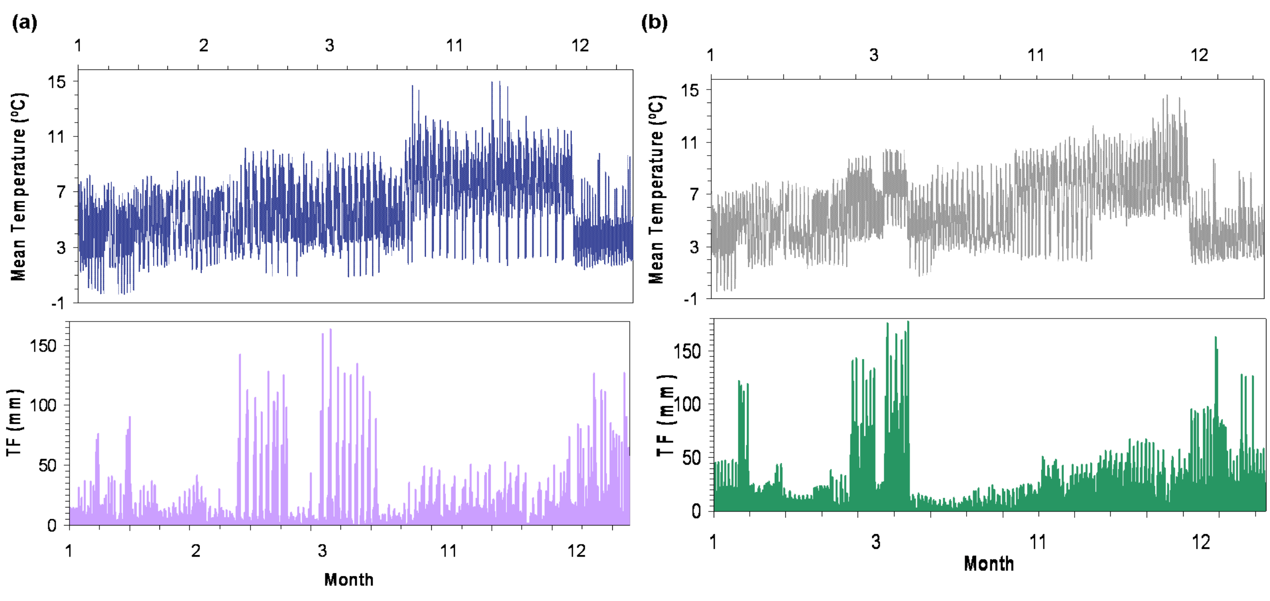

Figure 3.8: Winter event throughfall and average event temperature (a) coniferous; and (b) deciduous trees

3.2.2 Interception Loss

Figures 3.9 and 3.10 illustrate the variation in interception losses for different species. The results combined the variability among trees and storm events. For the summer season, the highest interception loss was demonstrated by Douglas-fir, and the lowest by Cherry trees. Copper beech had the highest variability in interception losses during summer; however, it is important to note that variability in the results was high for all species. Figure 3.9 emphasizes the outliers for Douglas-fir and Western red cedar. During winter the highest interception loss was yet again shown by Douglas-fir, followed by Western red cedar. Poplar and Oak had the lowest interception losses. Western red cedar had the highest variability for winter.

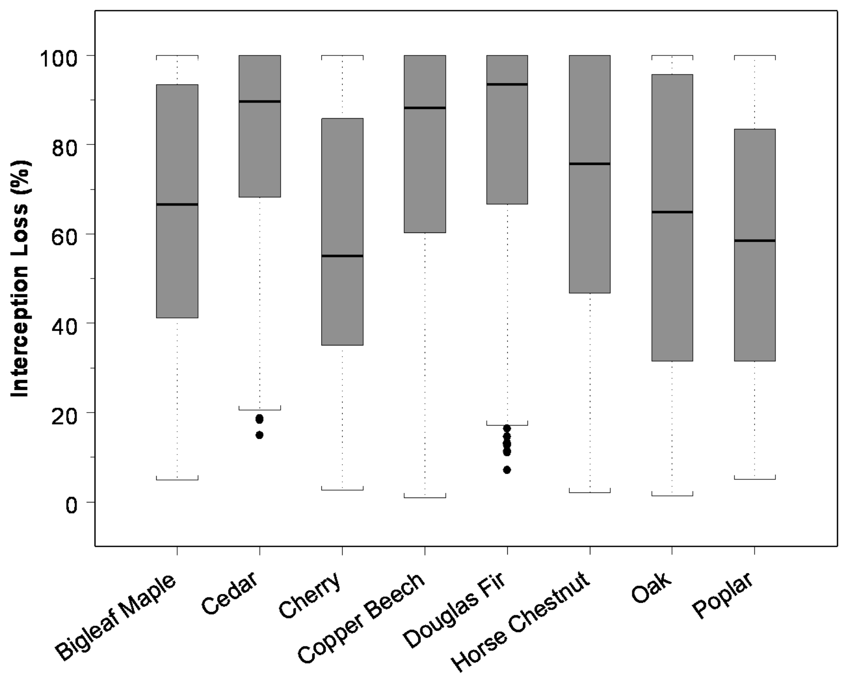

Figure 3.9: Box plot of percentage interception loss for different species in summer. The outliers are presented by black circles.

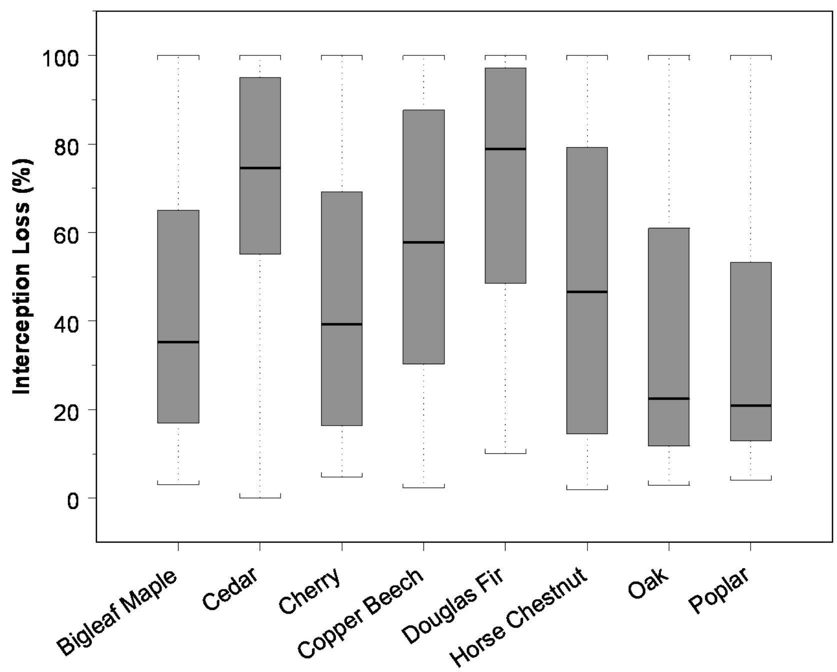

Figure 3.10: Box plot of percentage interception loss for different species in winter

3.2.3 Urban Trees vs. Control in Forest

Tables 3.2 and 3.3 illustrate the average interception loss (%) for all tree species within urban and forested areas for summer and winter season. In general, seasonal average interception losses are higher by both coniferous and deciduous trees located in the urban environments when compared to the ones in forested areas. It is important to indicate that the coniferous trees situated within forested areas showed 3.8 % higher average interception losses during winter season.

Table 3.2: Percentage of average interception loss during summer

	Coniferous	Deciduous
Control in Forest	78.8	55.6
Trees in Urban Environment	81.7	67.1

Table 3.3: Percentage of average interception loss during winter

	Coniferous	Deciduous
Control in Forest	74.1	36.5
Trees in Urban Environment	71.4	45.8

3.2.4 Climate and Precipitation Variability During an Event

Four discrete events were chosen between February 2007 and November 2008 for 9 trees (Tag numbers 586, 588, 590, 591, 18, 22, and 28) in the District of North Vancouver. Overall, the selected events fell into the high frequency categories, in terms of gross precipitation, intensity, and duration where they emphasized the seasonal variability (Figures 3.3 and 3.4). Canopy interception was derived from the difference between the P_g and T_F for individual events. The data for P_g were obtained from the reference climate station on the rooftop of the District of North Vancouver; however for comparison Table 3.4 includes P_g from a standard climate station in the District of North Vancouver and a non-standard rain gauge on the rooftop of North Vancouver's City Hall. These supplemental records were utilized to validate the tipping rain gauge data, thus ensuring correct identification of rainfall events.

Table 3.4: Rainfall depth from two other nearby stations

		Rain Gauge on the Rooftop of District of North Vancouver **Elevation = 130 m**	Standard Climate Station in the District of North Vancouver **Elevation = 130 m**	Rain Gauge on the Rooftop of City of North Vancouver **Elevation = 110 m**
Event	Duration of Measurement	P_G (mm)	P_G (mm)	P_G (mm)
1	March 10 –11, 2007	113.5	112.7	110.4
2	October 17 – 23, 2007	187.5	190.1	185.2
3	January 1 –2, 2008	27.4	29.2	25.8
4	June 9, 2008	24.3	25.2	24.8

Table 3.5 highlights the event characteristics. Selected events generated 352.8 mm of gross precipitation with a maximum hourly rainfall intensity of 4.47 mmh^{-1}. This intensity corresponds to a 2 year event in this area (Denault et al. 2006). These obtained results reflect on the rainfall

characteristics in the North Shore, where frontal system produces long durations and relative low rainfall intensities.

Table 3.5: Event characteristics

Event	Duration of Measurement	Duration (h)	P_G (mm)	Average rainfall intensity (mmh^{-1})	Maximum rainfall intensity (mmh^{-1})	Average Temperature (ºC)	Wind Speed ms^{-1}
1	March 10 –11, 2007	36.5	113.5	3.09	4.62	9.3	0.44
2	October 17 – 23, 2007	141	187.5	1.33	4.52	6.9	0.03
3	January 1 –2, 2008	10.5	27.4	2.55	4.51	3.5	0.03
4	June 9, 2008	14.75	24.3	1.62	4.22	8.2	0.03

Precipitation and above and within canopy climate data for coniferous (Douglas-fir, and Western red cedar) and deciduous (Copper beech and Horse chestnut) for event 2 are shown in Figures 3.11, 3.12, and 3.13. It is important to note that there are no data available for Poplar tree (#28) due to rain gauge failure (clogging) for event 2. 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 2 began at 0400 hours on October 17 and lasted 141 hours. During this period, 187.5 mm of precipitation was recorded by the reference rain gauge on the rooftop of District of North Vancouver. The precipitation intensity, humidity, wind speed, and temperature were typified as moderately low. Figures 3.11a, 3.12a, and 3.13a illustrate that there was not much variation between the measured temperatures above and below the canopy for all selected trees. Wind speed was below 0.1 ms^{-1}. Average humidity was above 95%. The amount of throughfall captured underneath each canopy averaged 45.6% and 90.9% (85.6 mm and 170.4 mm) for coniferous and deciduous trees, respectively. Figures 3.11b, 3.12b, and 3.13b show that throughfall levels for both species are not constant, but are dynamic. The difference in gross precipitation and net precipitation magnitude is shown in Figures 3.11c, 3.12c, and 3.13c.

Table 3.6 presents the delay in throughfall reaching the ground for all study sites. The delay ranged from 4.25 – 6.25 hours for event 2. This delay did not affect the peak in net precipitation; however, as shown by Xiao et al. (2002) this would delay the peak runoff for a storm. Throughfall ceased roughly between 0.25 – 1.50 hours after the rainfall stopped for tag numbers: 586, 590, 591, and 22. However, for the trees with tag numbers 588 and 18, the throughfall ceased approximately 12.50 hours before the end of event 2.

The average rainfall intensity for event 2 was determined by dividing the gross precipitation by the rainfall duration. Figures 3.11c, 3.12c, and 3.13c 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 (Brooks et al. 2003; Link et al. 2004)

Table 3.6: Lag time between gross precipitation and throughfall

Tag #	Event 1 Start Time (h)	Event 2 Start Time (h)	Event 3 Start Time (h)	Event 4 Start Time (h)
586	2.0	6.25	1.0	5.0
588	2.25	6.25	4.25	2.75
590	1.5	4.5	3.5	1.75
591	2.25	6.5	4.0	6.0
18	1.0	6.0	2.25	5.0
22	0.75	4.25	3.00	3.5
28	1.25	-	3.00	1.5

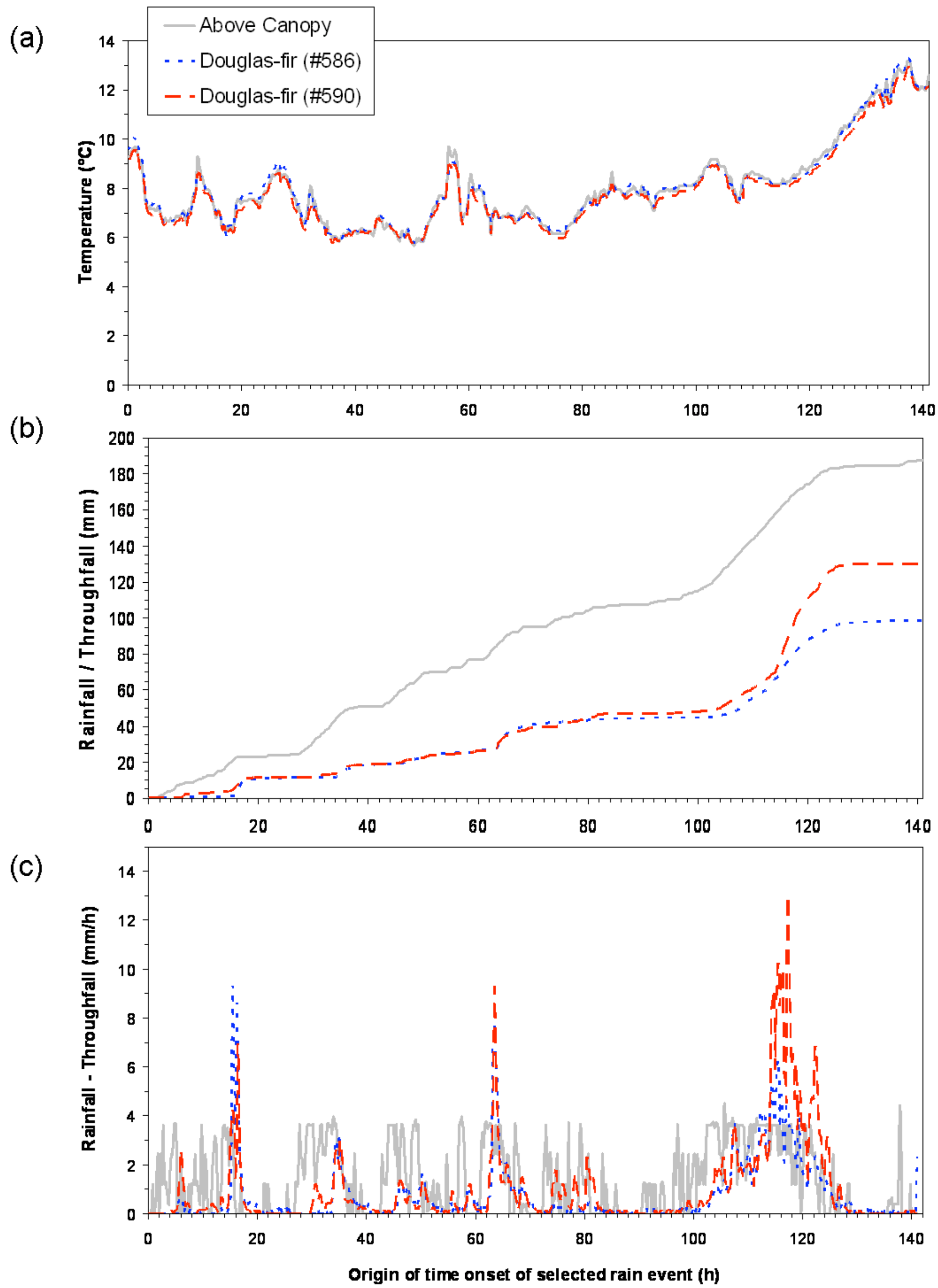

Figure 3.11: Meteorological and throughfall data for rainfall event two (Douglas-fir)

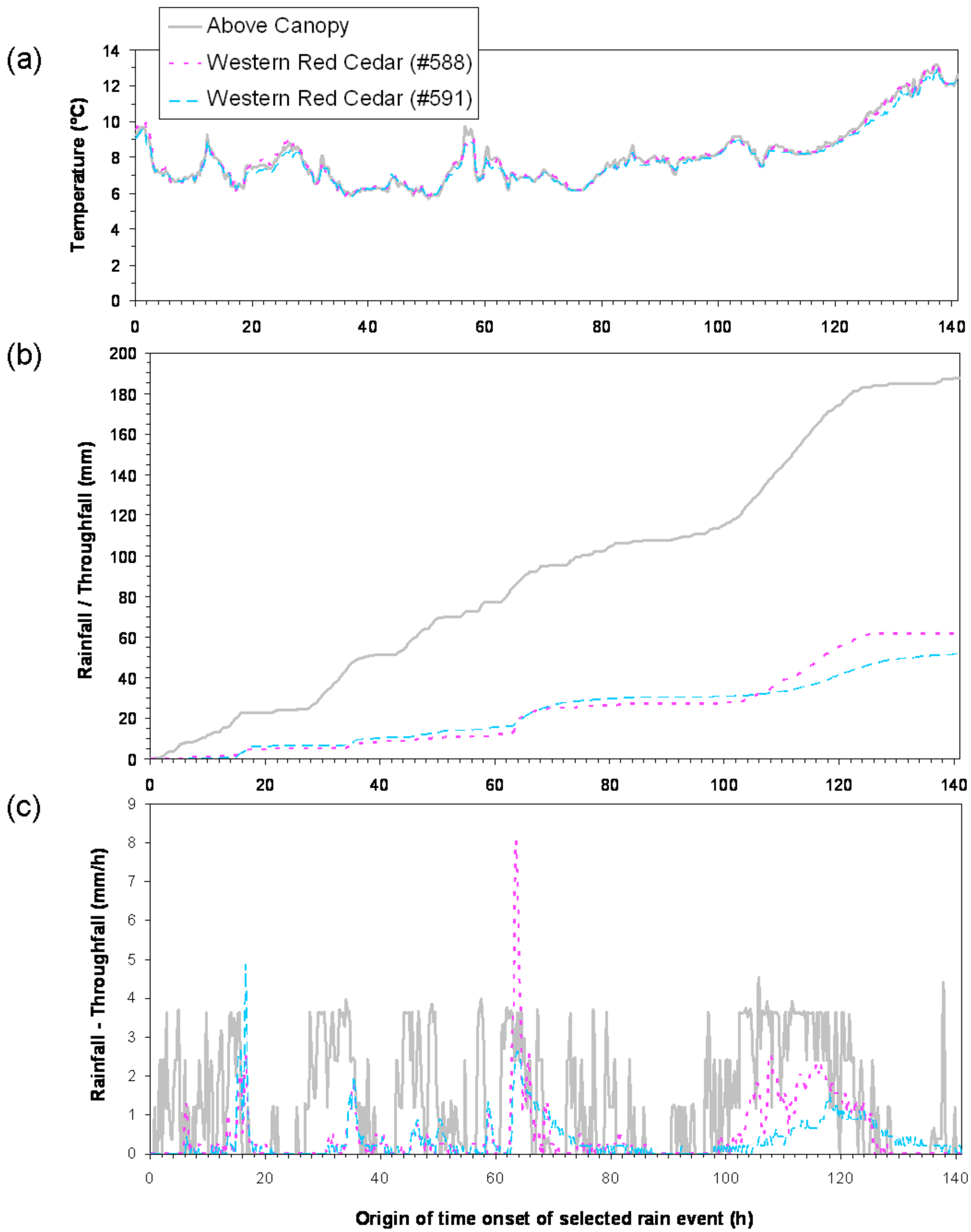

Figure 3.12: Meteorological and throughfall data for rainfall event two (Western red cedar)

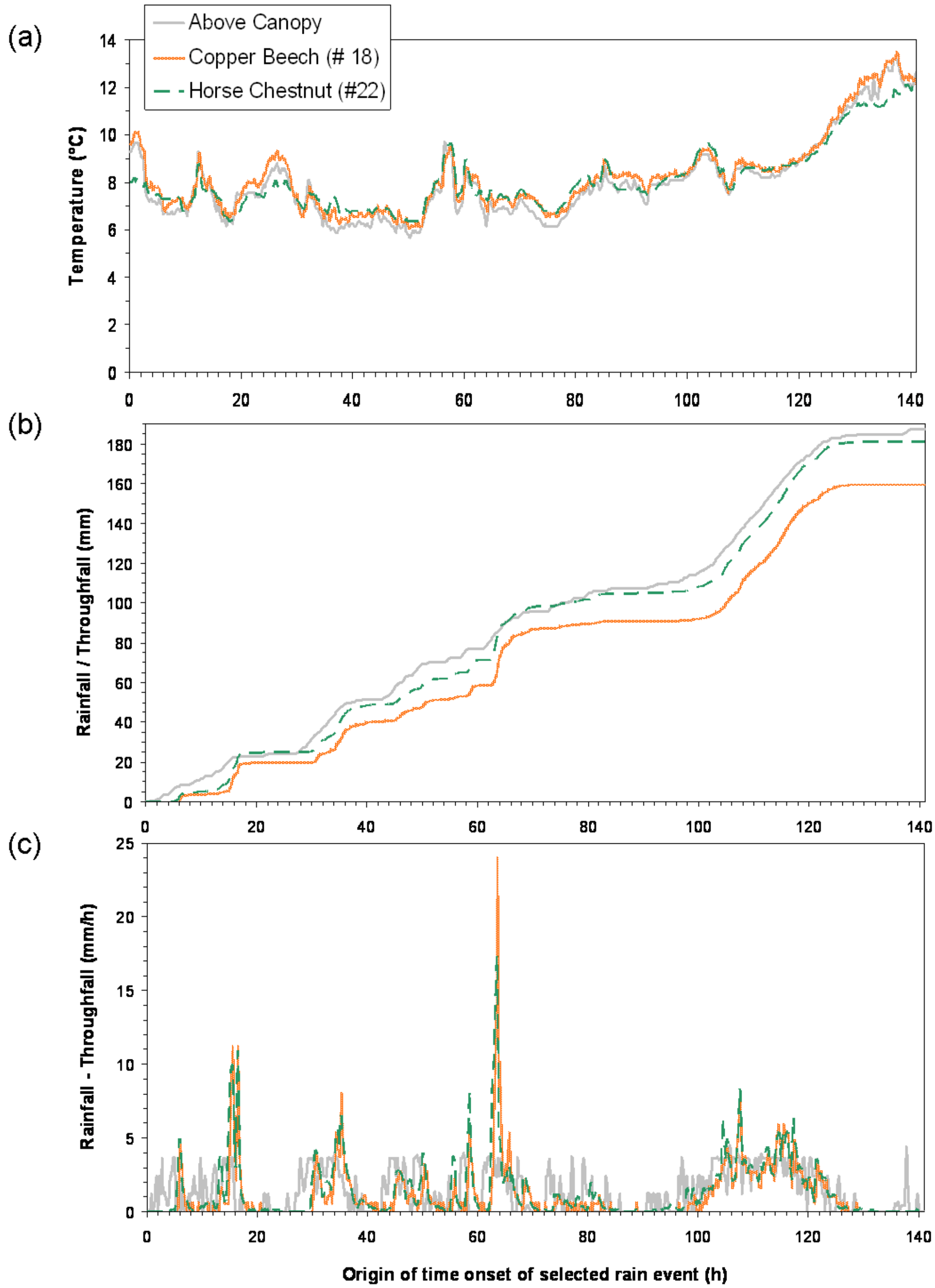

Figure 3.13: Meteorological and throughfall data for rainfall event two (Deciduous trees)

Table 3.7 summarizes the interception losses for the selected trees and events. When evaluating the average interception losses, it is evident that two of the cedar trees (#588, 591) overall showed the highest interception losses. Both Western red cedar trees were co-dominant; however, one was of good health condition and the other poor. Events 2 and 4 occurred during summer, when both Douglas-fir and Western red cedar had high interception losses compared to the deciduous trees. The highest interception loss was in event 4 by a dominant Douglas-fir of a poor condition. Based on the results, compared to Western red cedar the Douglas-fir trees showed a wider range of interception losses during the seasons. It is important to note that deciduous trees demonstrated lower interception losses than coniferous trees. The lowest and highest interception loss for deciduous trees was by a single standing Horse chestnut tree in good condition during event 2 and a single standing Copper beech in good condition during event 4 correspondingly. This high variability in the results was due to the species defoliation with the onset of the cooler weather in autumn and winter.

Event 4 was the smallest precipitation event and had the highest interception losses with 24.3 mm of gross precipitation over 14.75 hours duration. The average temperature was recorded as 8.2 ºC with maximum rainfall intensity of 4.22 mmh^{-1}. Event 3 had the shortest duration in comparison to the other selected events. In general, rainfall type plays a role in determining interception loss. For instance, a low intensity, long-duration frontal rainfall generates different interception loss than a high intensity short duration convectional storm (Deguchi et al. 2006; Pypker et al. 2005; Xiao et al. 2000b).

Table 3.7: Percentage of interception for the selected rainfall events

	Event 1	Event 2	Event 3	Event 4
Tag #	I_{net} (%)	I_{net} (%)	I_{net} (%)	I_{net} (%)
586	15.92	47.32	38.09	82.21
588	36.21	67.10	50.83	74.89
590	13.52	30.64	20.72	11.42
591	18.77	72.42	53.60	82.14
18	19.63	14.88	10.65	59.03
22	10.10	3.40	40.01	51.20
28	5.62	-	16.07	27.66

3.3 Variables Influencing Interception Loss

The potential influence of tree species, condition and type was tested with linear regressions for all the selected trees. The analysis included a factor variable (season) in interception loss between summer and winter. Histograms and quantile–quantile (QQ) plots of regression indicated that residuals were approximately normally distributed with no apparent heteroscedasticity. It is important to note that due to structural damage, the tree with tag number 16 did not produce any reliable data; thus, no substantial analysis was conducted on this site. Figures 3.14 to 3.17 illustrate the seasonal variation in the throughfall for a coniferous and a deciduous tree. As seen in Figures 3.14 and 3.15 for Western red cedar the intercepts were -1.43 mm and -4.82 mm while the slopes were equivalent to 0.30 and 0.61 for summer and winter, respectively. Calculated R^2 values were 0.90 (summer) and 0.89 (winter). Bigleaf maple intercepts were -5.2 mm for summer and -2.88 mm for winter as seen in Figures 3.16 and 3.17. The slopes were recorded to be 0.90 and 0.89 with R^2 equivalent to 0.98 and 0.97 for summer and winter correspondingly. The data appeared to have a clear seasonal trend in the residual plots, where more throughfall was seen during winter.

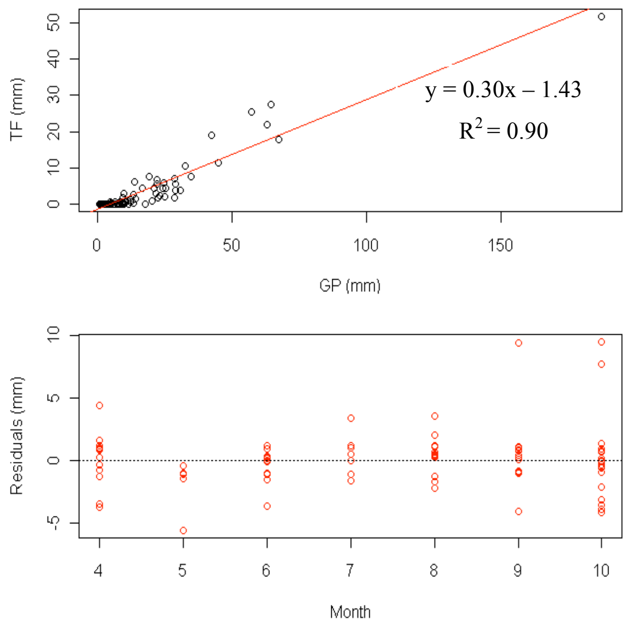

Figure 3.14: Relationship between throughfall and gross precipitation; and residual plot for a single standing Western red cedar in a good condition (tag # 591) during summer

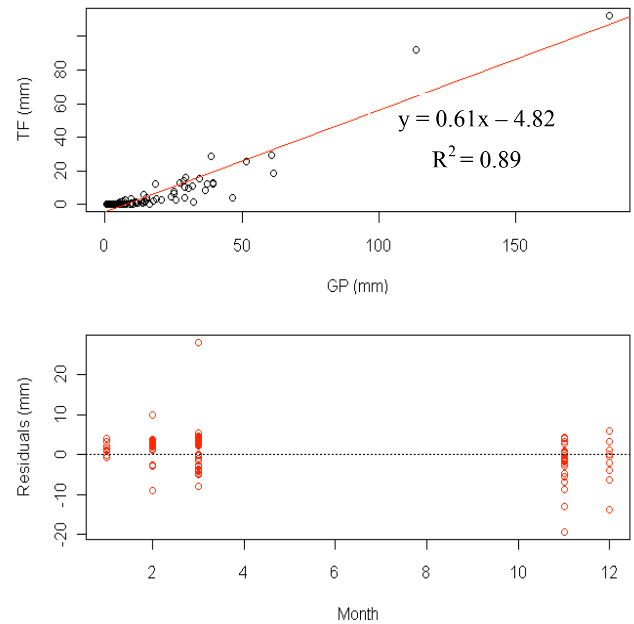

Figure 3.15: Relationship between throughfall and gross precipitation; and residual plot for a single standing Western red cedar in a good condition (tag # 591) during winter

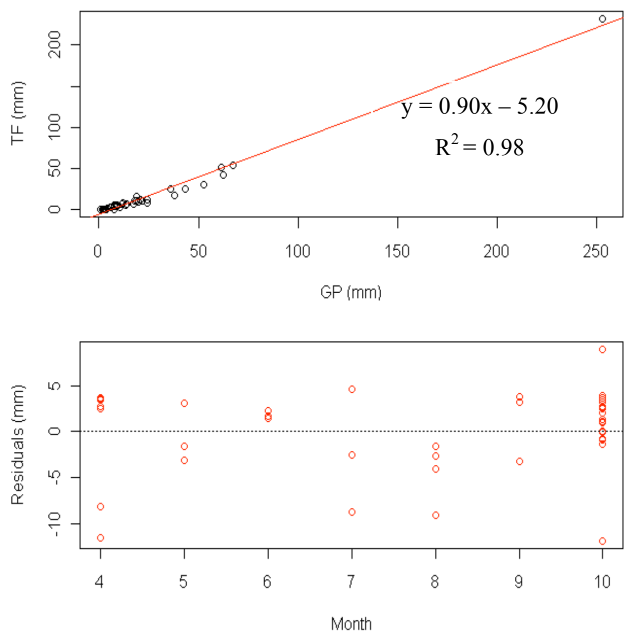

Figure 3.16: Relationship between throughfall and gross precipitation; and residual plot for a single standing Bigleaf maple in a good condition (tag # 597) during summer

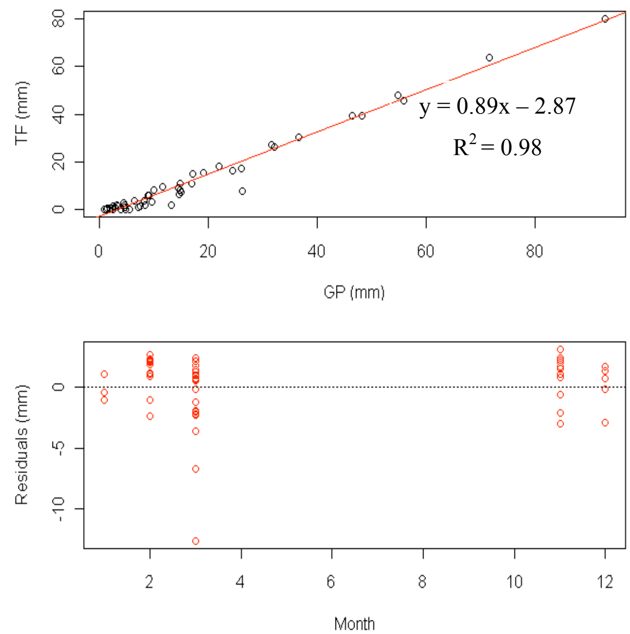

Figure 3.17: Relationship between throughfall and gross precipitation; and residual plot for a single standing Bigleaf maple in a good condition (tag # 597) during winter

Appendix A provides a summary of seasonal regression coefficients for individual trees. Equation 3.1 is used to determine whether the regressions between T_F and P_g significant. The significance level, α, was set to 0.05. The hypotheses tested were:

H_0: $\beta = 0$

H_1: $\beta \neq 0$

The test statistic is:

$$F = \frac{MSreg}{MSE} \qquad \text{Equation 3.1}$$

In all cases, the null hypothesis can be rejected, since the p-values for the F-statistic are less than 0.05. Seasonal regressions for all selected trees were significant.

Seasonal box plots of slopes and R^2 coefficients for different species are illustrated in Figures 3.18 to 3.21. Deciduous trees had higher slopes for both summer and winter with not much variation in range. Coniferous trees showed lower slopes, which can be explained by the lower amounts of throughfall passing through the canopies. Variation in range for coniferous trees was higher for both seasons. There are strong relations between species and throughfall for winter and summer: all R^2 for both seasons were above 0.9. There are outliers present for R^2 coefficients for Bigleaf maple and Douglas-fir trees during both seasons (Figures 20 and 3.21); however, for the slope coefficients it is only evident during the summer season.

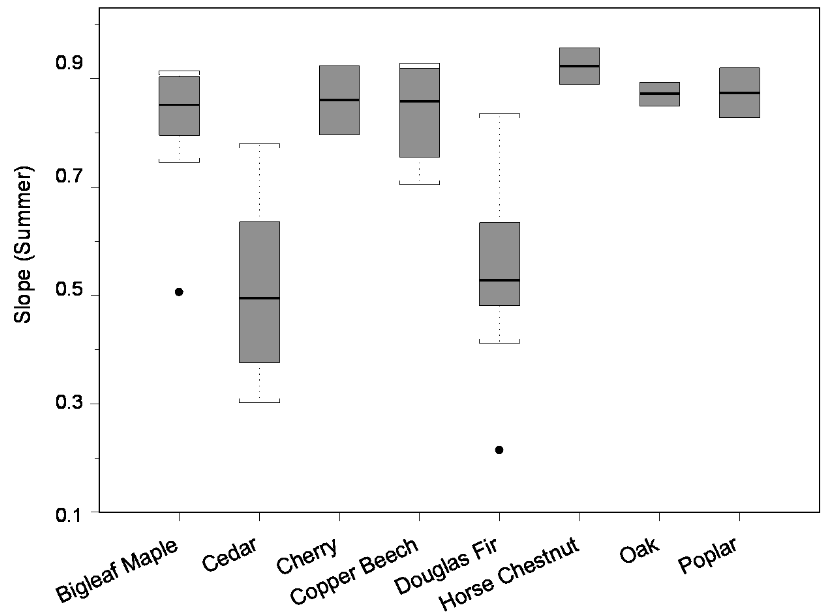

Figure 3.18: Box plot of slope coefficients for different species (summer). The outliers are presented by black circles.

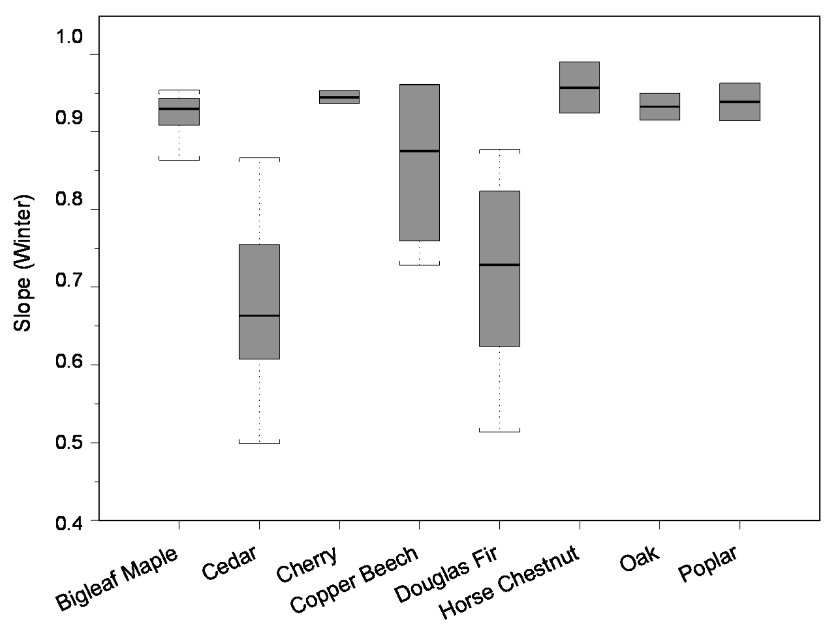

Figure 3.19: Box plot of slope coefficients for different species (winter)

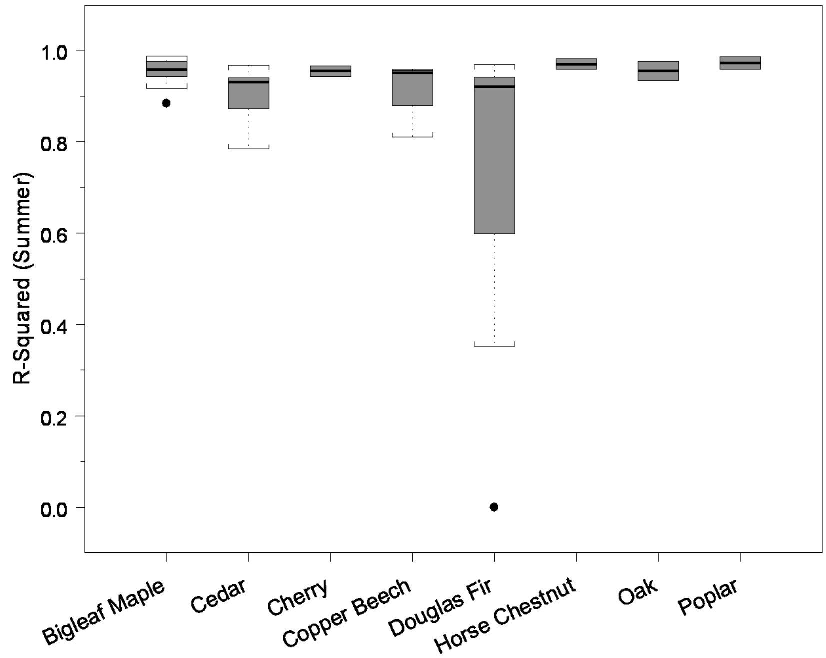

Figure 3.20: Box plot of R^2 coefficients for different species (summer). The outliers are presented by black circles.

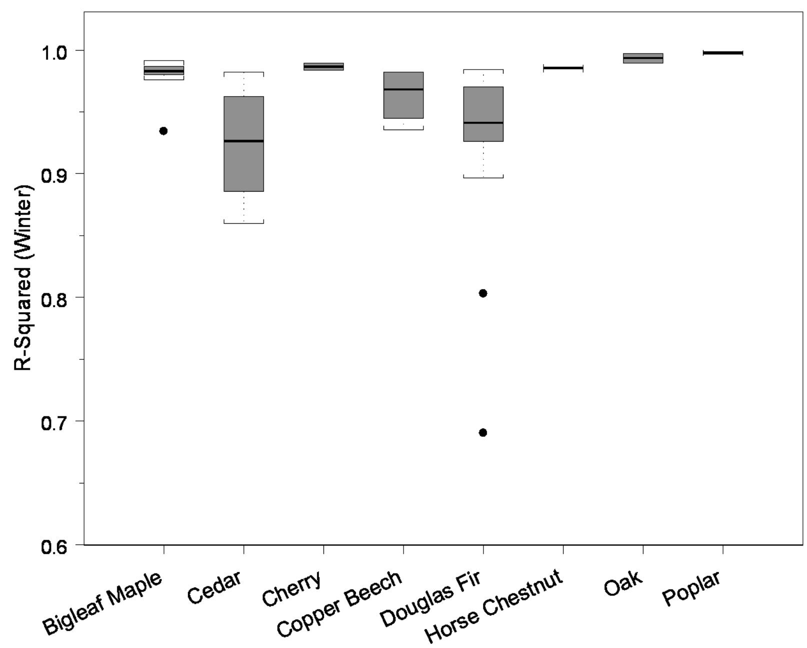

Figure 3.21: Box plot of R^2 coefficients for different species (winter). The outliers are presented by black circles.

3.3.1 Throughfall – Assessed Attributes Relationships

Table 3.8 shows the seasonal coefficients for different tree species, condition and type. These attributes are important in predicting the amount of throughfall, which depends on rainfall depth and seasonal variability. It is crucial to mention that the regressions obtained are from averaging the values obtained from individual trees. When evaluating regressions, it is evident that single standing Horse chestnut trees in poor condition had the highest slope for both seasons. Poplar and Copper beech trees, both single standing and in poor conditions demonstrated high slope values during winter season. During the summer season, Bigleaf maple trees (control in forest) and Poplar trees in good condition (single standing) had high slopes. R^2 values were highest in deciduous trees. When contrasting control trees, Bigleaf maple showed the highest slope and R^2 than Western red cedar and Douglas-fir for both seasons. Douglas-fir control trees demonstrated the lowest slope and R^2 during the summer.

Table 3.8: Seasonal regression (T_F vs. P_g) coefficients for different tree species, types and health conditions

Species	Condition	Type	Winter b_0[b]	Winter b_1[c]	Winter R^2	Winter SE[a]	Summer b_0[b]	Summer b_1[c]	Summer R^2	Summer SE[a]
Douglas-fir	Good	Co-dominant	-3.96	0.74	0.94	4.27	-2.36	0.59	0.95	3.03
Douglas-fir	Good	Dominant	-6.26	0.65	0.87	6.27	-2.17	0.31	0.64	4.5
Douglas-fir	Good	Single	-4.68	0.62	0.81	5.01	-3.43	0.52	0.67	5.23
Douglas-fir	Poor	Co-dominant	-5.54	0.78	0.96	3.76	-3.58	0.66	0.93	3.18
Douglas-fir	Poor	Dominant	-4.92	0.68	0.93	6.89	-1.93	0.51	0.46	3.77
Douglas-fir	Poor	Single	-4.21	0.86	0.98	3.32	-2.92	0.74	0.92	4.00
Douglas-fir		Control	-4.71	0.72	0.95	3.52	-2.05	0.51	0.77	4.09
Western red cedar	Good	Co-dominant	-3.87	0.65	0.91	3.87	-2.25	0.46	0.9	3.26
Western red cedar	Good	Dominant	-4.06	0.74	0.95	4.08	-4.44	0.75	0.96	3.81
Western red cedar	Good	Single	-4.11	0.62	0.93	4.26	-2.3	0.48	0.92	2.65
Western red cedar	Poor	Co-dominant	-5.06	0.64	0.89	5.9	-1.44	0.34	0.85	2.95
Western red cedar	Poor	Dominant	-3.34	0.6	0.93	3.75	-2.17	0.43	0.89	3.47
Western red cedar	Poor	Single	-5.97	0.71	0.94	4.46	-2.98	0.49	0.94	3.34
Western red cedar		Control	-4.22	0.7	0.91	4.07	-2.78	0.6	0.9	3.14
Bigleaf maple	Good/Broad	Co-dominant	-3.81	0.94	0.98	3	-4	0.86	0.97	3.68
Bigleaf maple	Good/Broad	Dominant	-3.17	0.89	0.99	2.72	-3.88	0.65	0.91	4.9
Bigleaf maple	Good/Broad	Single	-3.92	0.91	0.96	3.65	-5.18	0.88	0.97	4.02
Bigleaf maple	Poor/Less broad	Co-dominant	-3.31	0.92	0.98	2.73	-4.6	0.86	0.95	4.41
Bigleaf maple	Poor/Less broad	Dominant	-3.5	0.94	0.98	3.08	-4.7	0.81	0.93	5.44
Bigleaf maple	Poor/Less broad	Single	-2.89	0.93	0.99	2.79	-3.22	0.82	0.95	3.28
Bigleaf maple		Control	-2.74	0.94	0.99	2.33	-3.79	0.89	0.99	2.88
Cherry	Good/Broad	Single	-4.28	0.95	0.98	3.22	-4.5	0.92	0.97	4.25
Cherry	Poor/Less broad	Single	-2.1	0.94	0.99	1.53	-2.31	0.8	0.94	2.52
Copper beech	Good/Broad	Single	-3.65	0.83	0.96	3.61	-5.34	0.81	0.9	6.06
Copper beech	Poor/Less broad	Single	-3.91	0.96	0.98	2.63	-5.81	0.93	0.96	4.95
Horse chestnut	Good/Broad	Single	-3.86	0.92	0.99	3.35	-4.72	0.89	0.96	4.36
Horse chestnut	Poor/Less broad	Single	-3.4	0.99	0.99	2.36	-4.58	0.96	0.98	3.35
Oak	Good/Broad	Single	-2.33	0.91	0.99	2.96	-5.48	0.89	0.93	6.26
Oak	Poor/Less broad	Single	-1.94	0.95	0.99	1.54	-2.02	0.85	0.98	1.72
Poplar	Good/Broad	Single	-1.64	0.91	0.99	1.09	-3.54	0.92	0.99	2.97
Poplar	Poor/Less broad	Single	-2.53	0.96	0.99	2.06	-2.51	0.83	0.96	2.55

[a]SE = Standard Error
[b] b_0 = Intercept
[c] b_1 = Slope

A two-way analysis of variance is used to test the equality of seasonal means of slopes and intercepts obtained from regressions for Douglas-fir, Western red cedar, and Bigleaf maple. For the rest of species, the analysis of variance could not have been completed, since they did not have at least two observations for each factor level.

The significance level, α, was set to 0.05. Two sets of hypotheses were developed for health condition and tree type.

(1) Health condition:

H_0: Seasonal mean of slopes and intercepts for species' health conditions are equal.

H_1: Seasonal mean of slopes and intercepts for species' health conditions are not equal.

(2) Tree type:

H_0: Seasonal mean of slopes and intercepts for different tree types are equal.

H_1: Seasonal mean of slopes and intercepts for different tree types are not equal.

The probability values for ANOVA tests were all greater than 0.05 except for Douglas-fir trees' summer slope, with trees in poor condition having significantly higher slopes than trees in good condition (Table 3.9). With that exception, all the other null hypotheses cannot be rejected.

Table 3.9: Summary of results for ANOVA analysis

Condition: Poor – Good								
	Winter Intercept		Winter Slope		Summer Intercept		Summer Slope	
Species	F	P-Value	F	P-Value	F	P-Value	F	P-Value
Douglas-fir	0.003	0.96	2.14	0.18	0.04	0.85	7.28	**0.03**
Western red cedar	0.54	0.48	0.06	0.81	1.70	0.23	3.07	0.12
Bigleaf maple	1.01	0.34	0.48	0.50	0.08	0.78	0.32	0.59

Type: Dominant – Co-dominant – Single								
	Winter Intercept		Winter Slope		Summer Intercept		Summer Slope	
Species	F	P-Value	F	P-Value	F	P-Value	F	P-Value
Douglas-fir	0.22	0.81	0.58	0.58	0.75	0.51	3.96	0.07
Western red cedar	0.54	0.6	0.04	0.96	1.88	0.21	1.83	0.22
Bigleaf maple	0.11	0.89	0.22	0.80	0.01	0.98	1.77	0.23

Canopy storage capacity (S) for all the selected species was estimated from the regressions of T_F against P_g where the negative intercept was S. Table 3.10 illustrates average storage capacities for different species for each season. Average winter S for deciduous species were not calculated as they lose their leaves during this period. It is evident that all deciduous trees demonstrated high storage capacity during the summer season, when they retain their leaves. On the other hand, coniferous trees showed higher storage capacity during winter throughout the dormant season.

Table 3.10 shows the estimated summer canopy cover (c) for different tree species. In general, all tree species showed high canopy coverage during the summer season. Bigleaf maple trees showed the highest canopy cover, as a result of having larger leaves with greater surface areas. No hemispherical photographs were taken during the winter as we assumed that the coniferous trees maintained the same canopy cover throughout the year, while deciduous trees canopy cover approximated to 0 due to defoliation.

Table 3.10: Seasonal storage capacity (mm) and canopy cover (c) estimations

Species	Average Winter S (mm)	Average Summer S (mm)	Summer Canopy Gap Fraction	Summer Canopy Cover (c)
Douglas-fir	4.9	2.8	0.10	0.90
Western red cedar	4.4	2.6	0.10	0.90
Bigleaf maple	-	4.2	0.08	0.92
Cherry	-	3.4	0.10	0.90
Copper beech	-	5.5	0.13	0.87
Horse chestnut	-	4.6	0.11	0.89
Oak	-	3.7	0.09	0.91
Poplar	-	3.0	0.10	0.90

3.4 Efficiency of Throughfall Gauges

This section examines the effectiveness of the innovative throughfall gauges. Sources of error were the precision of data logger time accuracy (±1 min), the tipping buckets (±0.23 mm) and volume measurement (±1 mL). The measurement errors were small. Figure 3.22 represents the relationship between the results obtained from the roving bottles and the pipes (throughfall gauges). It appears that there is a strong relationship between the two measurement techniques. Regression analysis for individual trees was conducted (Table 3.11). All trees, except one (Douglas-fir, # 11) had R^2 values above 0.9. F-statistic test is used to determine whether the regressions between the results obtained from the bottles and the results obtained from the pipes are significant. The significance level, α, was set to 0.05. The hypotheses tested were:

H_0: The regression is not significant.

H_1: The regression is significant.

The probability values for the F statistics tests were less than 0.05 (Table 3.11); therefore, the null hypothesis can be rejected. Regressions for all selected trees were significant.

Equation 3.2 shows the chi-square (χ^2) test used to examine the significance of the differences between the throughfall obtained from the bottles and pipes. The significance level, α, was set to 0.05. The hypotheses tested were:

H_0: There is no difference between the throughfall captured by pipes and bottles

H_1: There is a difference between the throughfall captured by pipes and bottles

$$\chi^2 = \sum \left[\frac{TF_{PIPES_i} - TF_{BOTTLES_i}}{SE_{BOTTLES}} \right]^2 \qquad \text{Equation 3.2}$$

The probability values for the χ^2 tests were less than 0.05. Therefore, there is a difference between the throughfall captured by pipes and bottles as seen in Table 3.11. Consequently the null hypothesis can be rejected. The difference between the amount of throughfall captured by pipes and bottles for the duration of mid September to the end of August was 157.8 mm. It is evident that pipes are capturing 1.17 times more throughfall than bottles.

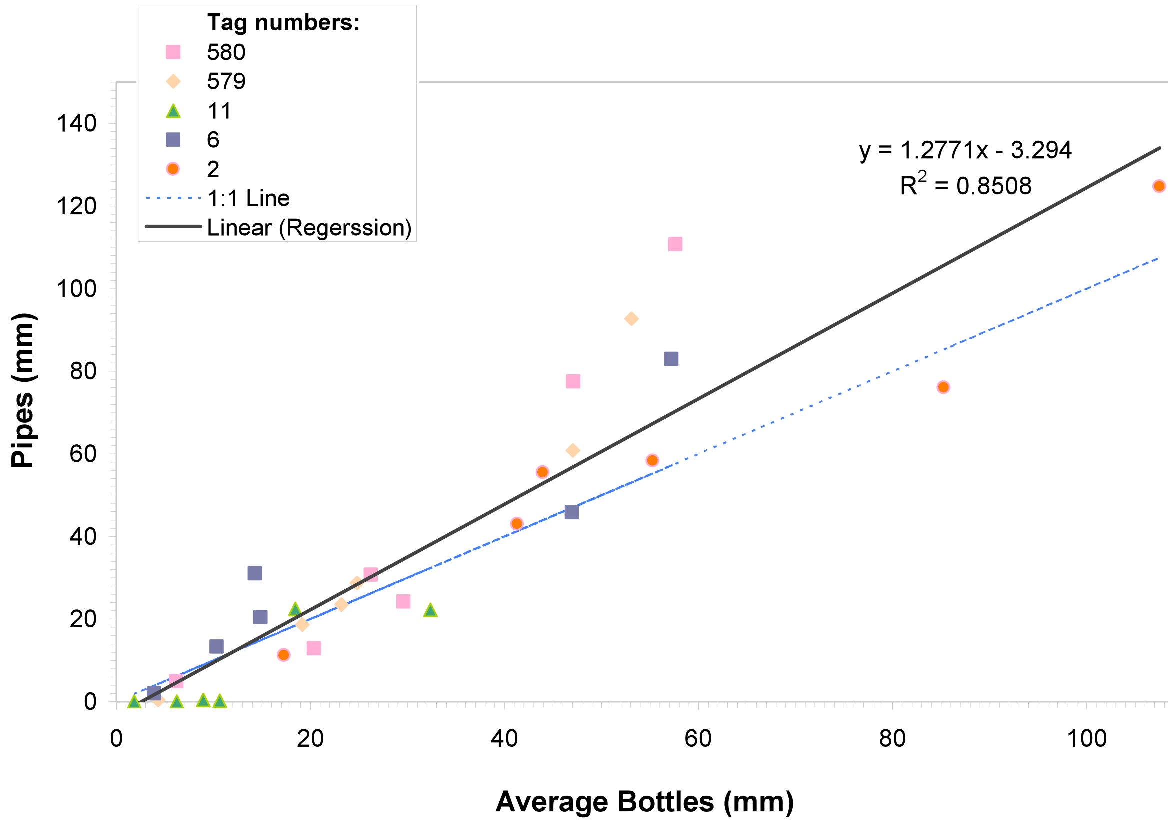

Figure 3.22: The relationship between throughfall measured by innovative throughfall gauges and bottles for 5 selected trees (6 events)

Table 3.11: Regression coefficients from throughfall gauges and bottles for the selected trees (n = 6 events)

Tag #	Species	Intercept	Slope	R^2	F	Significance F	Chi-Squared	χ^2 df	χ^2 Calculated	χ^2 Critical
2	Bigleaf maple	-3.98	1.12	0.94	61.62	0.0015	120.32	6	120.32	12.59
6	Douglas-fir	0.96	1.26	0.90	37.48	0.0040	70.98	6	70.98	12.59
11	Douglas-fir	-4.43	0.92	0.76	12.91	0.0230	32.02	6	32.02	12.59
579	Western red cedar	-13.59	1.79	0.95	73.55	0.0010	185.06	6	185.06	12.59
580	Western red cedar	-23.64	2.15	0.92	48.83	0.0022	44.18	6	44.18	12.59

Chapter 4
Discussion

4.1 Canopy Interception Loss

High temporal resolution and measurements of canopy rainfall interception at the individual tree level can be obtained using the innovative throughfall measurement system. The throughfall results indicate that interception is influenced by seasonal differences in foliation periods and rainfall characteristics. Figure 3.5 suggests that the relationship between throughfall and incident precipitation is higher during winter for deciduous trees. This may be as a result of having no foliage, where throughfall amounts were close to the amount of gross precipitation for all deciduous trees. In addition, for some deciduous trees there were far more winter than summer events. Our data show that, on average, deciduous trees' interception loss was about 45% of gross precipitation during the winter. Additionally, during the summer season, deciduous trees demonstrated the highest relationship as seen in Figure 3.6. This can be explained by the high surface areas of the leaves.

With reference to Figures 3.7 and 3.8 it can be said that the throughfall pattern is similar for both coniferous and deciduous trees; however, the magnitude differs. Moreover, temperature seemingly plays a role in controlling the amount of throughfall reaching the ground. During the months of May – June (Figures 3.7 and 3.8) throughfall amount was noticed to be lower. This can both be due to high temperatures and the gross precipitation characteristics (duration, amount, and intensity). The highest amount of throughfall was observed from October – March. Figure 3.8a shows a higher throughfall amount during March for coniferous trees. This can be explained by having higher rain gauge failures for deciduous tree species where numerous events were eliminated.

The interception loss for deciduous trees averaged to 67.1% and 45.8% of the gross precipitation for the summer and winter respectively. Based on our results, coniferous trees intercepted more rainfall than deciduous trees all year around. For coniferous trees our results demonstrate that on average the interception loss was approximately 81.7% and 71.4% of gross precipitation for summer and winter respectively. When comparing interception losses amongst species, both Douglas-fir and Western red cedar demonstrated outliers during the summer season (Figure 3.9). These outliers can be as a result of canopy structures' characteristics, climatic conditions or sampling error during events. In general, urban trees showed higher interception losses than control trees within forested areas.

4.1.1 Event Based Analysis

Interception loss is determined as the difference between gross precipitation and the sum of throughfall and stemflow. Based on the obtained throughfall data, the average I_{net}% for the four events ranged between 44.7% and 23.5% of gross precipitation for coniferous and deciduous trees respectively. Based on the variability in rainfall amount, intensity and duration, the interception losses for coniferous trees in the selected events ranged from 11.4% and 82.2%, which were 2.8 mm and 19.9 mm of gross precipitation correspondingly. While for deciduous trees the interception loss varied between 3.4% and 59.0%, which were 6.4 mm and 14.3 mm of gross precipitation in that order. The lowest interception losses occurred during events 1 and 2 for a Horse chestnut and a Poplar.

The results suggest that interception losses for both coniferous and deciduous trees are higher within urban environments compared to trees within forested areas. Link et al. (2004) suggested that annual interception losses in temperate forests were observed to range from 11% to 36% of gross precipitation in deciduous, and from 9% to 48% of gross precipitation in coniferous canopies. Bryant et al. (2005) reported 22.3% interception loss in a pine forest. Possible factors contributing to these differences are UHIs, greater distances between trees (edge effect), and open grown canopies. UHIs cause local scale variation in temperature differences between urban and natural forested areas. This is due to replacement of natural vegetation by man made structures where resulting in less evapotranspiration (Taha 1997). 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 et al. 2004). Urban tree canopies are classified as open grown trees due to no inter-tree competition; consequently, they have larger structural dimensions (e.g., larger storage capacity) than trees in forests (Brooks et al. 2003; Horton 1919; Xiao et al. 2002; Xiao et al. 2000b; Zipperer et al. 1997).

Tree health condition and type were assumed 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 co-dominant (poor health condition) and a single (good health condition) Western red cedar intercepted at higher rates compared to other trees of better health conditions and types. A dominant Douglas-fir with poor canopy condition showed the highest interception loss for event 4. Western red cedar trees generally had higher interception losses compared to Douglas-firs. This is due to the differences in canopy structure between the two tree species. For the event in June the interception losses were relatively high for all 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. It is evident that interception loss for the deciduous trees is very low during event 1, 2, and 3, where they do not possess any foliation.

The time delay in throughfall penetrating through the canopy was greatest for events 2 and 4, which ranged from 1.5 – 6.5 h. Event 1 did not show significant delay in throughfall (0.75 – 2.25 h). Event 3 had moderately higher time delays that were lower than event 1. It can be suggested that tree type and health condition played an important role in controlling the time delay. For the four events it was noticed that a Western red cedar tree that was single standing and in a good health condition showed a longer time delay in throughfall. In general coniferous trees had the highest time delay in comparison to deciduous trees. Additionally when evaluating the time delays amongst all species the single standing Poplar in a poor condition showed the earliest time delay in throughfall, followed by Horse chestnut.

Trees generally dampen rainfall intensity; however, there were instances where the throughfall intensity was equivalent to or higher than the actual rainfall intensity. The highest throughfall intensities in event 2 were seen at 63.5 h with rainfall intensity recorded to be 2.41 mmh^{-1}. The throughfall intensity exceeded the actual rainfall intensity except for a Western red cedar tree (tag # 591). The throughfall intensities for the two Douglas-fir trees (tag # 586 and 590) and a Western red cedar (tag # 588) were 6.54 mmh^{-1}, 9.30 mmh^{-1} and 8.0 mmh^{-1}, respectively. Throughfall intensities for Copper beech and Horse chestnut were recorded to be 23.96 mmh^{-1} and 17.37 mmh^{-1}. This variation can be explained by rainfall characteristics, meteorological factors and structure of the canopy. It is evident in Figure 3.11c - Figure 3.13c that high throughfall intensities are delayed in time for lower rainfall intensities. It is suggested that crown density wetness is a factor, where as the crown dampens the drip becomes larger, consequently resulting in higher throughfall intensities (Brooks et al. 2003; Crockford et al. 2000).

The observed reduction in throughfall intensity by tree canopies serves two purposes. First, it delays the 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 (Pypker et al. 2005; Xiao et al. 2002). All the selected events demonstrated a 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. Tree's health condition, type and specie can be suggested to contribute to the differences in throughfall intensities.

4.1.2 Controls on Interception Loss

When we compared the differences in interception losses between summer and winter for individual trees, we found a relationship between the amount of troughfall captured and the season. The canopy structure (leaves) is primarily responsible for two main effects on throughfall. First, it affects the ratio of throughfall to gross precipitation. Deguchi et al.(2006) suggested a decrease in the number of leaves appeared to cause an increase in throughfall. The second effect is the throughfall spatial variability caused by seasonal changes in the canopy structure. This variability can be the result of sampling error or the spatial heterogeneity associated with the canopy structure (Deguchi et al. 2006; Price et al. 2003). It can be noted that the changes in throughfall amount is attributed to the fact that LAI is one of the main factors determining interception loss, in terms of the relationship between LAI and S (Ford et al. 1978; Jetten 1996; Pypker et al. 2005). Interception in tree canopies is affected by the amount, intensity, and duration of precipitation, as well as the air temperature and wind speed (Crockford et al. 2000; Deguchi et al. 2006; Loustau et al. 1992).

In addition to the meteorological factors, there is a strong relationship between throughfall, tree species and health condition. Tree type did not seem to play a significant role in determining the amount of throughfall reaching the ground. Xiao and McPherson (2002) suggested that annual rainfall interception in Santa Monica's urban trees as follows: deciduous trees were responsible for 3.9%, coniferous trees accounted for 23%, and the remaining 73.1% was contributed by palm trees, and broadleaf evergreen trees (Xiao et al. 2000a). Interception can be suggested to be a function of growth form of trees, tree canopy density and structure.

4.1.3 Outcome of Throughfall Gauges

Compared to the traditional methods of measuring gross precipitation and throughfall (measured with funnels, troughs and plastic sheet net rainfall gauges), the innovative design used in this study had high accuracy and time resolution. In addition, these throughfal gauges were designed to overcome the weakness of traditional system, in order to capture the throughfall amount for single standing trees in urban environments. An expected advantage with the hanging pipes draining into shielded rain gauges and data loggers was minimized evaporation. An unanswered issue with the pipe system was the separation of drip from the canopy, as the method was designed to represent an average canopy area sampling. Moreover, random sampling of the length and width of the slits for the PVC pipes for 10 throughfall gauges illustrated that the surface areas remained unchanged over the two-year period. It can be noted that there was a lot of tension on the pipes as they hung from the trees, thus resulting in the slits appearing much smaller. One practical problem was associated with litter from the trees, which gradually accumulated in the pipes and rain gauges where they were removed manually every month. We assumed that the water absorbed by this debris was negligible. Table 3.11 shows that there is a significant difference between the throughfall captured by the pipes and the bottles underneath the canopies. Our results showed that the pipes captured 1.17 times more than the bottles. It is suggested that this is due to the effect of plant community structure, where secondary interception occurs in stratified forest communities where water drips from the canopy and is intercepted by lower plants (Asdak et al. 1998; Brooks et al. 2003; Dunkerley 2000). In many sites, especially Lighthouse Park, Roche Point Park, and Northlands Golf course the ground was covered by seedlings, shrubs and numerous types of ferns (0.5 – 1.5 m in height). Also the branches of many dominant and co-dominant trees seemingly overlaid one another, making it a denser environment for rainwater to penetrate. The estimated understory shrub coverage for the selected trees with tag number 2, 6, 11, 579, and 580 were as following: 55%, 10%, 20%, 70%, and 5% respectively. It is important to note that the selected Douglas-fir tree with tag number 11 had dense coniferous branches overlapping more than 20% of its canopy area particularly where the right pipe was located. Also, there were many smaller/shorter trees and seedling located within the vicinity of the canopy. As a result lower throughfall amount can be seen in both the pipes and the bottles.

Chapter 5
Conclusion

5.1 Review of Key Findings

The goal of this project was to shed some light on rainfall interception by single and stands of trees in urban environments of the North Shore of British Columbia. Rainfall interception was influenced by three factors: characterization and magnitude of the rainfall event, tree species and health condition, and meteorological factors. The trees' ability to dampen rainfall intensity and delay the stormwater to reach the ground was emphasized. Location and seasons contributed to the discrepancy of the interception losses. The inter-species variation on interception was evident as Western red cedar showed higher interception losses, longer time delays and lower throughfall intensities when compared to Douglas-fir and deciduous trees during event analysis. It is important to note that Douglas-fir followed by Western red cedar showed the highest interception losses during both summer and winter. Interception losses for coniferous and deciduous trees averaged to be 76.5% and 56.4% respectively. On average control trees located in forested areas showed 1.12 times less interception loss than urban trees.

The innovative throughfall gauges confirmed that the design worked effectively in capturing a good representation of throughfall from individual tree canopies. Our results suggested that 1.17 times more throughfall was captured by the pipes when compared to the bottles installed underneath the canopies. Based on the previous methods/research (roving bottles and rain gauges), the obtained interception losses from the throughfall data attained from the pipes should be higher than what we estimated.

The data obtained from this research will be used in the Water Balance Model powered by QUALHYMO (QUALity HYdrology MOdels). As urban development progresses, extensive areas of our natural landscape are converted into impervious surfaces such as roads, parking lots, driveways and buildings. Human-made drainage systems such as sewers and storm drains are built to enhance runoff movement through cities and into drainage and natural waterways, where the water quality is negatively impacted when runoff carries contaminants. Therefore, this tool will help determine the water balances at individual properties in order to provide data and additional information for different stakeholders to utilize in the planning of future urban development.

It is also important to note that we are in need of better stormwater management. Using natural vegetation as a low impact development and best management practice can be an effective technique as it controls stormwater runoff on site, mitigating the impacts of urbanization on urban hydrology at a local scale.

5.2 Future Research

There are many avenues down which this study can be expanded upon. Future research projects could focus on (a) measurement of stem and epiphyte moisture; (b) measurement of spatial variability of throughfall; (c) deeper look at the affects of trees' health condition on interception loss; (d) identifying soil moisture pattern; (e) assessment of seasonal variability of LAI; (f) application of different model in combination with detailed micrometeorological measurements to evaluate the effects of interception loss for urban trees; and (g) determining the amount of stormwater runoff which can be reduced and delayed from individual properties by urban trees.

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Appendix A

Seasonal regression coefficients for the 54 trees

Tag #	Winter b_0 [b]	Winter b_1 [c]	Winter R^2	Winter SE[a]	F statistic	d.f.	P-value	Summer b_0 [b]	Summer b_1 [c]	Summer R^2	Summer SE[a]	F statistic	d.f.	P-value
1	-4.86	0.85	0.97	3.50	2141	66	< 2.2e-16	-2.17	0.63	0.88	4.13	518.7	73	<2.2e-16
2	-2.67	0.95	0.99	2.72	5188	70	< 2.2e-16	-3.58	0.90	0.97	3.23	1634	59	<2.2e-16
3	-4.97	0.93	0.93	4.53	1067	75	< 2.2e-16	-5.15	0.85	0.95	3.45	1331	73	< 2.2e-16
4	-4.59	0.85	0.98	2.73	4212	76	< 2.2e-16	-2.88	0.70	0.94	3.05	1152	73	< 2.2e-16
5	-6.04	0.75	0.94	4.38	1273	76	< 2.2e-16	-3.58	0.64	0.87	4.00	450.9	66	< 2.2e-16
6	-7.59	0.82	0.95	4.68	1286	67	< 2.2e-16	-5.07	0.75	0.92	3.93	785.8	68	< 2.2e-16
7	-2.10	0.95	0.99	2.03	7840	71	< 2.2e-16	-3.46	0.91	0.98	2.08	4215	73	< 2.2e-16
8	-2.90	0.86	0.98	2.93	3140	56	< 2.2e-16	-2.75	0.51	0.88	3.32	494.5	65	< 2.2e-16
9	-3.12	0.93	0.98	2.98	4009	71	< 2.2e-16	-3.81	0.85	0.95	3.30	1463	73	< 2.2e-16
10	-3.37	0.94	0.99	2.49	5855	71	< 2.2e-16	-4.86	0.84	0.92	4.27	850.8	75	<2e-16
11	-9.63	0.72	0.80	8.65	289.9	71	< 2.2e-16	-1.99	0.21	0.35	4.96	45.84	84	<1.63e-09
12	-7.37	0.80	0.94	5.06	1039	71	< 2.2e-16	-2.17	0.42	0.60	5.84	113.5	76	< 2.2e-16
13	-6.82	0.72	0.93	4.89	889.6	71	< 2.2e-16	-3.30	0.53	0.80	4.20	329.4	80	< 2.2e-16
14	-8.87	0.87	0.98	4.13	976.4	18	< 2.2e-16	-1.78	0.39	0.93	2.15	666.3	50	< 2.2e-16
15	-3.40	0.64	0.97	2.83	2137	71	< 2.2e-16	-3.18	0.66	0.94	2.92	1272	84	< 2.2e-16
16	-3.43	0.55	0.93	7.37	107.7	8	6.43e-06	0.00	NA	0.00	NA	-	-	-
17	-4.48	0.73	0.94	5.00	1136	78	< 2.2e-16	-5.83	0.70	0.81	8.41	363.4	85	< 2.2e-16
18	-3.43	0.79	0.95	3.64	792.8	38	< 2.2e-16	-5.24	0.81	0.95	4.89	1067	58	< 2.2e-16
19	-2.33	0.91	0.99	2.96	5978	63	< 2.2e-16	-5.48	0.89	0.93	6.26	896.6	63	< 2.2e-16
20	-3.05	0.96	0.98	2.18	2111	39	< 2.2e-16	-4.96	0.91	0.95	4.88	1529	75	< 2.2e-16
21	-3.91	0.96	0.98	2.63	3193	58	< 2.2e-16	-5.81	0.93	0.96	4.95	1441	61	< 2.2e-16
22	-3.86	0.92	0.99	3.35	4844	73	< 2.2e-16	-4.72	0.89	0.96	4.36	1971	85	< 2.2e-16
23	-3.40	0.99	0.99	2.36	4186	62	< 2.2e-16	-4.58	0.96	0.98	3.35	3725	70	< 2.2e-16
24	-4.28	0.95	0.98	3.22	4741	78	< 2.2e-16	-4.50	0.92	0.97	4.25	2076	73	< 2.2e-16
25	-2.10	0.94	0.99	1.53	3813	41	< 2.2e-16	-2.31	0.80	0.94	2.52	816.4	49	< 2.2e-16
26	-1.94	0.95	1.00	1.54	4557	13	< 2.2e-16	-2.02	0.85	0.98	1.72	1317	32	< 2.2e-16
27	-1.64	0.91	1.00	1.09	26410	37	< 2.2e-16	-3.54	0.92	0.99	2.97	4168	61	< 2e-16
28	-2.53	0.96	1.00	2.06	9475	33	< 2.2e-16	-2.51	0.83	0.96	2.55	1643	69	< 2.2e-16
100	-2.40	0.65	0.87	3.76	277.6	42	< 2.2e-16	-1.99	0.56	0.93	2.27	765.3	55	< 2.2e-16
200	-2.15	0.50	0.91	3.44	635.8	66	< 2.2e-16	-2.42	0.45	0.94	3.85	1061	68	< 2.2e-16
579	-4.86	0.78	0.96	3.65	1954	76	< 2.2e-16	-2.40	0.54	0.86	3.62	505	79	< 2.2e-16
580	-4.53	0.70	0.94	4.05	1296	76	< 2.2e-16	-1.92	0.42	0.84	3.09	444.9	83	< 2.2e-16
581	-4.08	0.93	0.99	2.76	4698	65	< 2.2e-16	-3.53	0.81	0.96	2.72	1155	43	< 2.2e-16
582	-4.49	0.80	0.96	3.74	1915	72	< 2.2e-16	-4.37	0.78	0.95	3.05	1032	57	< 2.2e-16
583	-4.66	0.61	0.86	6.36	362.6	59	< 2.2e-16	-1.20	0.34	0.78	3.27	244.1	67	< 2.2e-16
585	-2.54	0.51	0.69	5.13	127.1	57	3.87e-16	-3.55	0.50	0.54	6.26	43.4	37	1.01e-07
586	-6.41	0.82	0.93	6.41	1088	84	< 2.2e-16	-3.86	0.51	0.92	3.77	710.4	62	< 2.2e-16
587	-2.89	0.51	0.87	4.08	375.8	58	< 2.2e-16	-2.11	0.38	0.93	2.91	734.2	55	< 2.2e-16
588	-5.45	0.68	0.91	5.43	840.6	82	< 2.2e-16	-1.69	0.35	0.91	2.64	845.1	79	< 2.2e-16
590	-3.57	0.88	0.98	3.14	5206	84	< 2.2e-16	-3.67	0.84	0.97	3.87	2105	67	< 2.2e-16
591	-4.82	0.61	0.89	5.70	612.5	79	< 2.2e-16	-1.43	0.30	0.90	2.37	809.1	89	< 2.2e-16
592	-3.45	0.92	0.99	2.51	7548	67	< 2.2e-16	-5.02	0.80	0.94	6.48	1131	66	< 2.2e-16
593	-3.24	0.89	0.98	2.96	2888	54	< 2.2e-16	-4.35	0.88	0.97	4.54	3024	82	< 2.2e-16
594	-3.39	0.93	0.98	2.63	2350	48	< 2.2e-16	-4.11	0.87	0.99	3.68	3898	49	< 2.2e-16
595	-2.06	0.64	0.96	1.97	855.5	37	< 2.2e-16	-1.94	0.60	0.94	2.34	837.3	52	< 2.2e-16
596	-3.49	0.73	0.98	2.84	2014	51	< 2.2e-16	-2.10	0.57	0.94	2.44	1237	73	< 2.2e-16
597	-2.87	0.89	0.98	2.76	1953	48	< 2.2e-16	-5.20	0.90	0.98	4.58	2600	40	< 2.2e-16
598	-2.90	0.57	0.95	3.89	1230	70	< 2.2e-16	-2.35	0.41	0.92	4.04	828.2	70	< 2.2e-16
599	-3.07	0.55	0.91	4.78	749.3	77	< 2.2e-16	-4.18	0.60	0.95	4.53	1389	70	< 2.2e-16
1033	-3.10	0.91	0.98	2.87	3029	51	< 2.2e-16	-2.86	0.75	0.94	3.33	1082	66	< 2.2e-16
1408	-3.54	0.95	0.98	3.25	2786	58	< 2.2e-16	-4.48	0.91	0.98	4.64	2966	70	< 2.2e-16

Tag #	Winter b_0 [b]	Winter b_1 [c]	Winter R^2	Winter SE[a]	F statistic	d.f.	P-value	Summer b_0 [b]	Summer b_1 [c]	Summer R^2	Summer SE[a]	F statistic	d.f.	P-value
1409	-3.33	0.62	0.90	5.82	658.5	76	< 2.2e-16	-1.84	0.48	0.96	3.02	1991	74	< 2.2e-16
1411	-3.62	0.68	0.94	4.42	980.9	61	< 2.2e-16	-4.50	0.73	0.97	4.56	1960	65	< 2.2e-16
4607	-3.89	0.94	0.98	3.18	3631	60	< 2.2e-16	-5.59	0.77	0.92	7.57	844.1	76	< 2.2e-16

[a]SE = Standard Error

[b] b_0 = Intercept

[c] b_1 = Slope